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The Evolution and Active Management of the Future Electricity Distribution Networks Providing Ancillary Services

ACTA WASAENSIA 475

Vaasan yliopisto
UNIVERSITY OF VAASA

ACADEMIC DISSERTATION

To be presented, with the permission of the Board of School of Technology and Innovation of the University of Vaasa, for public examination on the 17th of December, 2021, at noon.

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Julkaisija	Julkaisupäivämäärä	
Vaasan yliopisto	Joulukuu 2021	
Tekijä(t) Katja Sirviö	**Julkaisun tyyppi** Artikkeliväitöskirja	
ORCID tunniste	**Julkaisusarjan nimi, osan numero** Acta Wasaensia, 475	
Yhteystiedot Vaasan yliopisto Tekniikan ja innovaatiojohtamisen yksikkö Sähkötekniikka PL 700 FI-65101 VAASA	**ISBN** 978-952-476-994-5 (painettu) 978-952-476-995-2 (verkkoaineisto) https://urn.fi/URN:ISBN:978-952-476-995-2 **ISSN** 0355-2667 (Acta Wasaensia 475, painettu) 2323-9123 (Acta Wasaensia 475, verkkoaineisto)	
	Sivumäärä 241	**Kieli** englanti

Julkaisun nimike
Lisäpalveluja tarjoavien tulevaisuuden sähkönjakeluverkkojen kehittyminen ja hallinta

Tiivistelmä

Ilmastotavoitteiden vuoksi energiamurros, energiasektorin voimakas kehittyminen, harppaus uuteen tuotantotapaan ja järjestelmään tapahtuu sosioteknisessä, -ekonomisessa ja -ekologisessa viitekehyksessä, jonka myötä sähköjärjestelmä kehittyy kohti älysähköverkkoa (Smart Grid), tulevaisuuden energiajärjestelmän keskeistä infrastruktuuria. Tämän väitöskirjan painopisteenä on sähkönjakelujärjestelmän sosiaalistekninen kehittymispolku kohti älysähköverkkoa, missä ihmiset, koneet, laitteet ja toimintajärjestelmät ovat toisistaan riippuvaisia ja niiden keskinäinen vuorovaikutus kasvaa. Älysähköverkkojen kehittämisen ydin on uusiutuvan energiantuotannon osuuden, hajautetun energiantuotannon ja varastoinnin lisääminen sekä näiden hyödyntäminen energiajärjestelmän toiminnassa. Hajautettujen energiaresurssien (tuotanto, varasto, kuorma) hallinnalla tavoitellaan sähköjärjestelmän joustavuuden ja luotettavuuden lisäämistä sekä paikallisen energiaomavaraisuuden kasvua.

Sähköjärjestelmän joustavuutta edistetään hajautettujen energiaresurssien tarjoamilla lisäpalveluilla. Hajautettujen energiaresurssien integrointi ja toiminta sähkönjakeluverkossa tuo haasteita verkon kehittämiselle, koska siihen osallistuu useita erilaisia sidosryhmiä ja toimijoita, joiden tarpeet on täytyttävä. Keskeistä tulevaisuuden sähkönjakeluverkon kehittymisessä on megatrendien, trendien sekä kehittyvien teknisten ja regulatiivisten näkökulmien sekä taloudellisten hyötyodotusten lisäksi toimijoiden dynaamisten ja erilaistuvien roolien tunnistaminen ja analysointi. Tässä väitöskirjassa tarkastellaan energiamurroksen viitekehyksiä, tulevaisuuden energiajärjestelmän visioita sekä energiamurroksen onnistumisen edellytyksiä sähkönjakeluverkkojen kehittämisessä. Keskeisiksi konsepteiksi nostetaan aktiivinen sähkönjakeluverkko ja mikroverkko. Tulevaisuuden sähkönjakeluverkkojen hallinnassa todetaan siirtoverkko- sekä jakeluverkkotason lisäpalvelujen mahdollistamisen olevan keskeisiä. Konseptien kehittämisen ja realisoinnin jouduttamisessa osoitetaan hardware-in-the-loop (HIL) -testauksen olevan avainasemassa. Väitöskirjan tuloksena on sähkönjakeluverkkojen kehittymisen sosiaalistekninen ja nelivaiheinen tiekartta, joka kuvaa tavoiteskenaarion eli älysähköverkkovision kehittymispolun.

Asiasanat
Microgrid, mikroverkko, älysähköverkko, hajautetut energiaresurssit, aktiivinen sähkönjakeluverkko, reaaliaikasimulointi, sähkönjakeluverkon kehittyminen

Publisher	Date of publication	
Vaasan yliopisto	December 2021	
Author(s) Katja Sirviö	**Type of publication** Doctoral thesis by publication	
ORCID identifier	**Name and number of series** Acta Wasaensia, 475	
Contact information University of Vaasa School of Technology and Innovations Electrical Engineering PO. Box 700 FI-65101 Vaasa Finland	**ISBN** 978-952-476-994-5 (print) 978-952-476-995-2 (online) https://urn.fi/URN:ISBN:978-952-476-995-2 **ISSN** 0355-2667 (Acta Wasaensia 475, print) 2323-9123 (Acta Wasaensia 475, online)	
	Number of pages 241	**Language** English

Title of publication

The Evolution and Active Management of the Future Electricity Distribution Networks Providing Ancillary Services

Abstract

Through the climate targets, the energy transition, a revolution in the energy sector, takes place in the socio-technical, -economic, and -ecological frameworks. The power system is evolving towards a Smart Grid along with the energy transition, envisioned as the future energy system's critical infrastructure. This dissertation examines the development of the power system from a socio-technical perspective, as the power system is a typical socio-technical system where people, machines, and operating systems are interdependent and interact. The increase in the share of renewable energy generation, the growth in distributed generation (DG) and storage, and their utilisation in the electricity system's operation are essential for developing Smart Grids. Distributed energy resources (DERs), including DG, storage, and controllable loads, are used to increase the power system's flexibility, reliability, and local energy self-sufficiency. Ancillary services (ASs) provided by DERs increase the flexibility of the power system. The integration of DERs poses challenges for developing the electricity distribution networks, as it involves several stakeholders and actors whose needs must be satisfied. Central to developing future electricity distribution networks is recognizing and analysing megatrends, trends and the developing technical, economic and regulatory signals, and identifying the changing and differentiating actor roles. This dissertation examines the frameworks of the energy transition, visions, and scenarios of the future energy system and the preconditions for the energy transition's success concerning the electricity distribution networks. The active electricity distribution networks (ADNs) and microgrids are raised as the key concepts to develop an intelligent electricity distribution grid. The management needs of the electricity distribution networks are mapped, which states that the provision of various ASs for both transmission and distribution levels is central. In accelerating the development and implementation of new or advanced concepts, hardware-in-the-loop (HIL) testing is recognised as a key role. The thesis's result is a socio-technical, four-phase roadmap of the electricity distribution networks' evolution towards the vision, describing the target scenario, the operation in Smart Grids.

Keywords

Microgrid, Smart Grids, distributed energy resources, active electricity distribution network, real-time simulation, electricity distribution network evolution

ACKNOWLEDGEMENT

This thesis work was carried out during 2013 – 2021 at the University of Vaasa and started in the Smart Electric Systems research group in the Department of Electrical Engineering and Energy Technology, currently in the School of the Technology and Innovations through an organisational change.

Several research programmes funded the thesis work. The first period 2013 – 2014, was funded from a national Smart Grids and Energy Markets (SGEM) programme that Tekes mainly funded. The next phase, 2017 – 2021, was funded by the international DeCAS programme, the regional Smart Energy Systems Platform (SESP), and Vaasa Innovation Platform for Future Power Systems (Vinpower) programmes, and the national Fleximar and SolarX research programs. I am grateful for the funding of the eight-week laboratory access in 2018 to the OFFIS's Smart Energy Simulation and Automation (SESA) laboratory within the EriGRID's transnational access (TA) programme from the EU's Horizon 2020. I am also grateful for the scholarship for a postgraduate course from Sähköinsinööriliiton säätiö.

I am grateful to my supervisors for their invaluable advice, continuous support, and patience during my thesis work. My thesis supervisors were Emeritus Professor Erkki Antila, Professor Kimmo Kauhaniemi, and Professor Hannu Laaksonen. Professor Antila inspired and motivated me to conduct this thesis, and he got me interested in electricity distribution grid management. Professor Kauhaniemi, the responsible supervisor, directed me to consider the idea of network evolution, particularly towards microgrids. Professor Laaksonen attracted my research interest in utilising distributed energy resources in the various services of the power system. I thank you all most humbly.

I sincerely appreciate the pre-examiners, Professor Pertti Järventausta from Tampere University of Technology, Finland and Professor Pierluigi Mancarella from University of Melbourne, Australia.

I warmly thank those involved in the practical work and collaboration, Petra Berg, Mike Mekkanen, Lauri Kumpulainen from the University of Vaasa, Ari Salo from Vaasan Sähköverkko, Davood Babazadeh and Felipe Castro from OFFIS, Nikos Hatziargyriou and Panagiotis Pediaditis from NTUA.

I express my heartfelt thanks to my friends Minna, Katja, Lauri, Johanna, Sampo, and Terhi for being there and supporting me with this task.

Tarja, I thank you for the valuable and supporting discussions.

I am truly grateful to my family. I want to express my deepest thanks and apologies to my dearest children Olli-Eemeli, Paula, Miska, Mitro, and Lauri. You are the reason that I pursued this task. To explain this task for you, I quote the song The Story (words and music by Phillip Hanseroth) interpreted by Dolly Parton:

> "I climbed across the mountain tops
>
> Swam all across the ocean blue
>
> I crossed all the lines, and I broke all the rules
>
> But, baby, I broke them all for you
>
> Because even when I was flat broke
>
> You made me feel like I got a million bucks
>
> You do
>
> I was made for you".

Special thanks to you, my husband, Heikki. You are my great love – we are a team in both good and bad circumstances.

Mother, I want to give you my deepest thanks. You know me thoroughly and everything I did. The power of your love supported this task too.

Father, I am so sorry that you had to leave in the middle of everything, and we could not share this experience and the scores.

My dearest sister Terhi, you are the most positive and encouraging person I know. I will always save the magnifying glass you gave me when I started this work, with the words: "whatever you examine, do it carefully". I hope I did so.

Contents

Figures

Tables

Abbreviations

ADN	Active Distribution Network
ADNP	Active Distribution Network Planning
ADNM	Active Distribution Network Management
AI	Artificial Intelligence

AMI	Advanced Metering Infrastructure
AS	Ancillary Service
BAU	Business As Usual
BBB	BeagleBone Black
BESS	Battery Energy Storage System
CHIL	Controller Hardware-In-the-Loop
CHP	Combined Heat and Power
CM	Capacity Market
CO_2	Carbon dioxide
CPP	Critical Peak Pricing
DA	Distribution Automation
DB	Demand Bidding
DER	Distributed Energy Resource
DG	Distributed Generation
DLC	Direct Load Control
DMS	Distribution Management System
DNO	Distribution Network Operator
DR	Demand Response
DSM	Demand Side Management
DSO	Distribution System Operator
EC	European Commission
ED-CPP	Extreme Day Critical Peak Pricing
EDP	Extreme Day Pricing
EEA	European Environment Agency
EENS	Expected Energy Not Supplied
EMT	Electro Magnetic Transient
ENTSO-E	European Network of Transmission System Operators for Electricity
EPRI	Electric Power Research Institute
ES	Energy Storage
ESAIFI	Expected System Average Interruption Frequency Index
ETIP	European Technology & Innovation Platform
EU	European Union
EV	Electric Vehicle
FCP	Frequency Containment Process

FCR	Frequency Containment Reserves
FCR-D	Frequency Containment Reserves for Disturbances
FCR-N	Frequency Containment Reserves for Normal operation
FFR	Fast Frequency Reserves
FPGA	Field-Programmable Gate Array
FRP	Frequency Restoration Process
FRR	Frequency Restoration Reserves
FRT	Fault Ride Through
GHG	Green House Gas
GIS	Geographical Information System
GOOSE	Generic Object-Oriented Substation Event
HAN	Home Area Networks
HIL	Hardware-In-the-Loop
HL-UC	High-Level Use Case
IBP	Incentive Based Programmes
ICT	Information and Communication Technologies
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IEEE	Institute of Electrical and Electronics Engineers
IES	Integrated Energy System
IoT	Internet of Things
IRL	Integration Readiness Level
LC	Low Carbon
LV	Low Voltage
MEAE	Ministry of Employment and Economic Affairs of Finland
MG	Microgrid
MLP	Multi-Level Perspective
MMS	Microgrid Management System
MV	Medium Voltage
NIST	National Institute of Standards and Technology
OC	Overcurrent
PBP	Price Based Programme
PHIL	Power Hardware In the Loop
POI	Point Of Interconnection
PSRL	Power System Readiness Level

PUC	Primary Use Case
PV	Photovoltaic
RDI	Research, Development and Innovation
RES	Renewable Energy Resource
RMS	Root Mean Square
RPW	Reactive Power Window
RTP	Real Time Pricing
SGAM	Smart Grid Architecture Model
SET	Strategic Energy Technology
SIL	Software-In-the-Loop
SNET	Smart Networks for Energy Transition
SNM	Strategic Niche Management
SOP	Soft Open Point
SRL	System Readiness Level
STET	Socio-technical Energy Transition
STS	Socio-technical Scenarios
TDN	Traditional Distribution Network
TDNP	Traditional Distribution Network Planning
TM	Transition Management
TOU	Time Of Use
TRL	Technology Readiness Level
TRM	Technology Roadmapping
TSO	Transmission System Operator
TUC	Test Use Case
UC	Use Case
UML	Unified Modelling Language
VUF	Voltage Unbalance Factor
VPP	Virtual Power Plant
WT	Wind Turbine

Publications

This dissertation is based on the following appended papers:

I Sirviö, K., Kauhaniemi, K., & Antila, E. (2013). ”Evolution Phases for Low Voltage Distribution Network Management”. IEEE PowerTech Conference, Grenoble, doi: 10.1109/PTC.2013.6652449.

II Sirviö, K., Berg, P., Kauhaniemi, K., Laaksonen, H., Laaksonen, P. & Rajala, A. (2018). ”Socio-technical Modelling of Customer Roles in Developing Low Voltage Distribution Networks”. CIRED Workshop on Microgrids and Local Energy Communities, Ljubljana, doi: 10.34890/411.

III Sirviö, K., Laaksonen, H., & Kauhaniemi, K. (2018). ”Active Network Management Scheme for Reactive Power Control”. CIRED Workshop on Microgrids and Local Energy Communities, Ljubljana, doi: 10.34890/103.

IV Sirviö, K., Välkkilä, L., Laaksonen, H., Kauhaniemi, K., & Rajala, A. (2018). ”Prospects and Costs for Reactive Power Control in Sundom Smart Grid”. Proceedings of 2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe 2018), Sarajevo, doi: 10.1109/ISGTEurope.2018.8571695.

V Sirviö, K., Mekkanen, M., Kauhaniemi, K., Laaksonen, H., Salo, A., Castro, F., Ansari, S., & Babazadeh, D. (2019). ”Controller Development for Reactive Power Flow Management between DSO and TSO Networks”. Proceedings of 2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe 2019), Bucharest, doi: 10.1109/ISGTEurope.2019.8905578.

VI Sirviö, K., Mekkanen, M., Kauhaniemi, K., Laaksonen, H., Salo, A., Castro, F., Ansari, S., & Babazadeh, D. (2019). “Testing an IEC 61850-based Light-weighted Controller for Reactive Power Management in Smart Distribution Grids”. IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society, Lisbon, doi: 10.1109/IECON.2019.8927232.

VII Sirviö, K. H., Mekkanen, M., Kauhaniemi, K., Laaksonen, H., Salo, A., Castro, F., & Babazadeh, D. (2020). ”Accelerated Real-Time Simulations for Testing a Reactive Power Flow Controller in Long-Term Case Studies”. Journal of Electrical and Computer Engineering, article ID 8265373, doi: 10.1155/2020/8265373.

VIII Sirviö, K., Kauhaniemi, K., Ali Memon, A., Laaksonen, H., & Kumpulainen, L. (2020). ”Functional Analysis of the Microgrid Concept Applied to Case Studies of the Sundom Smart Grid”. Energies, 13(16), Article ID 4223, doi: 10.3390/en13164223.

IX Sirviö, K., Laaksonen, H., Kauhaniemi, K., & Hatziargyriou, N. (2021). ”Evolution of the Electricity Distribution Networks – Active Management Architecture Schemes and Microgrid Control Functionalities”. Applied Sciences 11(6), Article ID 2793, doi: 10.3390/app11062793.

Author's contribution

Sirviö is the first and main author of all publications (Publication I-IX), and she defined their research design. She chose the qualitative research methodology and methods for all publications, wrote the original articles' body text, and edited the articles at different stages. Other specific contributions are presented below.

Publication I: Sirviö collected and managed the research material. She analysed the data and chose the tools. Sirviö verified and analysed the findings and visualised the results. Kauhaniemi and Antila provided comments on the paper.

Publication II: Sirviö and Berg collected, and Sirviö managed the research material. Berg presented MLP and SNM theories, which Sirviö applied to LV distribution network evolution. Sirviö analysed the data and chose the tools. Sirviö verified and analysed the findings and visualised the results. Berg, Kauhaniemi, H. Laaksonen, P. Laaksonen, and A. Rajala provided comments on the paper.

Publication III: Sirviö collected and managed the research material. She analysed the data and chose the tools. Sirviö developed a control algorithm and case studies. She verified and analysed the findings and visualised the results. Laaksonen and Kauhaniemi provided comments on the paper.

Publication IV: Sirviö collected and managed the research material. Sirviö analysed the data and chose the tools. Sirviö provided a control algorithm and developed case studies. Välkkilä provided economic calculations. Sirviö verified and analysed the findings and visualised the results. Laaksonen, Kauhaniemi and Rajala provided comments on the paper.

Publication V: Sirviö and Mekkanen collected and managed the research material. Sirviö analysed the data. Sirviö, Castro and Mekkanen chose the tools. Sirviö developed the real-time simulation models of the power system and the controller and case studies. Castro developed the migration code. Mekkanen and Ansari implemented the real-time simulation models of the communications. Mekkanen implemented the control algorithm into the BBB hardware. Sirviö and Mekkanen verified and analysed the findings. Sirviö visualised the results. Kauhaniemi, Laaksonen, Salo, Castro, Ansari and Babazadeh provided comments on the paper. Sirviö acquired funding for the research visit.

Publication VI: Sirviö and Mekkanen collected and managed the research material and analysed the data. Sirviö and Mekkanen chose the tools. Sirviö utilised the SIL, and CHIL real-time simulation platform developed in Publication V. Mekkanen implemented the control algorithm into the FPGA hardware and provided the round-trip latency calculations. Sirviö and Mekkanen verified and analysed the findings and visualised the results. Kauhaniemi, Laaksonen, Salo, Castro, Ansari and Babazadeh provided comments on the paper. Sirviö acquired funding for the research visit.

Publication VII: Sirviö collected and managed the research material. She analysed the data and chose the tools. Sirviö utilised the SIL and CHIL real-time simulation platform developed in Publication V. Sirviö verified and analysed the findings. Mekkanen, Kauhaniemi, Laaksonen, Salo, Castro, and Babazadeh provided comments on the paper. Sirviö acquired funding for the research visit.

Publication VIII: Sirviö collected and managed the research material. She analysed the data and chose the tools. Sirviö developed the energy management and the power balance management use cases. Kauhaniemi and Memon provided the protection use cases. Sirviö verified and analysed the findings. Kauhaniemi, Memon, Laaksonen, and Kumpulainen provided comments on the paper.

Publication IX: Sirviö collected and managed the research material and chose the tools. Sirviö verified and analysed the findings. Laaksonen, Kauhaniemi, and Hatziargyriou provided comments on the paper.

1 INTRODUCTION

Global climate change has led to the goal of reducing greenhouse gas (GHG) emissions. The European Union (EU) has set strategies and targets for reducing carbon dioxide (CO2) emissions, including the Climate and Energy Package 2020, the Climate and Energy Framework 2030, and a long-term climate strategy until 2050. The aim is to transform Europe into an energy-efficient and climate-neutral society by 2050, a net-zero GHG emission economy with a significant share of renewable energy. By 2030 the GHG emissions should be decreased by 40 % compared to 1990 levels, the share of renewable energy 32 %, and 32.5 % improvement in energy efficiency. The European Commission (EC) proposes an updated Climate Target Plan 2030, with a 55 % GHG reduction target. It was published together with the amended proposal for a European Climate Law, making the 55 % target compulsory. (EC, 2020a, 2020b)

The energy transition is ongoing globally, and the visions of the future energy system and Smart Grids are developed worldwide. The Smart Grids comprise the power system from bulk generation via transmission and distribution to the customers with flexibility and self-healing capabilities. The distributed energy resources (DERs) are the critical enabler. The Electric Power Research Institute (EPRI) proposed a concept of the Smart Grids in 2002. Since then, the researchers and various stakeholders have established strategies, goals, and pathways to develop the Smart Grids. The Smart Grids are envisioned to be operated intelligently, securing safe and reliable electricity distribution, offering energy savings, achieving efficient use of energy, and actioning in the advanced energy markets (EC, 2006; EPRI, 2009; Energy Information and Security Act, 2007). Visions for the Smart Grids or the future energy system are presented for the U.S. (Energy & Office of Electricity Delivery and Energy Reliability, 2009). State Grid Corporation of China released its vision and developmental roadmap in 2009 (Brunekreeft et al., 2015).

The EC has set up European Technology & Innovation Platforms (ETIPs) as part of a new Strategic Energy Technology (SET) Plan, bringing together a range of energy stakeholders and experts to support decision-making in the energy transition. The ETIP on Smart Networks for Energy Transition (SNET) guides the research, development, and innovation (RDI) supporting the energy transition in Europe. ETIP SNET presents a recent vision 2050 for the EU countries (ETIP SNET, 2018). (ETIP SNET, 2017)

1.1 Background and motivation

In order to achieve the ambitious climate targets, the future energy infrastructure must be upgraded so that the different energy vectors are interconnected, which are the systems of electricity, heating and cooling, gas, and data (ETIP SNET, 2018). Various energy conversions are utilised to use energy cleanly, efficiently, and flexibly in the future energy infrastructure, where the future power system or the Smart Grids act as the backbone (ETIP SNET, 2018). From the environmental perspective, the Smart Grids' primary objective is to reduce GHG emissions essentially by utilising local renewable energy resources (RESs), which also improves efficiency by reducing electricity transmission losses.

The development of the Smart Grids and the related political, societal, and economic implications are considered in the transition theories and frameworks (Bettin, 2020). Transition pathway development includes socio-ecological, socio-economic, socio-technical, and action-oriented perspectives (EEA, 2019). In the Smart Grid operation, the future electricity distribution networks or intelligent electricity distribution networks are described to operate flexibly by connecting different actors and stakeholders. Actors are the system operators of the electricity distribution networks, including the person roles, equipment, and systems. Stakeholders are actors who have economic or social benefit expectations. The existing actors like regulators, utility companies, vendors, and customers, and the emerging actors like aggregators and prosumers face questions like what kind of role(s) they have in the future electricity networks and which kind of systems fulfil the various needs. Therefore, the Smart Grids' development pathway should be originated and described so that various actors and stakeholders can comprehend and experience it and recognise the so-called "windows of opportunities" as named in (Geels, 2002).

New concepts are developing for future electricity distribution networks based on DERs utilisation. Two famous concepts utilising DERs are the active distribution networks (ADNs) and the microgrids. Pilots of the ADN solutions and the microgrids have been created around the world numerously, and the recent reviews and the surveys of projects give good descriptions of the concepts and the main drivers of the microgrids implementation (Chen et al., 2020; Farrelly & Tawfik, 2020; Gangale et al., 2017; Hirsch et al., 2018; Parag & Ainspan, 2019; Warneryd et al., 2020).

However, the current electricity distribution system's pathway to the vision 2050 (ETIP SNET, 2018) or the Smart Grids' flexible operation should be a concrete plan, a road map, including the major steps or milestones needed to reach the vision. Also, it should serve as a communication tool helping articulate the stakeholders' strategic thinking. The pathway should illustrate the network evolution by phases. Different stakeholders could then understand the system's common functionalities and operational scenarios from the outlined presentation of the management system's schemes and structure.

The roadmap development in different levels is crucial and becoming topical. CSIRO & Energy Networks Australia (2017) published a ten-year (2017-27) transformation roadmap of the power system towards Australia's 2050 goals. Electricity Networks Association (2019a) published an excellent example of a roadmap for the electricity distribution networks in New Zealand, including action plans for the stakeholders' collaboration. A draft of "Roadmap for commercialising microgrids in California" is getting attention in recent research of implementing Smart Grids and microgrids objectives (Ajaz & Bernell, 2021; Gust et al., 2021).

The core elements of the future electricity distribution networks (like loads, energy generation units, storage units, smart meters, and protection devices) are aimed to provide services and functions for the conceptual-level functions, like microgrid functions (Publication VIII). The development of functionalities and services provided by the DERs is an essential topic in ADN planning and operation, as indicated in Ehsan & Yang (2019), Ghadi et al. (2019), R. Li et al. (2017), Ul Abideen et al. (2020), and Xiang et al. (2016). The services, operations, and functionalities across the voltage levels are increasingly started to be explored. Nevertheless, the evolving network actors (such as consumers, energy and grid companies, network management systems, and DER units) have been addressed to a small extent from the operational opportunities perspective they can provide at the different development stages of the electricity distribution networks. Therefore, a holistic analysis is needed. First, a behavioural system analysis of the future evolving electricity distribution networks by developing operational scenarios is needed. Secondly, the behavioural system analysis should be processed in a structural analysis, giving an advantageous basis for common understanding with all the stakeholders.

A set of functions implement the developed functionalities through the control and management systems. Especially microgrids management is topical since they must be able to operate independently and coordinate the operation of several DERs and subsystems. Therefore, an overall microgrid management system (MMS) needs to be specified. The MMSs can realise the concept(s) and algorithms by different methods. Also, the development and testing platforms must be established. For that purpose, various real-time simulation and hardware-in-the-loop (HIL) testing platforms are increasingly utilised because of their accelerating effect in the RDI.

The development of the power systems should be realised based on standardized solutions. The IEEE and IEC standards for AC microgrids are developing, especially for the control and management. Standards for microgrids have been published in some extent (IEC, 2017, 2018, 2020; IEEE, 2018a, 2018b, 2018c, 2019, 2020) and some are coming in the next few years (IEC, 2021, 2022a, 2022b, 2023). For example, different vendor-specific microgrid controllers are developed and launched (ABB, 2017; Emerson, 2017; Schneider Electric, 2016; Schweitzer Engineering Laboratories, 2018; Siemens, 2018; Sustainable Power Systems, 2015) and tested (Liu et al., 2016). However, vendor-defined solutions might not meet the interoperability and grid-code requirements. Also, there is a lack of standardised testing requirements for microgrid control (Joos et al., 2017), but they are started to emerge (for example IEEE 2030.8). Despite the situation of standardisation, the different solutions for microgrid management are becoming increasingly global.

Overall, the evolution of the electricity distribution networks can be claimed to consist of the successful realisation of the new concepts for the active electricity distribution network management in the power system transition phenomenon. Therefore, a comprehensive roadmap of the evolving electricity distribution networks should be developed in a manner that the stakeholders can associate with their needs. The roadmap should be constructed by understanding the megatrends, the general level trends and drivers, and the weak signals in concrete. Further, based on previous, the roadmap aid in recognising research opportunities, developing concepts, standardisation, developing solutions in practice, piloting and learning from them, and figuring out the critical enablers to a successful realisation.

1.2 The objective of the thesis

The development path(s) of the electricity distribution networks must be established by progressing the emerging concepts in the ADNs and microgrids development, testing, piloting, implementation, and defining the so-called “windows-of-opportunities”. A clear general overview of the electricity distribution network evolution with the operational scenario descriptions is needed – a socio-technical roadmap from the current electricity distribution networks towards the intelligent microgrid networks.

Therefore, this thesis aims to make a holistic and realistic roadmap of the currently developing electricity distribution networks towards the ADN or intelligent microgrids network where DERs' flexibility is utilised.

The first goal is to define the electricity distribution networks' evolution phases. The second goal is to develop the control algorithm(s) for the ADN control and management with the related research and testing platform, especially for studying the microgrids' service provision requirements. One example is the reactive power control and the demand flexibility services provided in the microgrid's grid-connected situation, thus also applicable in all ADN evolution stages in general. The third goal is to make principal descriptions of the operational scenarios and the classified actors with their relationships of the developing electricity distribution networks. The descriptions can be utilised for the management system development, for example, to integrate the upper-level network's operational targets and the other stakeholders' targets. A particular focus is on the development of the low voltage (LV) distribution networks and customers and the microgrid concept because of their essential role in the Smart Grids.

The socio-technical perspective of the electricity distribution networks' evolution is prioritised, while economic, business, regulation and legislation aspects are considered only where necessary in this thesis.

Therefore, the discussion and analysis of the benefits of the microgrids and ADNs are omitted from this research since they relate to the techno-economic approach and the business cases. The benefits should be considered, like the profits that stakeholders receive from the concept. The benefits could be, for example, infrastructure investment suspension, reduced energy purchases, improved efficiency, reduction of emissions, improvement of reliability, and ancillary services (ASs) (Marnay et al., 2015).

The socio-technical approach of this research is limited to:

- electricity distribution networks' evolution in the suburban or rural area,
- defining and classifying existing and emerging actors of the electricity distribution networks,
- ADN operations for the ASs,
- microgrid concept,
- case studies utilising the local pilot network, Sundom Smart Grid, representing a suburban or rural area in Finland or the Nordic countries,
- testing the functions by offline and real-time simulation methods.

The objectives of this thesis are pursued by setting research questions (Q1 – Q5) and providing answers to them in the publications presented in Figure 1. Hence, the publications present the research conducted based on the research questions. The research questions are presented in more details in Chapter 2.

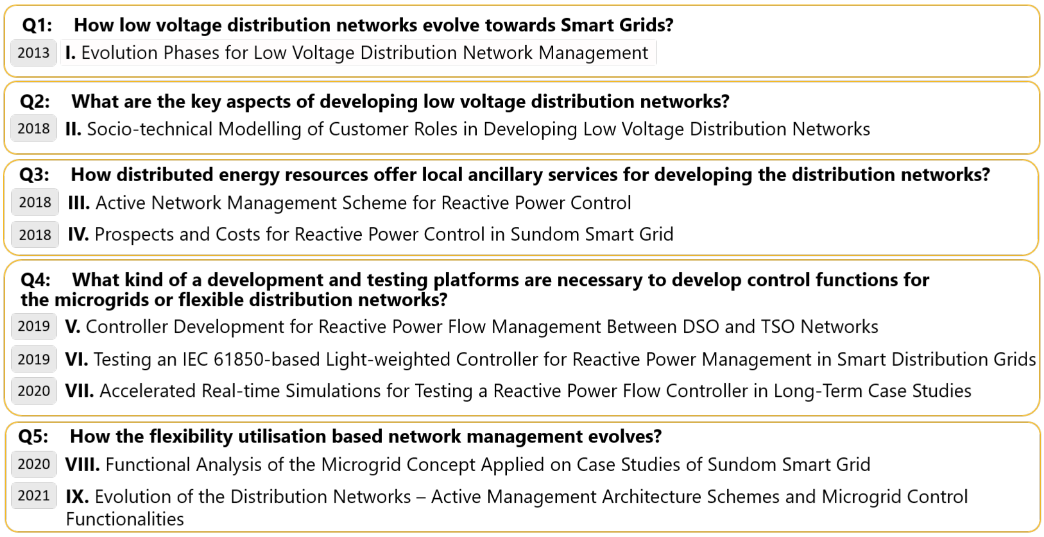


Figure 1. Outline of the publications through the research questions.

1.3 Scientific contribution

The scientific contributions of this thesis include the definitions, frameworks, methods, procedures, and solutions, listed in the following.

1) Definitions and frameworks:
- a definition of the evolution phases of the electricity distribution networks and the customer evolution phases and
- a framework setting and a method for developing socio-technical roadmaps for evolving electricity distribution networks.

2) Methods and procedures:
- a method for accelerating the real-time simulations, and a method for testing a controller in the accelerated real-time simulations,
- a method for conducting a functional analysis of microgrids from the concept level to practice,
- a procedure for generating and analysing operational scenarios of the electricity distribution networks by the evolution phases,

3) Solutions:
- a solution for a reactive power controller developed from a control algorithm to a light-weighted intelligent electronic device (IED) for a

converter connected distributed generation (DG) unit enabling the provision of ASs for the distribution system operators' (DSOs'), i.e. local ASs,

- a solution for the management architecture schemes for the evolving electricity distribution networks, and
- an outline of the roadmap towards future electricity distribution network or intelligent microgrids network.

1.4 Outline of the thesis

This dissertation consists of a summary section and the appended original publications. The summary is divided into seven chapters, as follows.

Chapter 1 introduces the topic, defines the research objectives, presents the research questions and the scientific contributions, and outlines the thesis.

Chapter 2 presents the research methodology and methods and introduces the research approach by refining the research questions.

Chapter 3 discusses the energy transition and reviews Smart Grids, active distribution networks, and the visions of microgrids

Chapter 4 presents the active management of electricity distribution networks consisting of network planning, operation, demand-side management (DSM), ASs and reserves, and a case study of reactive power control management with DER units for the local AS.

Chapter 5 explains the importance of realising new concepts for the Smart Grids in a sustainable way addressing standardisation, testing, and piloting. The chapter demonstrates a case study for developing a lightweight IED controller for local ASs.

Chapter 6 presents the development of a comprehensive socio-technic roadmap towards future electricity distribution networks.

Chapter 7 presents the conclusions and contributions of the research as well as a discussion of future research.

1.5 Summary of publications

This thesis includes nine publications. The author of the dissertation is the primary and corresponding author of all these publications. The publications are organised according to the research themes, and their main contribution is summarised in the respective chapter of this thesis. The research themes and allocations of the publications are presented in Figure 2.

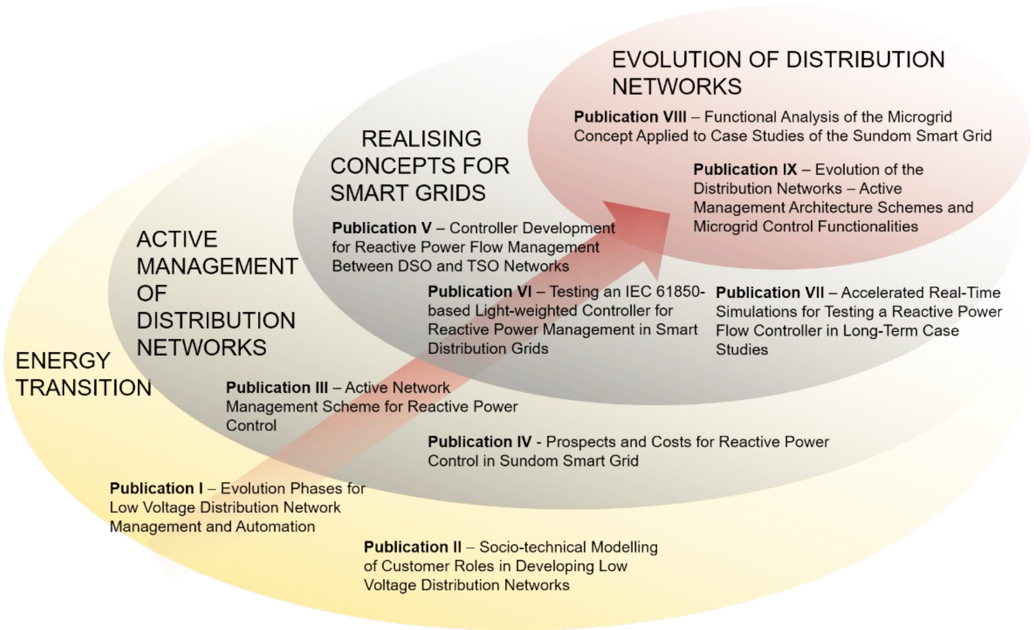


Figure 2. Publications by the thesis research themes.

Publication I – Evolution Phases for Low Voltage Distribution Network Management and Automation

The evolution phases of the LV distribution networks are named and introduced as the Traditional, the Self-sufficient in Electric Energy, the Microgrids, and the Intelligent Network of Microgrids. The operational scenarios in each evolution phase are described by the use-case (UC) descriptions related to electricity distribution in the network's normal operation and disturbance situations, illustrating the evolving operations between the actors at the different domains. This approach gave a basis for further studies to develop electricity distribution network scenarios and management.

Publication II – Socio-technical Modelling of Customer Roles in Developing Low Voltage Distribution Networks

This paper presents a new framework to define and model an actor's / a customer's evolution in the evolving LV distribution networks as a socio-technical system. The framework is based on the multi-level perspective (MLP) and the strategic niche management (SNM) approaches. The framework combines actor evolution with object-oriented unified modelling language (UML). The classifications of the evolving customers are introduced following the LV distribution networks' evolution phases defined in Publication I. The classified customers can be exploited in the SNM to understand the customers' development path and their associated actors within the dynamics of the socio-technical environment. The benefits of the models created within the MLP and SNM frameworks are the articulation of expectations and visions and the creation of networks in the SNM. For example, in developing the microgrid concepts, the framework opens new perspectives for a socio-technical system development through the understanding of the transitions in the electricity distribution networks and the practices that are needed.

Publication III – Active Network Management Scheme for Reactive Power Control

Different reactive power flow requirements between the distribution and transmission networks, at the point of interconnection (POI), were considered for the Sundom Smart Grid in Vaasa, Finland. The "Future Reactive Power Window" was formulated for the Sundom Smart Grid, giving the boundary conditions for the control scheme formulation. A reactive power management scheme was developed to control the converter of the medium voltage (MV) network connected, 3.6 MW wind turbine (WT). The simulation results show that coordinated reactive power management schemes across the different voltage levels utilising DG control could be feasible for the voltage support as a local AS.

Publication IV - Prospects and Costs for Reactive Power Control in Sundom Smart Grid

Based on the "Future Reactive Power Window" requirements for the Sundom Smart Grid, reactive power flow between the distribution and transmission networks was considered by utilising the MV and LV network-connected DERs. Various simulation cases and economic calculations studied the reactive power flow across the voltage levels. The results showed that coordinated reactive power management across different voltage levels presents significant issues from the technical and economic perspectives for developing future distribution networks.

Publication V – Controller Development for Reactive Power Flow Management Between DSO and TSO Networks

A reactive power controller for the WT converter was developed further from the previous algorithm (Publication III and IV) into a lightweight IED. The controller development stages are presented, starting from preliminary algorithm development in the Simscape Power Systems offline simulations to real-time software-in-the-loop (SIL) simulations to real-time controller-hardware-in-the-loop (CHIL) simulations. The control solutions and its relevant communication system were designed based on the standard IEC 61850 using generic object-oriented substation event (GOOSE) protocol and implemented on two hardware platforms, the field-programmable gate array (FPGA) and the BeagleBone Black (BBB). Finally, the solution was tested using a CHIL setup on the OPAL-RT co-simulation platform. The operation of the controller was investigated at different development stages for the MV distribution network. The research outcome includes suggestions for developing the real-time simulation platform for long-term case studies and discussing the improvement possibilities of the controller.

Publication VI – Testing an IEC 61850-based Light-weighted Controller for Reactive Power Management in Smart Distribution Grids

The performance of the reactive power control scheme developed on the lightweight IEDs (in Publication V) was tested. The FPGA and BBB-based IEDs' functioning was evaluated through the CHIL versus SIL tests in terms of communication latency, processing time, and control action execution. The results show that the FPGA performed better than the BBB compared to the SIL simulation results. Therefore, the lightweight IED based on the FPGA could be more suitable for microgrid controller development. Hence, an open-source IEC 61850 standard based lightweight IED can provide a base for advanced microgrid control research.

Publication VII – Accelerated Real-Time Simulations for Testing a Reactive Power Flow Controller in Long-Term Case Studies

The Sundom Smart Grid case study presents the development of an accelerated real-time co-simulation method and the testing platform for long-term simulations. The reactive power flow between the distribution and transmission networks was controlled by the MV network connected WT converter. This research demonstrated how to accelerate the long-term real-time simulations by different setups of the input data.

Moreover, the paper clarifies how the input data processing affected the results in the long-term real-time simulations. The SIL and CHIL tests showed that it is possible to find a data-reading cycle, a time factor, a coefficient T_d to accelerate the long-term real-time simulations.

Further, based on the test results, a suitable I or PI controller can be derived for the accelerated real-time tests that prevent oscillations in the closed-loop controlled system. As a result, the recommendation is to carry out the offline SIL simulations using the real-time simulation models with various coefficient T_d and verify that the results are equal. The time factor(s) for the real-time SIL and CHIL simulations can then be selected. The results from these simulations would be expected to be close to the offline simulation results excluding the effects of communication latency. The developed method could be used to define the test procedure, for example, for the CHIL applications in microgrid controller development, especially for the weekly, monthly, or yearly usage of the distribution-network-connected DER units for the different ASs. A more detailed stability analysis for the proposed method and a detailed technical analysis of the proposed approach is needed. This paper aims to present the potential benefits and the related issues for the developed method for accelerating real-time simulations.

Publication VIII - Functional Analysis of the Microgrid Concept Applied to Case Studies of the Sundom Smart Grid

This paper focuses on defining microgrids' functions regardless of the practical solution that benefits understanding MMS functioning and making a system of systems. Moving from top-down, from the abstract level of the microgrid concept, and going closer to practice until testing, a UC modelling method was utilized. General microgrid functions were represented as higher-level use-cases (HL-UCs). Next, the primary use cases (PUCs) for a real distribution network were developed for the Sundom Smart Grid. Further, various sets of simulation cases were aligned with the test use cases (TUCs) and vice versa. The simulation cases were selected to function in different time frames. A real-time co-simulation (phasor, and electromagnetic transient, EMT) setup was used for the ASs studies of reactive power flow control and demand response (DR) in the SIL practice. The CHIL tests in the EMT platform were executed for the protection TUCs. The relation of a functionality between the concept and a single case study was highlighted. The functional analysis could be beneficial when applying the microgrid concept, for example, to the management system development in a real-world case. By utilising the different UC levels, the potential entities can be detected where development or improvement of the concrete solutions is necessary. Several microgrid functions operating in parallel and affecting each other were studied with the TUCs and the related simulations, as presented in this publication. The active power and reactive power are controlled simultaneously for the different ASs.

Publication IX – Evolution of the Distribution Networks – Active Management Architecture Schemes and Microgrid Control Functionalities

A method for analysing the evolution of the electricity distribution networks comprising both the MV and LV distribution networks is presented. The research consists of both dynamic and static descriptions of the distribution network evolution. The dynamic descriptions are behavioural descriptions (or operational scenarios) for the network operations represented by various UCs. The static relationships between several classes of actors are presented with diagrams illustrating the network structure and the communication between the actors operating the system. Four evolution phases of the electricity distribution networks are redefined and analysed, followed by the active management architecture schemes and the microgrid control functionalities using a UML tool. The system descriptions are made for energy management, power balance management, and protection. The generated method and graphical models of the management architecture schemes and microgrid control functionalities can be used, for example, for scenario building in the distribution network roadmap development, joint understanding creation of the distribution network system operation, management systems development, testing development, and analysis of several parallel running control algorithms.

1.6 Other publications by the author with closely related topics

Kumpulainen, L., Rinta-Luoma, J., Voima, S., Kauhaniemi, K., Sirviö, K., Koivisto-Rasmussen, R., Valkama, A-K., Honkapuro, S., Partanen, J., Lassila, J., Kaipia, T., Haakana, J., Annala, S., Järventausta, P., Valkealahti, S., Repo, S., Verho, P., Suntio, T., Rautiainen, A., Nikander, A., Pakonen, P., (2016). "Sähkömarkkina- ja verkkovisio 2035 & Roadmap 2025". Project Report. Roadmap 2025.

Laaksonen, H., Hovila, P., Kauhaniemi, K., Sirviö, K., (2018). "Advanced Islanding Detection in Grid Interactive Microgrids". CIRED 2018 CIRED Workshop Proceedings: Microgrids and Local Energy Communities, Ljubljana, Slovenia, June 7-8, 2018

Kadam, S., Schwalbe, R., Übermasser, S., Groiß, C., Einfalt, A., Laaksonen, H., Sirviö, K., Hovila, P., Blažič, B., (2018). "Active and reactive power requirements at DSO-TSO interface: a cases study based on four European countries". CIRED Workshop Proceedings: Microgrids and Local Energy Communities, Ljubljana, Slovenia, June 7-8, 2018

Sirviö, K., Mekkanen, M., Kauhaniemi, K., Babazadeh, D., (2019). ”Sundom Hardware-In-the Loop Living Lab”. Technical Report. ERIGRID transnational access.

Kumpulainen, L., Kauhaniemi, K., Farughian, A., Sirviö, K., Memon, A., Voima, S. Mekkanen, M., Kumar, H., (2019). VINPOWER Vaasa innovation platform for future power systems: Final report

Laaksonen, H., Sirviö, K., Aflecht, S., Hovila, P., (2019). ”Multi-objective active network management scheme studied in Sundom smart grid with MV and LV network connected DER units”. Proceedings of 25th International Conference on Electricity Distribution: CIRED 2019: Madrid, 3-6 June 2019.

Hillberg, E., Oleinikova, I., Uhlen, K., Iliceto, A., Hojčková, K., Brandão, D., Pudjianto, D., Sirviö, K., Gonzalez, J. C., Babazadeh, D., Srivastava, R., Wong, S., Fuchs, A., Rossi, J., Brolin, M. (2020). “micro vs MEGA perspectives: Grid development for the future power system”. Cigre session 28, Paris.

Hillberg, E., Oleinikova, I., Uhlen, K., Iliceto, A., Hojčková, K., Brandão, D., Pudjianto, D., Sirviö, K., Gonzalez, J. C., Babazadeh, D., Srivastava, R., Wong, S., Fuchs, A., Rossi, J., Brolin, M. (2020) “micro vs MEGA: trends influencing the development of the power system”. International Smart Grid Action Network (ISGAN) Power Transmission & Distribution Systems, discussion paper.

Parthasarathy, C., Sirviö, K., Hafezi, H., Laaksonen, H. (2021) “Modelling Battery Energy Storage Systems for Active Network Management – Coordinated Control Design and Validation”. IET Renewable Power Generation.

Pediaditis, P., Sirviö, K., Ziras, C., Kauhaniemi, K., Laaksonen, H., Hatziargyriou, N. (2021) “Compliance of Distribution System Reactive Flows with Transmission System Requirements”. Applied Sciences.

2 RESEARCH METHODOLOGY AND METHODS

The theoretical framework of this thesis is multidisciplinary. In the field of technology, the trends, drivers, markets, and various requirements set the input and boundary conditions for the power system's development and operation. The business perspective focuses on the feasibility of the investments and the business cases. Understanding electricity market operations and consumer behaviour set the boundary conditions for operating models from technical and economic perspectives. Consequently, the social perspective is an enabler for successful business cases with enhanced technologies.

2.1 Research methodology

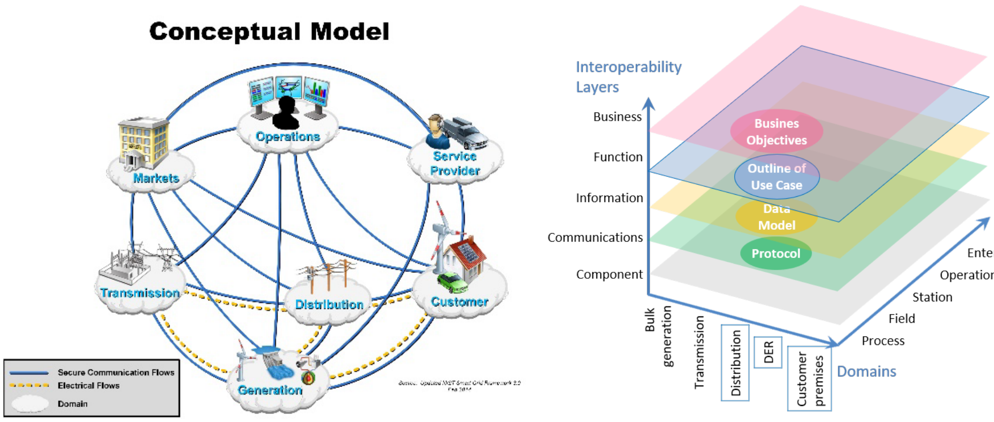
This thesis is based on the postmodern philosophy of science. It is essential to combine different branches of science to create an interdisciplinary approach to the research issues (Tuomi & Sarajärvi, 2009). Postmodern research can be introduced as selective research, including ideas based on different research (Churton & Brown, 2010).

The evolution and transition of the power system is a probabilistic problem, meaning that the research findings are not expected to explain all cases all the time. Generally, a probabilistic problem aims to interpret the information obtained from the available research findings by looking after regularities or laws (Gerstein et al., 1988), extracting maximum information from the data gained. The information is presented in a compact form for use in development, planning, and decision making (Lye, 2009). An outcome from research or a probabilistic problem can be a test or trial result. The conclusions explain a preferably high ratio of possible cases.

Evolutionary path development for future distribution networks builds on scenario building theories. The fundamentals of scenario building for the future are (i) recognising the facts of the present situation, (ii) a vision of a better future, (iii) state of mind, and (iv) action (Hiltunen, 2019). The prerequisite for scenario building or anticipating and envisioning tomorrow is understanding the prevailing facts, summarised by imagination (Hiltunen, 2019). Besides, the weak signals (Dufvas, 2019; Griol-barres et al., 2020; Hiltunen, 2010) can be individually used since they are the indicators of changing and emerging topics. The weak signals may be related, for example, to technologies, behaviours, markets, and regulations. They supplement the trend analysis. In this thesis, the megatrends, trends, and weak signals create the envisioned future scenarios expressed by the various UCs.

The research relies on the US objectives in NIST Framework and Roadmap for future Smart Grids (NIST, 2014), EU objectives with the ETIP-SNET's energy system vision 2050 (ETIP SNET, 2018), national objectives with the Finnish Energy and Climate Roadmap (MEAE, 2014b), the future scenarios of the Low Carbon Finland (MEAE, 2020c) projects, the scenarios of the Roadmap 2050 project (Kumpulainen et al., 2016), and the vision from the Finnish Smart grid working group (MEAE, 2018b). Other supporting material was used as appropriate. It consists of requirements and guidelines.

The NIST Framework of Smart grids composed of seven domains (NIST, 2014) is presented in Figure 3(a). The three-dimensional Smart Grid Architecture Model (SGAM) is the European framework for Smart grids (CEN-CENELEC-ETSI Smart Grid Coordination Group, 2012). The SGAM is presented in Figure 3(b). It can be used as a framework to develop UCs or functional scenarios, system architectures, communication technologies, and information and information models (Gottschalk et al., 2017; Uslar et al., 2013). The SGAM model can represent data flows between different actors integrated into different system architectures. In this research, the NIST and SGAM frameworks were utilised mainly for evaluating the actors and UCs of the developing distribution networks in future power grids.



(a) (b)

Figure 3. (a) NIST Framework of Smart grids (NIST, 2014), (b) Smart Grid Architecture Model; adapted from CEN-CENELEC-ETSI Smart Grid Coordination Group (2012).

2.2 Research approach

Thesis objectives are met by setting relevant research questions and providing answers to them through the research that has been carried out. The research results are presented in the publications that focus on the questions (Figure 1).

This section describes the approaches for addressing the research questions. The mind maps presented in this section describe what was focused on, how the research questions have been analysed from different perspectives through the publications, and how the topics relate to each other. The focused topics are highlighted (dartboards), and the mind maps include all the related topics that need to be considered to some extent. A summary mind map of this thesis presents the whole research scope.

The first research question – How low voltage distribution networks develop towards Smart Grids? – was answered by examining the visions, definitions, roadmaps, and functional requirements for smart grids, microgrids, and related elements. By analysing them, generalisations were made regarding electricity distribution networks development. Further, thresholds were discovered for determining different evolution phases for the electricity distribution networks. The development phases made it possible to connect the actors and functions that establish the UCs for different operations in developing electricity distribution networks. The mind map for the first research question is presented in Figure 4, and the results are presented in Publication I.

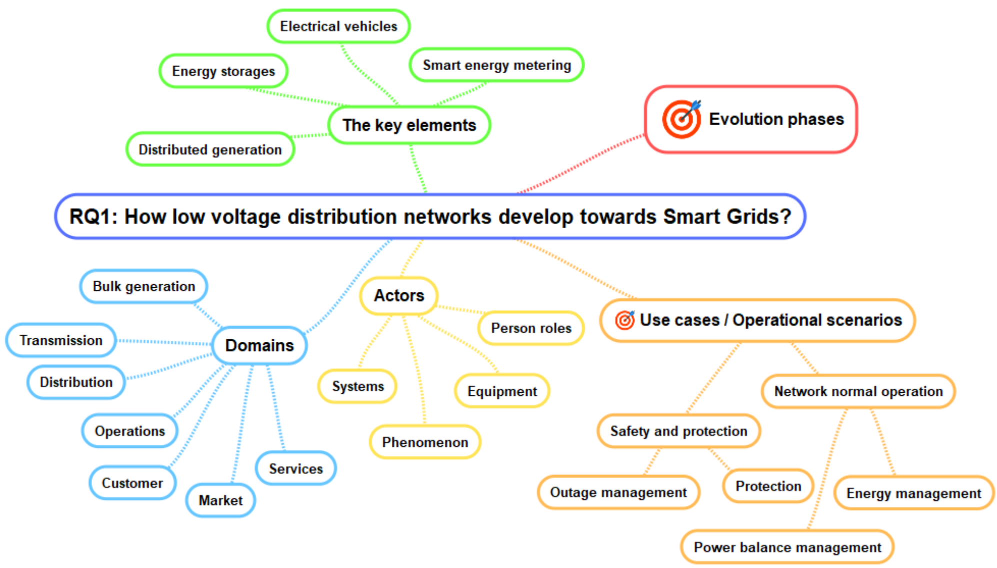


Figure 4. Mind map of the Research Question 1 – How low voltage distribution networks develop towards Smart Grids?

The answer to the second research question – Which are the key aspects in developing the low voltage distribution networks? – was sought by examining the socio-technical factors and scenarios for the Smart Grid. The customers' activities were the focus, considering the development of customers and their different roles.

Publication II shows the approach used to describe customer development in the evolution of the LV distribution network. Socio-technical dynamics were merged with transition management theories and evaluated and aligned with the phases of the LV distribution networks. The mind map for the second research question is presented in Figure 5.

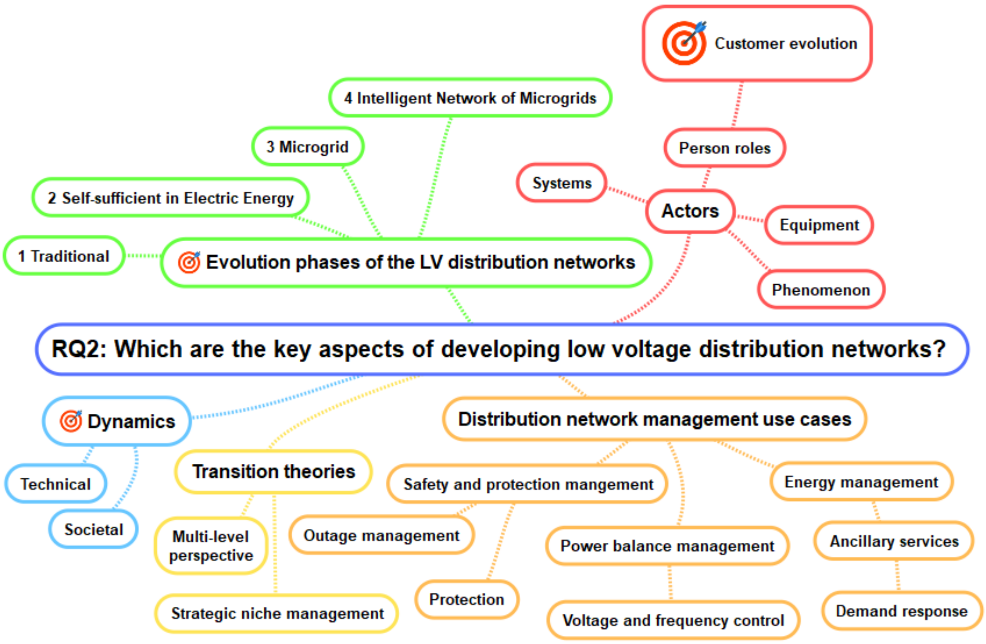


Figure 5. Mind map for Research Question 2 – Which are the key aspects of developing low voltage distribution networks?

For the third research question – How distributed energy resources offer local ancillary services for developing the distribution networks? – a microgrid or an active distribution network was studied for offering ASs with the DER. Case studies were conducted with a real developing distribution network, the Sundom Smart Grid. The management of reactive power at the transmission system operator's (TSO's) and DSO's interconnection point was studied as a local AS to prevent the TSO penalty fees. Publication III presents reactive power control of the DER units as a service solution for the DSO.

Furthermore, different scenarios, and their economic effects, are presented in Publication IV. The mind map for the third research question is presented in Figure 6.

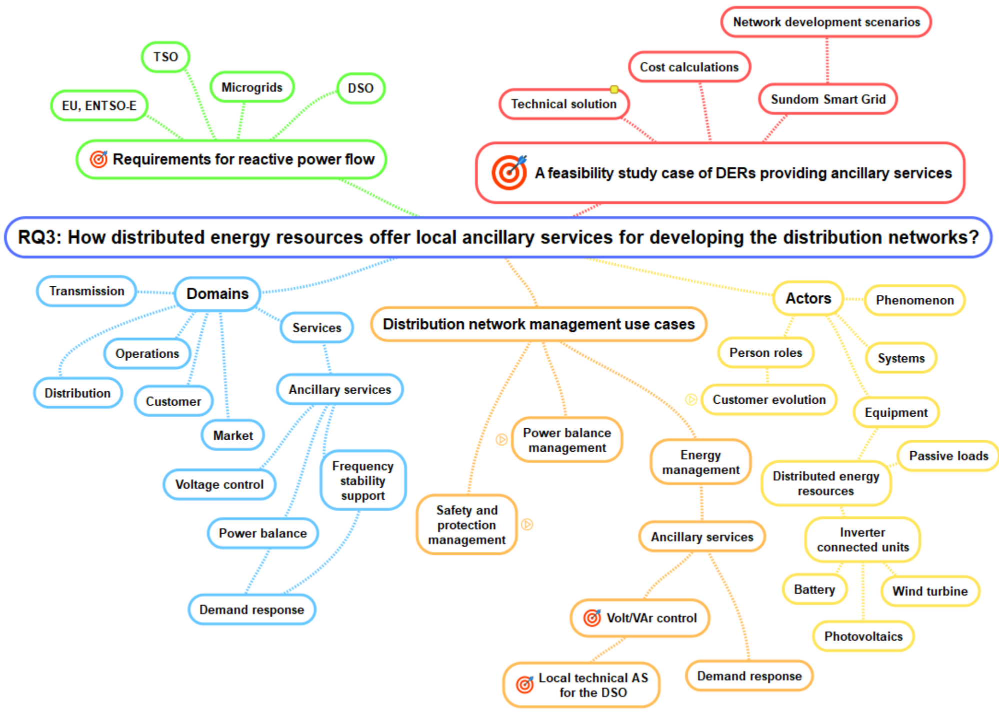


Figure 6. Mind map for Research Question 3 – How distributed energy resources offer local ancillary services for developing the distribution networks?

The fourth research question – What kind of development and testing platforms are necessary to develop control functions for the microgrids or the active distribution networks? – was solved by first developing a real-time simulation and a CHIL test platform intended to enable the development and testing of AS concepts. In this research, the study case was the Sundom Smart Grid development towards a microgrid vision considering the increasing share of DER. Publication V introduces the previously developed control algorithm for reactive power management implemented in SIL on the real-time model developed for the Sundom Smart Grid and further to test real controller hardware as a lightweight IED interacting with the simulated power system in real-time. Publication VI compares different simulation methods, the offline, the real-time SIL. Publication VII defines, develops, and tests a method to accelerate long-term real-time simulations, valuable in testing controllers in the AS case studies. The mind map for the fourth research question is presented in Figure 7.

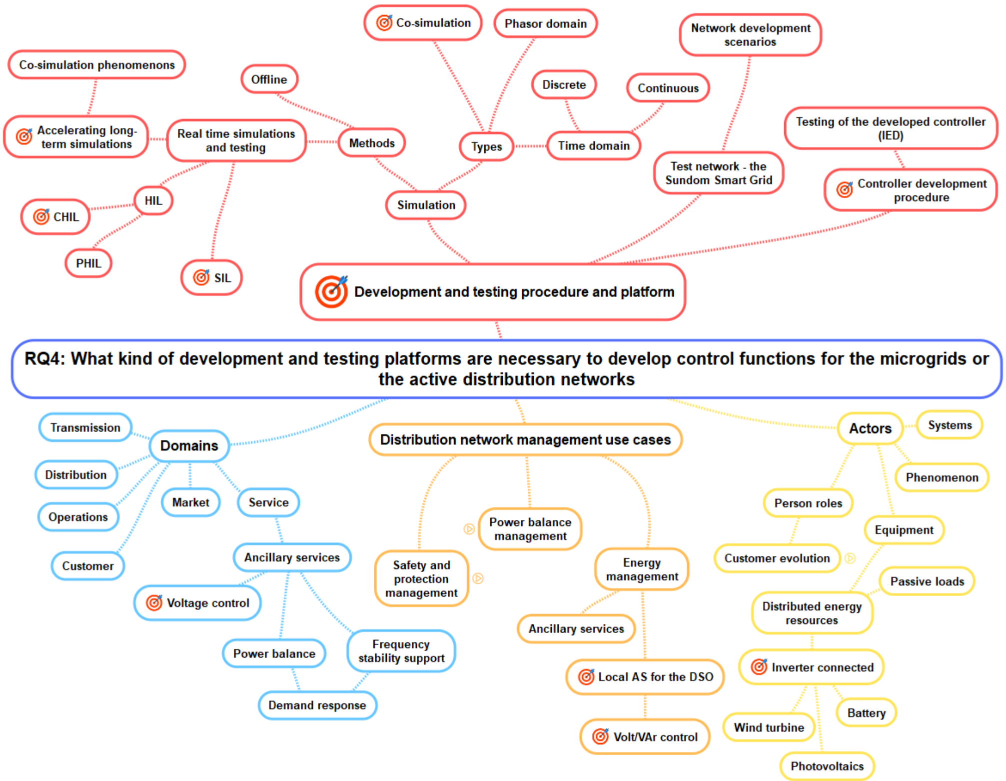


Figure 7. The mind map for Research Question 4 – What kind of development and testing platforms are necessary to develop control functions for the microgrids or the active distribution networks?

The fifth and last research question – How the flexibility utilisation-based network management evolves? – is answered by examining the evolution and the management of the LV and MV distribution networks. The conceptual microgrid functions were analysed in Publication VIII using the UC method. The selected UCs was made into real-time simulation models, and the selected functions were made into control algorithms in SIL for DR and reactive power management. The intention was to run two ASs schemes provided by a microgrid in parallel to recognise possible interaction. In Publication IX, the evolution of the MV and LV distribution networks was defined in more detail. The related management architecture schemes were discovered. The UML method was used to model the structures and the actors' static relationships at different network development stages. The mind map for the last research question is presented in Figure 8.

Figure 8. Mind map for Research Question 5 – How the flexibility utilisation-based network management evolves?

Figure 9 presents the summary of all the research topics, which are associated with the research themes (i–iv) that are presented in chapters (3–6): electricity distribution network evolution to (i) energy transition, distribution network management and ancillary services to (ii) active management of the distribution networks, development and testing procedures and platforms for (iii) realising concepts for the Smart Grids and electricity distribution network evolution and distribution network management for (iv) the evolution of distribution networks.

Figure 9. Mind map for conducting the thesis research.

2.3 Research methods and tools

The research was carried out using both quantitative and qualitative methods. The research material contains data from the literature, measurement data from a real distribution network, the Sundom Smart Grid (described in detail in Publication

III – VIII), information from electricity network operators, and input from the system providers. The primary sources are scientific publications, standards and norms, research project reports, surveys (e.g. survey made for University of Vaasa's VEBIC Smart Grid research platform development, 2020), workshops (e.g. workshops of University of Vaasa's VEBIC Smart Grid research platform development, 2020; workshops of VINPOWER project, 2018, 2019), and expert discussions with the network actors. The collected data were grouped and sorted along with the research themes and questions. The information was analysed using qualitative methods.

The methods of data analysis are qualitative content as well as document analysis. For forming the behavioural and structural analysis of the future distribution networks, the UML methods and tools were used to organise the collected data and visualise the constraints and interactions. The distribution system actors were defined, in which data was classified according to their features; roles and characteristics. The conclusions are presented in the UML diagrams, which are UC stories, UC, class, and sequence diagrams.

Offline simulation tools were used for algorithm deployment for developing concepts and testing them. Further, for developing the control algorithm for a real device, a suitable real-time co-simulation and a testing platform were developed and utilised. Hence, the real-time simulation with the CHIL testing method was used to prove the concept from theory to practice. An accelerated long-term real-time simulation method was developed.

Table 1 represents the methods used in data collection and analysis, tools used in this research, and the results of each publication. The methods and tools used for UML were Visual Paradigm and Enterprise Architect. Simscape Power Systems (newly Simscape Electrical), Simulink, and Powerfactory were used for the offline simulations. OPAL-RT's co-simulation platform was used for real-time simulation. The ePHASORSIM solver simulated the power system dynamics and power flow in the phasor mode. The control actions and communications were simulated in the eMEGASIM in the discrete time-domain. Excel and Matlab were the general tools used to process, calculate, and migrate data. Matlab was mainly used for simulation and test result illustrations.

Table 1 presents the outcome and models with the tools used. The UC stories, UC diagrams, and class diagrams are the results related to Publications I and II. The result from Publication III is a reactive power control algorithm running in Simscape Power Systems and Simulink. The calculation model for the reactive power flow cost in the TSO/DSO interconnection point was developed with Excel, resulting in the tool related to Publication IV. The Publication V and VI results are a script exporting a Powerfactory power system model into an Excel representation, a real-time co-simulation platform, the real-time SIL and CHIL (BBB and FPGA based) controllers for reactive power flow control of the WT converter, the configuration files for light-weighted IEC61850 based controllers for Intel Quartus Software, FUHUA, and libIEC61850. Related to publication VI, Wireshark was used for capturing the GOOSE messages in the Ethernet. Concerning Publication VII, the result models, scripts, and the controllers from Publications V and VI were utilised.

Concerning Publication VIII and IX, UML UCs, activity and class models, and diagrams are the outcome of Enterprise Architect. In Publication VIII, the former real-time simulation models and the SIL controller for reactive power control were used. However, a new SIL controller for load control for DR purposes was a result.

Table 1. The data collecting and analysing methods, tools, and results.

	Data collecting	Methods/Tools	Data analysis	Results
PUB I	Literature	UML/Visual Paradigm	Qualitative	Use Case (UC) models
PUB II	Literature	UML/Visual Paradigm	Qualitative	Classes, Class diagram
PUB III	Literature & Measurement data from the SSG	Offline simulation/Simscape Power Systems	Qualitative & Quantitative	Future reactive power window for the SSG & Management scheme and algorithm
PUB IV	Literature & Measurement data from the SSG	Cost calculation/Excel	Qualitative & Quantitative	Calculation model for reactive power fee caused at the TSO/DSO interconnection point
PUB V	Literature & Measurement data from the SSG	Offline simulation/Powerfactory, Migration/Excel, Real-time SIL&CHIL/ePHASORSIM+eMEGASIM Configuration of BBB/Quartus, FUHUA, libIEC61850	Qualitative & Quantitative	IEC61850 based IED/HW BBB controller for reactive power flow control
PUB VI	Literature & Measurement data from the SSG	Real-time SIL&CHIL/ePHASORSIM+eMEGASIM Configuration of BBB and FPGA/Quartus, FUHUA, libIEC61850, Data transfer capture/Wireshark	Qualitative & Quantitative	IEC61850 based FPGA IED/HW controller for reactive power flow control
PUB VII	Literature & Measurement data from the SSG	Offline simulation/Powerfactory, Excel, Real-time SIL&CHIL/ePHASORSIM+eMEGASIM	Qualitative & Quantitative	Real-time simulation platform for long-term case studies
PUB VIII	Literature & Measurement data from the SSG	UML/Enterprise Architect Offline simulation/ePHASORSIM&eMEGASIM	Qualitative & Quantitative	UC repository UC models & diagrams Activity diagrams SIL controller
PUB IX	Literature	UML/Enterprise Architect	Qualitative	UC repository UC models & diagrams Class diagrams Socio-technical roadmap, template

3 ENERGY TRANSITION

This section focuses on the two first research questions: How low voltage distribution networks evolve towards Smart Grids? What are the key aspects of developing low voltage distribution networks?

Climate change puts pressure on changing the prevailing energy system that is a revolution of RESs. A structural change in the energy system is happening, and the energy transition is affecting the whole energy chain. The future power system is envisioned universally. However, the potential evolution path(s) should be recognised in all Smart Grid domains (Figure 3a).

In this section, the energy shift is considered in energy transition frameworks, and the transition dynamics are introduced. Following that, the European and the national level energy scenarios are presented. This thesis builds on the visions of the future energy system and the essential concepts in the Smart Grid domains. The ADN and the microgrids concepts, which are central boosting technologies the energy transition, are briefly introduced regarding the electricity distribution networks. The outcome of Publication I and II are presented to complete the research questions.

3.1 Energy transition frameworks

Achieving climate-neutral Europe, long-term sustainability objectives require the transformation of core societal systems, which can be understood by transition dynamics, as presented in EEA (2019), where four systemic change perspectives are defined. The **socio-ecological perspective** explains ecology and earth system transformations through social sciences. The **socio-economic perspective** explains how economic activity affects and how social processes modify it. The **socio-technical perspective** has insights from evolutionary economics, innovation studies, and institutional theory. **Action-oriented perspectives** give insights into different roles of actors (individuals, communities, or other groups) in systemic change by enhancing other systemic approaches, for example, increasingly in socio-technical research.

This research focus is on the socio-technical perspective, in which the characteristics of transitions are defined in EEA (2017) as follows:

1. "Transitions are co-evolutionary processes that require multiple changes in socio-technical systems. Transitions involve both the development of technical innovations and their use in societal application domains. This 'use' includes adoption by consumers (markets and integration into user

practices) and broader processes of societal embedding, which may require changes in regulations, markets, infrastructures and cultural discourses.

2. Transitions are multi-actor processes, entailing interactions between businesses, different types of users, scientific communities, policymakers, social movements and special interest groups.
3. Transitions are radical shifts from one system to another. The term 'radical' refers to the scope of change, not to its speed. Radical innovations may be sudden and lead to creative destruction, but they can also be slow, proceeding in a step-wise fashion.
4. Transitions are often long-term processes (40-50 years). While breakthroughs may be relatively fast (e.g. 10 years), the preceding innovation journeys through which new socio-technical systems gradually emerge usually take much longer (20-30 years)."

The socio-technical transitions in the energy and power systems are discussed in Adil & Ko (2016), EEA (2019), Jacobsson & Bergek (2011), Smith et al. (2005), and G. Verbong & Geels (2007, 2010). In sustainable transition, the end-customers' behaviour plays a central role, which is analysed, for example, in Claudy et al. (2013), by discussing the attitude-behavioural gap for renewable energy systems.

This thesis is limited to the socio-technical transition in electricity distribution grids with an action-oriented perspective, meaning that network functional level UCs are considered. However, the business level UCs and techno-economic examinations are excluded. However, in addition to the socio-technical evolution of power grids, the socio-economic perspective is essential (EEA, 2019). Bigerna et al. (2016) reviewed the socio-economic features of Smart Grids development.

Van Den Bergh et al. (2011) presents the theoretical frameworks for sustainability transitions, which are 1) the innovation systems approach to transitions, 2) the MLP and the SNM frameworks, 3) transition management (TM), and 4) evolutionary-economic views and multi-agent modelling of transitions. In this research, the MLP approach was the most suitable for the socio-technical analysis of power system evolution because of the key concepts in which it is applicable: "Multiple (competing) technologies, structural change, multiple levels (niche, regime, landscape), multiple phases, coevolution, networks, transformation, reconfiguration, technological substitution, de-alignment and re-alignment", and its policy view: "Align technologies and user practices. Strategic niche management (SNM) – reflexive management of real-world experiments" (Van Den Bergh et al., 2011).

Geels (2002, 2011) presents the MLP framework describing technology transition to sustainability that combines technology trajectories, technology regimes, and new combinations that result in paths and trajectories. Technological transitions are processes occurring over long time periods in socio-technical systems involving technologies, actors or user practices, regulation, industrial networks, infrastructure, and symbolic meaning or culture. The MLP illustrates the transition through three analytical levels: niches, regimes, and landscape. The existing socio-technical system refers to the regime level characterised by dominant rules, institutions, and technologies. Innovations and pilots emerge at the niche (micro) level, trying to enter the regime level. The landscape-level stimulates and puts pressure on the regime and niche levels covering environmental and demographic trends, political ideologies or macro-politics, societal values or cultural patterns, and macroeconomic patterns. The changes in the landscape happen because of exogenous factors, such as wars, economic crises, natural disasters, and political upheaval. The regime and niche levels are influenced by the landscape (macro) level. The policy is needed to destabilise the established regimes to promote radical niches towards the regime (Kern, 2012).

Figure 10 presents the MLP analysis tool that deals with the complexity and resistance in transition. The radical innovations emerge in niches where the eager actors promote technology and social innovations. The innovations, which can diverge from the current regime practices, can be boosted in the niches influenced by the markets and regulation that usually requires landscape developments that would open the "windows of opportunity" at the regime level. (Geels, 2002)

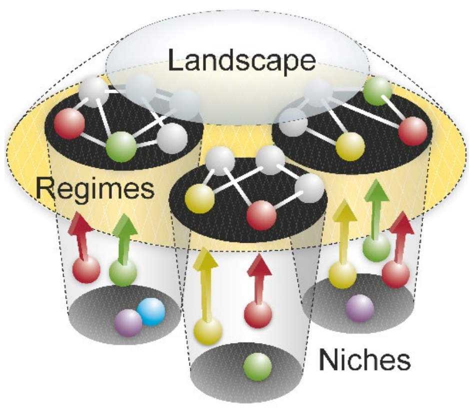


Figure 10. Multi-Level Perspective. Adapted from Geels (2002).

This thesis is interested in the MLP framework (Geels, 2004) and the idea of the multi-regime and multi-system interactions (Papachristos et al., 2013) in studying the socio-technical transition of power systems. Particularly the emergence of niches, niche-regime interactions (Diaz et al., 2013), the window of opportunity

(Berkhout et al., 2010), the acceleration of innovations (Markard et al., 2020), and the development pathways (Berkhout et al., 2010) are of interest.

By reflecting the MLP framework for the power grid's transition towards Smart Grids, niches can be new concepts like the ADNs or microgrids. The current power system presents the regime level. The SNM extends the MLP by taking the socio-technical regime as a research subject with a particular technology like the Smart Grids. SNM supports the socio-technical experiments where the different stakeholders are encouraged to collaborate and exchange information, knowledge, and experiences. The SNM aims to build a shared understanding behind a product or concept with the stakeholders and actors whose coordinated actions are necessary to shift the related technologies and practices. The goal of the SNM is to achieve an interactive learning process that would facilitate the emergence of new technology. Consequently, new, more sustainable systems, operational practices, and services might emerge based on new experiences and ideas through open socio-technical research and learning processes through the experiments, improving societal embedding and the uptake of new technologies.

Summarising previous information, the movement evolution towards Smart Grids is a socio-technical transition through the technologies and new concepts in the niche level, trying to enter the regime level influenced by the landscape level. Figure 11 presents an exemplary case where equipment like photovoltaics (PV) and battery energy storage systems (BESS) or concepts like microgrids, virtual power plants (VPPs), or DR are functioning simultaneously in niches. Successful management of the niche experiments is needed to obtain these new systems and concepts in the implementation of the Smart Grids and further to new practices at the regime level. The major contributing factor influencing the landscape level is the environmental trend which puts development pressure on the niche and regime levels. As a result, significant changes occur in the electricity distribution networks because of the interconnection of various DER, and new concepts like different microgrids emerge for active network management.

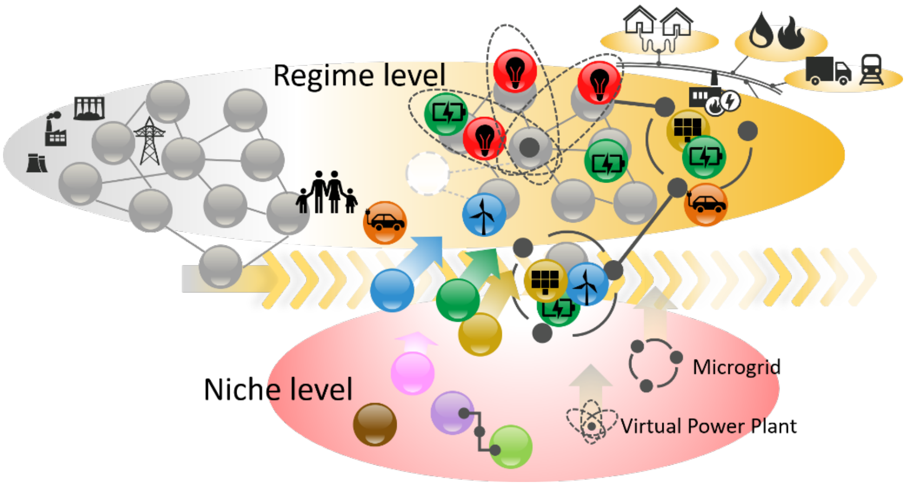


Figure 11. Niches for the Smart Grids technologies in the MLP.

3.2 European energy scenarios

The ETIP-SNET's vision 2050 defines energy transition: "The energy transition integrates energy storage and power conversion within the various energy carrier grids using the electricity system as its "backbone"." Moreover, the future integrated energy system (IES) consists of the physical systems, markets, communications, and digital infrastructure layers. Figure 12 presents the physical system of the future energy infrastructure. (ETIP SNET, 2018)

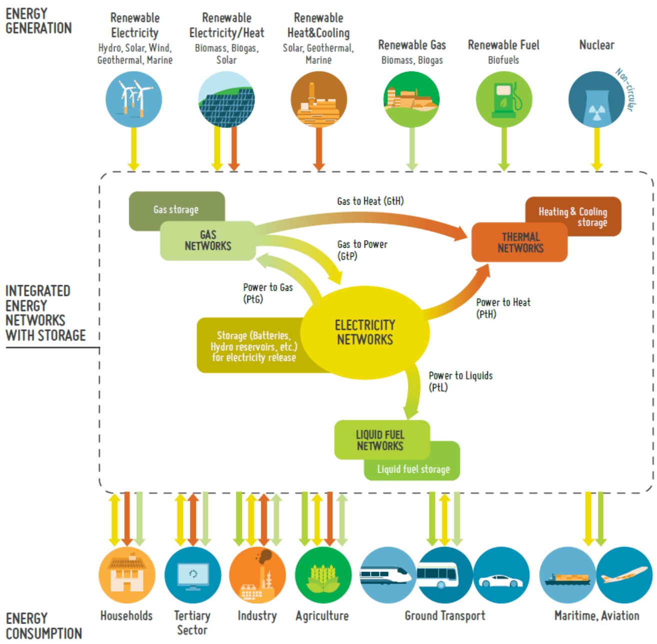


Figure 12. The future integrated energy systems with conversion and storage devices. (ETIP SNET, 2018)

Table 2 presents the building blocks and the critical functionalities across the energy system's value chain to execute the IES pathway. Key research areas are aligned to address the practical focus of achieving the functionalities (ETIP SNET, 2020).

Table 2. Functionalities to be achieved by the year 2030 and the key research areas. Adapted from ETIP SNET (2020).

BUILDING BLOCKS (VISION 2050)	FUNCTIONALITY	RESEARCH AREAS
The efficient organisation of energy systems	F1 Cooperation between system operators	
	F2 Cross-sector integration	1) Consumer, prosumer, and citizen energy community
	F3 Integrating the subsidiarity principle - The customer at the centre, at the heart of the Integrated Energy System	
Markets as key enablers of the energy transition	F4 Pan-European wholesale markets	2) System economics
	F5 Integrating local markets (enabling citizen involvement)	
Digitalisation enables new services for Integrated Energy Systems	F6 Integrating digitalisation services (including data privacy, cybersecurity)	3) Digitalization
Infrastructure for Integrated Energy Systems as key enablers of the energy transition	F7 Upgraded electricity networks, integrated components and systems	
	F8 Energy System Business (incl. models, regulatory)	4) Planning – holistic architectures and assets
	F9 Simulation tools for electricity and energy systems (software)	
Efficient energy use	F10 Integrating flexibility in generation, demand, conversion and storage technologies	5) Flexibility enablers and system flexibility
	F11 Efficient heating and cooling for buildings and industries in view of system integration of flexibilities	
	F12 Efficient carbon-neutral liquid fuels & electricity for transport in view of system integration of flexibilities	6) System operation

The European Network of Transmission System Operators for Electricity (ENTSO-E) indicates the attributes of the future electricity being a system of systems that works as one. The future power system provides seamless integration of growing DER shares. The system enables alignment with the needs of all assets connected to the grid and further integrated with other sectors. Innovation and cooperation are the driving elements. (ENTSO-E, 2019)

3.3 National energy scenarios

This section reviews the national measures for the energy transition within the scope of this thesis. As a starting place, the Ministry of Employment and the Economic Affairs of Finland (MEAE) published the National Energy and Climate Strategy 2013 (MEAE, 2013a, 2013b).

Next, the Energy and Climate Roadmap 2050 (Energia- ja ilmastotiekartta 2050) MEAE (2014a) aims to guide at the strategic level towards a low-carbon society. Energy and Climate Roadmap 2050 highlights various options for reducing emissions, the most important of which are the energy system transition to a nearly zero-emission system, energy self-sufficiency, and supply security. Finland is highly dependent on energy, and the energy consumption per capita is high. Therefore, it has traditionally been invested in energy efficiency. Even though Finland is among the top countries in energy efficiency, its energy self-sufficiency is low. Finland is a pioneer in the development of energy technology in many areas. Koljonen et al. (2014) presents the Low Carbon Finland 2050 platform research project outcome as the basis for the Energy and climate roadmap 2050. Four alternative development paths or scenarios were developed towards low-carbon Finland by 2050: Continuous Growth, Stagnation, Savings, and Change. This thesis focuses on following the development paths of the Continuous Growth and Change scenarios. In the Continuous Growth scenario, the Finnish industry operates based on higher value-added products and concepts. The introduction of new technologies is fast, and the development of services is rapid. Smart solutions are widely used. In the Change scenario, people's values and attitudes create the conditions for change. The structural changes in society and the development of technology are very rapid.

The Climate Change Act (Ilmastolaki 609/2015, 2015; Climate Change Act 609/2015, 2015) was established to support the strategy work. The strategy work conducted further, and the climate and energy strategy was updated in 2016 with a Government report on the National Energy and Climate Strategy for 2030 (MEAE, 2017a, 2017b), with an extensive background report (Työ- ja elinkeinoministeriö, 2017). A review of a fully renewables-based energy system and identification of the possibilities and challenges in different sectors and the energy system-level challenges (MEAE, 2016) was giving the background information for the government's strategy work.

The MEAE settled on a Smart Grid Working Group to research the potential of Smart Grids for the electricity market, resulting in the description of A Flexible and Customer-driven Electricity System (MEAE, 2018a). The Smart Grid vision for Finland 2025 put the customer in the centre for giving them better opportunities to participate in the electricity market. The primary goals are improving the security of supply and creating new business opportunities for companies. The Smart Grid Working Group emphasises market-based demand flexibility, independent flexibility service providers, flexibility services, active customer, energy communities, ES services, cybersecurity, complementary energy system, and the regulatory and economic aspects, which are concluded in Figure 13 by the proposed implementing order. (MEAE, 2018c)

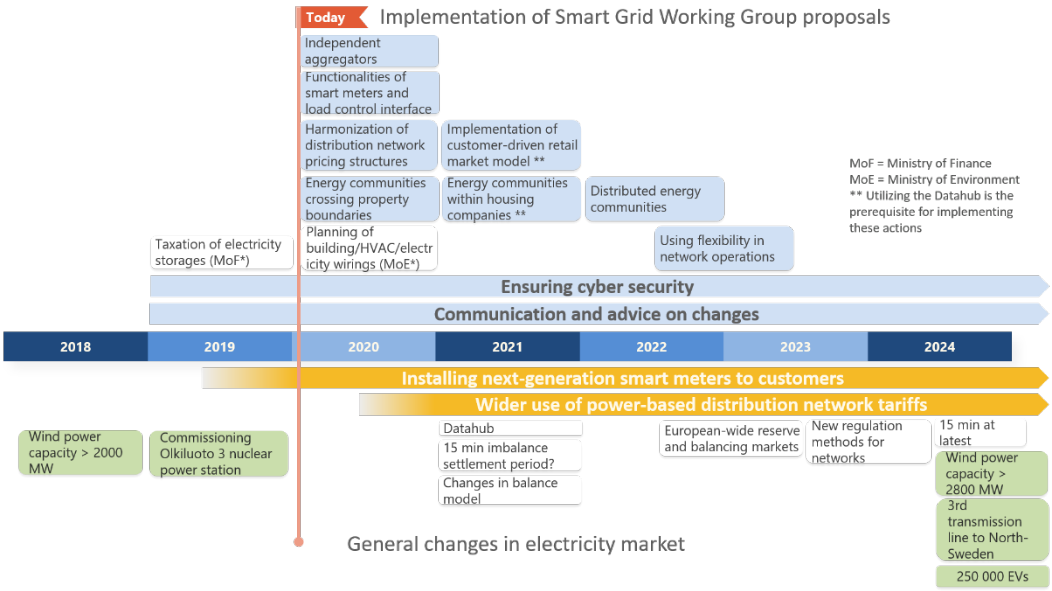


Figure 13. Order for implementing the Smart Grid working group's proposals. Adapted from (MEAE, 2018a)

The MEAE has started preparing a new strategy in April 2020 (MEAE, 2020a), aiming to be presented to Parliament in autumn 2021 (MEAE, 2020b). It includes reviews under the five dimensions of the EU; low carbon (renewable energy, energy efficiency, energy markets, energy security, and RDI measures), adaptation to climate change, energy and greenhouse gas balances, and comprehensive impact assessments of selected policy mixes. Other current energy and climate policy themes can also be highlighted in the strategy, such as energy supply security. The strategy's preparation will also consider the EC's legislative proposals related to the Communication on the Green Deal to tighten the 2030 targets and sector inquiries in various ministries. (MEAE, 2020b)

The active climate actor groups have been recently identified and analysed (Järvelä & Turunen, 2019), and the ongoing low carbon roadmap creation for 2035 aims for carbon-neutral Finland by 2035 (MEAE, 2020c).

In 2016, The Electricity Research Pool presented a vision and a road map of the Finnish power system: Vision for the future electricity network and electricity market 2035 & a road map 2025. The vision describes the Finnish electricity system in 2035, including a flexible power system, a resource-efficient city, lively countryside, and an active customer, as presented in Figure 14.

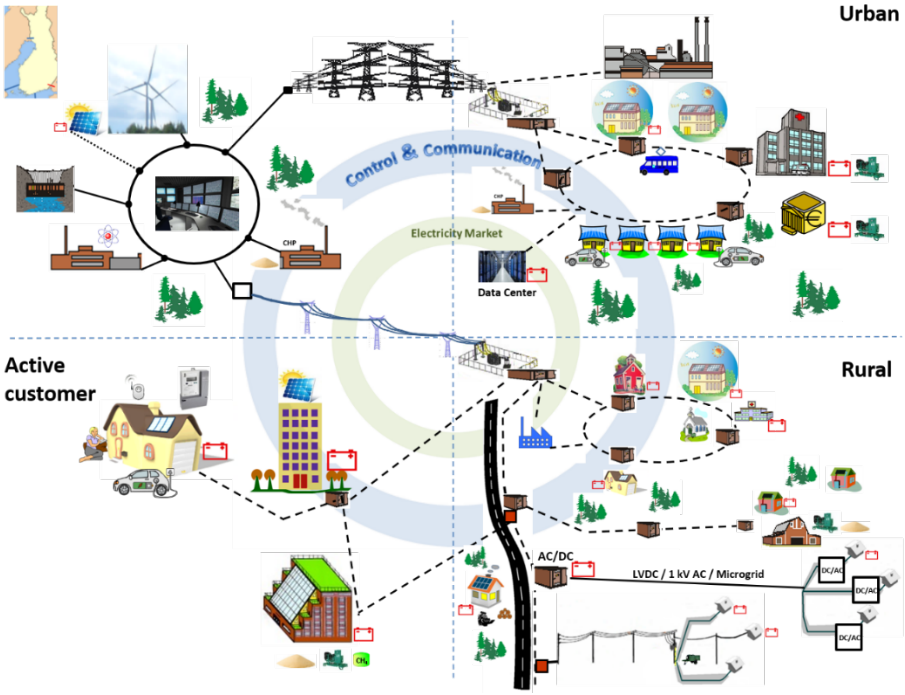


Figure 14. The vision of the Finnish power system in 2035. (Kumpulainen et al., 2016)

Kumpulainen et al. (2016) examined the future electricity grid's role and the electricity grid business by trends towards four boundary scenarios A, B, C and D illustrated in Figure 15 by considering the proportion of DER and the activity of customers and network.

The Scenario A network is active based on small-scale DER, microgrids, and energy communities, which operate locally but can also be aggregated into larger entities for sales in the electricity and flexibility markets. Scenario B has a more centralised solution with large wind farms and energy storages. In scenarios between A and B, "Active distribution network as a distributed energy resources (DER) marketplace" generation is centralised and decentralized appropriate. The customers and the network operators are active players in both. This combination is becoming common, and therefore the power balance of the entire power system must be managed centrally, utilising both large and small units. The Finnish TSO, Fingrid, actively develops a power system towards this combination scenario (Järventausta, 2021). (Kumpulainen et al., 2016)

In Scenario “Finland as the Nordic nuclear power country” (evolution towards C), electricity generation is centralised nuclear power, but elsewhere in the Nordic region, the main form is renewable energy. The Finnish regional price volatility is increasing. Customers optimise their consumption according to the spot price (the seller is the active operator). The distribution network is passive, and there is a need for investment, which the regulation model supports. The distribution network load peaks are growing. In the scenario “Customers disconnect from the grid into their own microgrids” (evolution towards D), small-scale renewable production and energy storage enables customers’ microgrids to disconnect from the utility grid into islands. The regulation does not allow an active role for the distribution network company, so the network remains a passive actor. The business of the electricity sales company is changing. This thesis relies on evolution paths within scenarios A and B and as highlighted in Figure 15. (Kumpulainen et al., 2016)

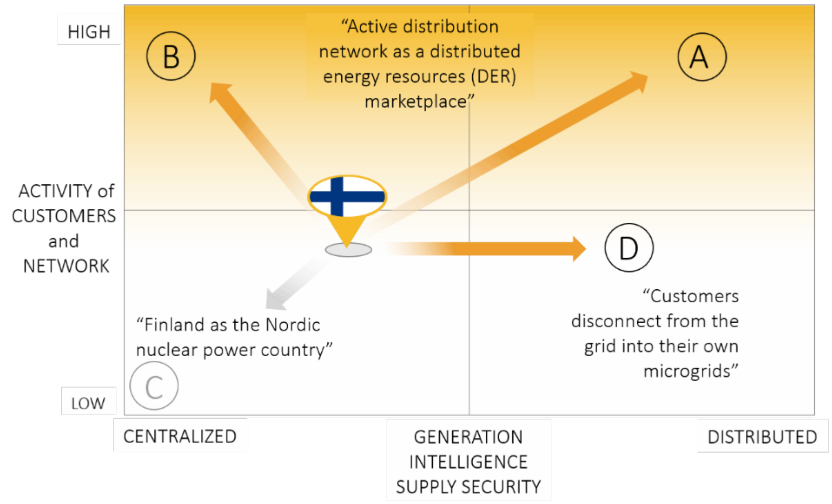


Figure 15. Four fields of future scenarios for the Finnish electricity networks. Adapted from (Kumpulainen et al., 2016)

Finnish Energy, supporting the energy sector in Finland, published a Low carbon roadmap (Finnish Energy – Low Carbon Roadmap, 2020) presenting two scenarios, which are business as usual (BAU) and low carbon (LC) scenario for the year 2050. In the LC scenario, the demand for industrial electricity in Finland significantly increases compared with the BAU. The increasing electricity demand is achieved by nuclear and wind power generation, whose share of the total generation increases significantly. The share of combined heat and power (CHP) in district heating remains significant in the LC scenario compared to the BAU scenario. Total fuel consumption decreases, but wood-based fuel consumption increases in the LC scenario. Electricity and district heating production achieve near-zero emissions in both scenarios. In the LC scenario, industries’ decarbonisation causes a significant increase in electricity demand than the BAU. The electricity network has to adapt to the increasing electricity flows and balancing of the system in different weather conditions. CHP and district heating have a vital role in ensuring the power system's security of supply in the LC scenario's flexibility requirements. CHP plants optimize the ratio of electricity and heat production, in which in high electricity price time, electricity production is increased. The flexibility is gained by utilizing the energy storages in district heating system. The heat pumps-and electric boilers utilise low electricity prices and can offer flexibility on the demand side.

The review of the energy transition reflected in the EU. National level energy visions in sections 3.1 – 3.3 emphasise the key enablers, which coincide by (i) IES, (ii) the DER implementation and utilisation for systems flexibility via the enhanced markets, (iii) placing the active customer in a significant position, (iv) interconnection between various actors, and (v) active networks and microgrids. Digitalisation is a prerequisite in energy transition, and the shared understanding of the development path is the cornerstone of the transition. Adoption of RESs is intended beneficial but puts also challenges to be solved. Therefore, new concepts are to be developed to satisfy the stakeholders' needs and resolve the challenges. The following section describes the ADN and microgrid concepts, which adoption status can explain the socio-technical transition in the power system.

3.4 Active distribution networks and microgrids

This section explains trends, enablers and challenges in electricity distribution networks because of the energy transition. Thereupon ADN and microgrids conceptual definitions are briefly presented. In this research, these high-level technical concepts respond to challenges and opportunities, thus enabling the evolution of electricity distribution networks needed in the energy transition.

RESs are the primary technology driver and enabler of the power systems' energy transition in electricity distribution networks, but also essential enablers are DERs, ASs, flexibility reserves, marketplaces for ASs, and the enhanced network controls and supervisory systems. DERs comprise electricity generation, consumption, and storage. Local energy generation via the DG units can be based on RES or fossil fuels, and they can be dispatchable or non-dispatchable. The power system's desired flexibility is achieved with the controllable DER units, including DG based on renewables, loads, and energy storage implemented in various capacities, voltage levels, and technologies. The social enablers of the energy transition are the dynamics to be noticed in stakeholders. The key actors or stakeholders are the customers (Gangale et al., 2013; Kirsi et al., 2016; Publication II; G. P. J. Verbong et al., 2013; Zafar et al., 2010). The other important stakeholders are the DSOs, the aggregators, and the electric energy providers.

The technological challenges arise in optimisation and security. The DER technologies' implementation can cause challenges because of the two-way power flow in the grid and the DER units' operation through the power electronic interfaces. For example, they are causing challenges to the protection system. There can be a lack of inertia in the system because the reduced short circuit currents and the fault currents' direction can vary. Information and communication technologies (ICT) are needed to be developed for managing the DER locally, especially in the LV distribution networks.

New concepts emerge for the electricity distribution networks for leveraging the DERs. The most prominent concepts are the ADN and the microgrid for various DER's optimal operation and control strategies. The concept of active distribution networks was defined by GIGRE Working Group C6.19 as follows: "Active distribution networks (ADNs) have systems in place to control a combination of distributed energy resources (DERs), defined as generators, loads and storage. With these systems in place, the ADN becomes an Active Distribution System (ADS)." (Fabrizio Pilo et al., 2014). The microgrid concept is described in IEEE standardisation as "a group of interconnected loads and distributed energy resources (DER) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island modes." (IEEE, 2018a). Microgrids are also defined in IEC-TS 62898-1 (IEC, 2017).

The benefits of Microgrids are mostly thought to be the improvement of the secure electricity supply because of the islanding capability in the main supply disruption. Also, the microgrids are required to provide various services, such as supporting the operation of the distribution network or the transmission system through ASs. The microgrids impact the main power system, for example, by reduced peak loading.

This thesis focuses on the microgrid concept, which can be considered a comprehensive ADN approach. The microgrid concept builds on various DER utilisations, including DG, energy storage (ES), and controllable loads. The operation modes of the microgrids are grid-connected, islanded, and transition. The interconnection switch manages the electrical connection to the main grid. A control system is needed to manage the energy, the power flow, and the protection.

3.5 Transformation in low voltage distribution networks

The upgrade of the electricity distribution networks must meet the visions and requirements of future energy systems. In particular, the LV distribution networks are under heavy pressure to change because they are traditionally passive and rarely automated. In the future, LV distribution networks must also operate for ADN operational goals, even independently as a microgrid. A roadmap is required from the current passive network to the vision of its' active operation in IES.

Sirviö (2012) introduced four evolutionary phases of the LV distribution networks. The phases are (i) Traditional, (ii) Boom of Distributed Generation, (iii) Microgrid, and (iv) Intelligent Microgrid. Consequently, Publication I continued this research and also presented operational descriptions of the evolution phases by developing UCs for (i) Traditional Network, (ii) Self-sufficient in Electric Energy, (iii) Microgrid, and (iv) Intelligent Network of Microgrids. The UCs were defined for the network normal operation and control management and the distribution network safety and protection management. The actors are grouped based on the NIST's definitions of Smart Grids domains (Figure 3a). Figure 16 presents the studied LV Microgrid phases a) network structure and b) operation modes.

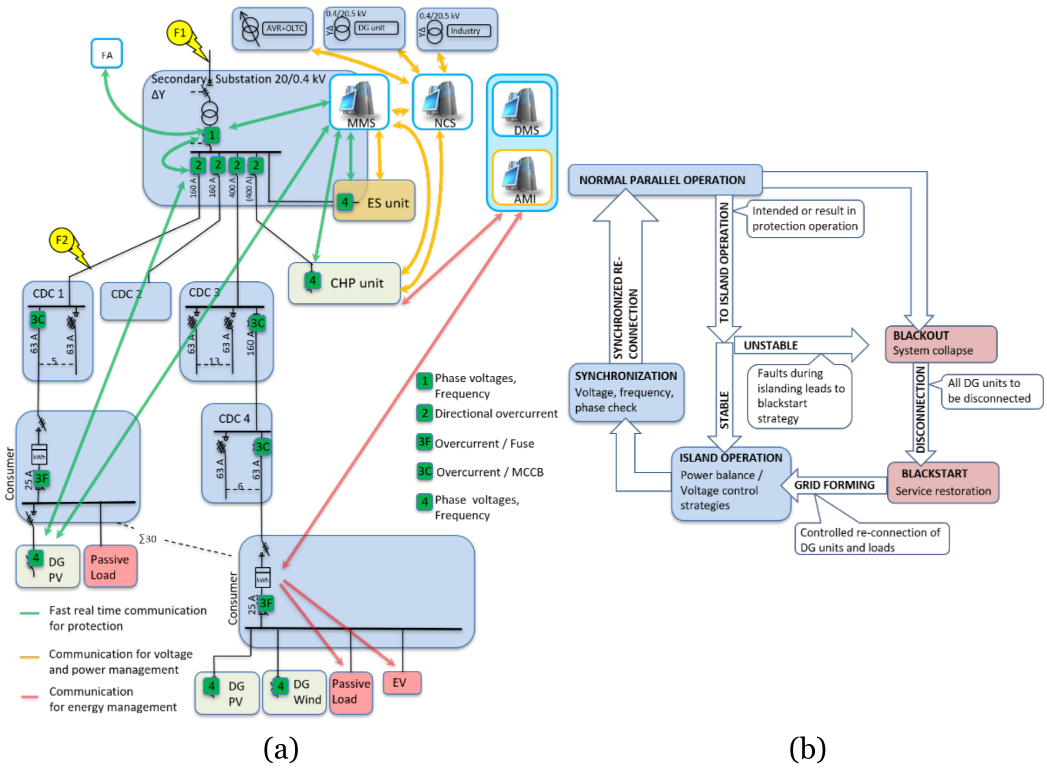


Figure 16. The Microgrid phases: (a) the network structure, (b) operation modes (Publication I)

The customers play a key role in future distribution networks. Therefore developing customer roles alongside the LV distribution network evolution was concerned in Publication II. Modelling the developing customer roles was conducted in the socio-technical context by combining the MLP and SNM frameworks and utilising the UML method. Figure 17 presents an extended UML class diagram of the developing customers: (i) Consumer in the Traditional phase, (ii) Responsive Consumer and (iii) Prosumer in the Self-sufficient phase, (iv) Partner in the Microgrid phase and (v) Strategic partner in the Intelligent Network of Microgrids phase. In the diagram, the Consumer a class presents a customer type generalisation, identifying common elements of entities. Therefore, Consumer, as a superclass or a parent, has the most general attributes (-), operations (+), and the relationships that can be shared with/inherit to subclasses or children, to the customer classes (ii-v). A subclass has more specialised attributes and operations. The customers' inheriting relationships with the key actors are presented.

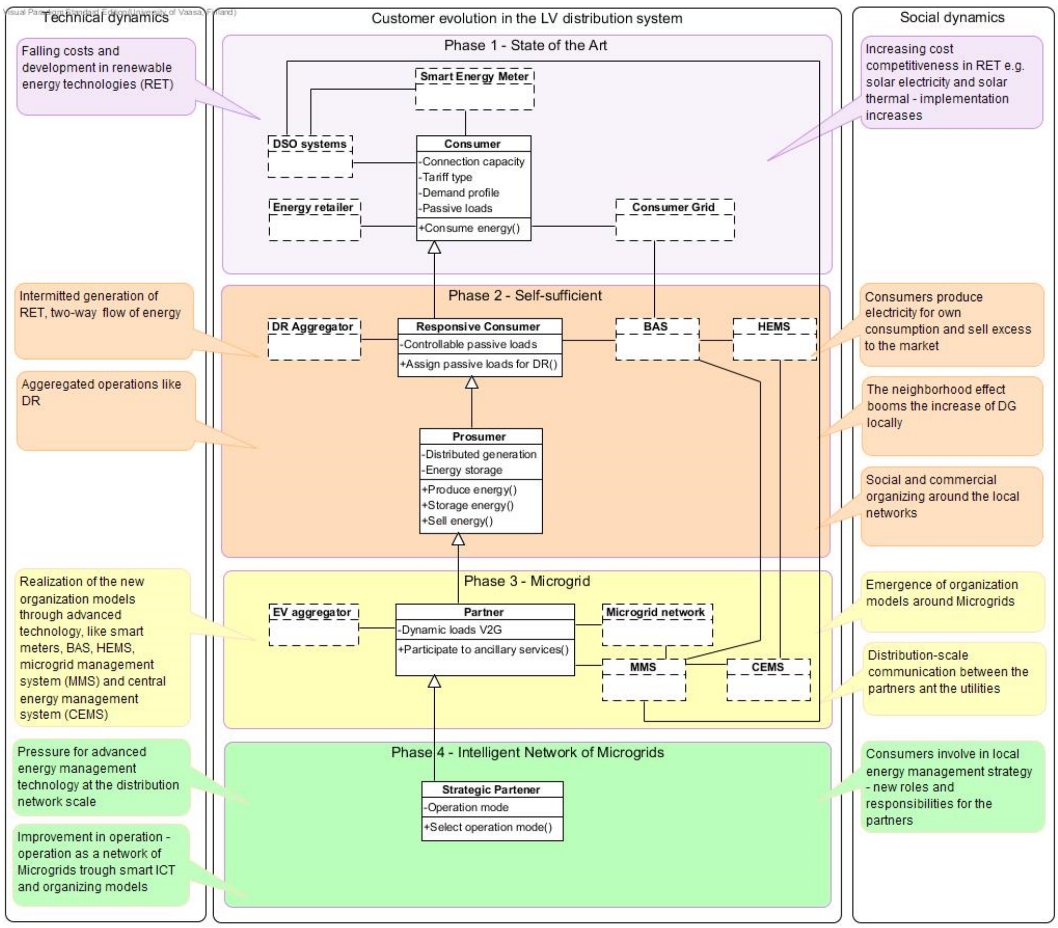


Figure 17. Customer evolution in the developing LV distribution system. (Publication II)

4 ACTIVE MANAGEMENT OF DISTRIBUTION NETWORKS

This section focuses on the third research question: How distributed energy resources offer local ancillary services for developing distribution networks?

Electricity distribution networks are evolving extensively towards ADNs. Differences between the traditional distribution networks (TDNs) versus ADNs can be described by understanding their differences because of the share of implemented DER in the network operations. As a result, the ADN extends the TDN with load forecasting (Zhong et al., 2014), network planning (Al Kaabi et al., 2014; Gianni Celli et al., 2007; Xiangning Lin et al., 2014; Martins & Borges, 2011; F. Pilo et al., 2010), and power management and control (Gabash & Li, 2012; Gill et al., 2014).

Consequently, the operational requirements and, accordingly, the ADNs planning principles differ from the present system. The way electricity is sourced and consumed is currently changing. The possibilities to control the generation and consumption is enhancing, even from the domains of customers. The customers and DNOs are becoming more active, allowing ASs to develop. The traditional DNO operations are changing to DSO operations (Western Power Distribution, 2020). The DSOs are responsible for the ADN operation by applying suitable active distribution network management (ADNM) schemes to satisfy stakeholders and network constraints most efficiently in compliance with the regulatory framework and the energy policies.

In this section, ADN planning, operation, and management are discussed. Further, a broader overview of DSM, AS, and reserves are presented. How DERs can provide ASs are discussed. In conclusion, a case study of an ADNM scheme for reactive power control by DERs for the DSO's AS is presented via the outcomes of Publications III and IV.

4.1 Planning of active distribution networks

The evolution and active management of the future electricity distribution networks build on the development and changes of the network planning focus because of the prospects of DER. Basically, long-term planning aims to ensure the electricity distribution networks providing electricity at the lowest cost possible with the required quality. Traditionally, the planning objectives are for minimizing the power losses, the capital investments and maintenance costs and the cost of energy not supplied (Neimane, 2001). Thus, traditional distribution network planning (TDNP) focuses on the optimal sizing, location, and reinforcement of substations, transformers, and feeders to find the most economical solution (with a single objective function) (Georgilakis & Hatziargyriou, 2015; Willis, 2004). An extension of TDNP can be seen in the optimal sizing and location of DERs, transforming the planning to move towards active distribution network planning (ADNP) (Xiang et al., 2016). In ADNP, investments and DER problems are considered jointly. The main objectives are cost, technical features, and performance.

The ADNP mainly involves the DER participation, interactive information system(s) and smart automation technology integration, highlighting the system control in planning. Hence, ADNP integrates multi-energy and active management strategies into TDNP because of the diverse use of DERs. Significant cost savings can be obtained through DER control instead of the passive “fit and forget” method. Therefore, the consideration of multiple controls is of great interest in planning (Georgilakis & Hatziargyriou, 2015). Various control operations can be active and reactive power control of the DG units, online network reconfiguration, DR and generation curtailment (Georgilakis & Hatziargyriou, 2015), and energy storages control.

Including the DG units in planning the distribution networks increases the optimisation process’s complexity (López et al., 2018; Zubo et al., 2017). The challenges of the interconnection of DERs into the electricity distribution networks must be solved at the ADN planning stage. For example, the uncertainties of energy consumption or generation in various time series. ADNP can be improved significantly by the spatial forecast, the satellite maps, and the geographical information system (GIS) (Gabash & Li, 2012). The LV distribution networks are of great developmental concern since the increase of the active customers’ DERs affects the network management. Furthermore, microgrids can be considered flexible resources in ADNP (G. Celli et al., 2016; Millar et al., 2014).

Consequently, the development of the ADN planning tools, particularly LV-specific and microgrid-specific planning or simulation tools is essential. The simulation is discussed in Section 5.2.

4.2 Operation and management of active distribution networks

Connection challenges with the DERs and the potential to offer flexibilities lead the operational development change in the electricity distribution networks. ADN operation needs enhanced network management.

The traditional power system is built on the idea that the bulk power plants generate electricity for consumer needs through a one-way flow. The operational idea of Smart Grids is to provide multidirectional power flow reliably, efficiently, flexibly and to enable operations in enhanced markets. Because of the power system transformation, the operation of power systems is becoming more complex and demanding. New stakeholders, new energy sources, fluctuating demand, new regulations have to be considered, and grids need to respond to increasing volatility.

Operations refer to the concept of multiple systems working together to achieve the operational targets, which include economic, technical, or environmental targets. In the electricity distribution networks, a high-level technical target can be to improve power quality and power supply reliability. Economic target aims to minimise operational cost and environmental targets aim to reduce the carbon footprint. The power quality assurance and improvement refer to the functionalities to manage voltage amplitude and frequency. Power supply reliability refers to managing failures in the power system through asset and protection management for example.

The main ADN objective functions are either minimisation or maximisation optimization problems relevant to the distribution network stakeholders' financial interests and the technical and legal boundary conditions. Minimization objectives can be of 1) power losses, 2) total operational cost, 3) voltage deviations or voltage unbalance factor (VUF), 4) DG curtailment, 5) switching operations of distribution network components, 6) expected system average interruption frequency index (ESAIFI) and expected energy not supplied (EENS), 7) DG reactive power support, 8) imported power from transmission network and operational costs of ANM schemes. Maximization objectives can be of 1) the DGs' reactive power injection to grid to minimize the imported reactive power from transmission network, 2) the exported power to the transmission network, 3) the total profit of either DSO or consumer, 4) consumer's benefit, 5) the installed DG capacity, 6) RES exploitation and 7) voltage limits satisfaction. (Evangelopoulos et al., 2016)

The increasing number of DERs in network operation can cause local or system-wide challenges to be solved, depending on the DERs penetration level. A low proportion of DERs cause local challenges, including unsuitable voltage profiles, malfunctions in protection operation, and lower power quality. A high DER share may also cause system-wide problems, including effects on network stability, uncontrolled reactive power flows, impact on power reserves, and a need for ADNM schemes. (Papic, 2012)

The DERs utilization and the various desired operational scenarios of future electricity distribution networks require advanced planning and development of control technologies. ADNM needs to be developed for implementing different operating modes via enhanced ADN concepts. The ADNM schemes enable the distribution network operation with high DG penetration and microgrids. On top of that is the higher-level ADN concept description itself, and next can be, for example, microgrids and VPPs for carrying out some sub-objectives. The implementation of the ADNM concepts at the real-life applications level can vary, thus giving the ultimate targets, terms, and conditions of operation. For example, a microgrid application can be a utility grid or an isolated grid. Grid-connected mode requirements do not apply to the isolated microgrid. The concepts define the functionalities to be obtained, such as power balancing, congestion management, fault management, resiliency, and responding to external orders (Publication VIII). The management schemes (and architectures) are developed for achieving (and implementing) the desired functionalities of a concept.

An ADNM scheme can be considered a functionality that applies to a single system or element in a larger whole. Each element or subsystem has a specific goal in producing a functionality, possibly regardless of how the others perform. Although each element may have an independent function, this does not necessarily mean that its operation does not affect other elements' operation and the whole system's operation. The performance of an individual element can determine the whole system's operational outcome. Basically, every individual element has a particular task in the system operation, which might not be completed if another single element's task is not satisfied. Although an element's operational performance might substantially impact the system operational success, the completion of the operation by some method is essential. This philosophy is the basic idea of developing adaptive schemes needed in self-healing and flexible power systems.

Figure 18 presents the potential ADNM schemes where AS offered by DERs have an essential role (D'Adamo et al., 2011; Evangelopoulos et al., 2016; Laaksonen et al., 2021; Peponis et al., 1996). The ADN main aims of operation give the main frame for an operational target, which can be technical, economic or environmental. ADN management sections relate to the active management of voltage, power flows, protection, assets, power losses and customers.

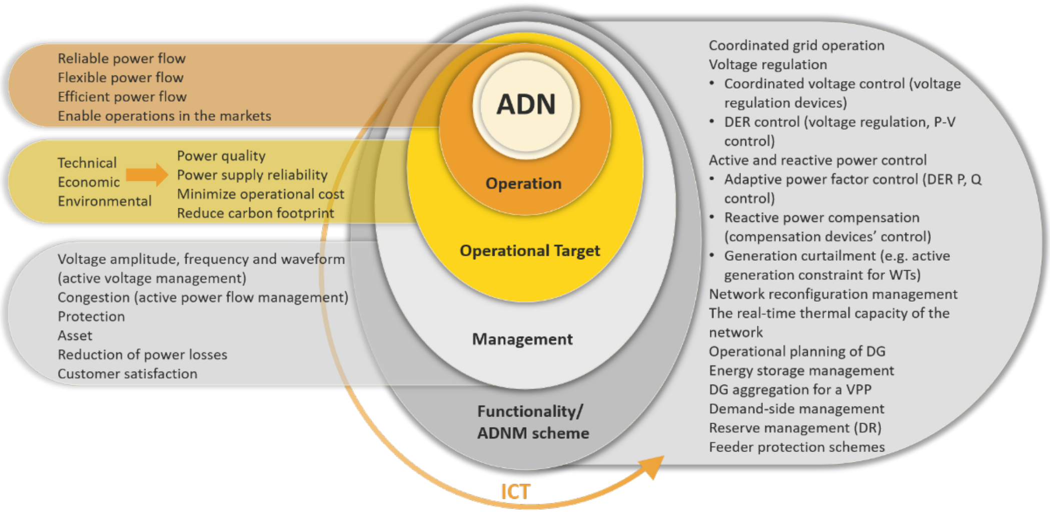


Figure 18. Active distribution network operation, operational target, management and management schemes.

4.3 Demand-side management

The DERs are topical to provide flexibility on the demand side in future distribution networks. Thus load-control strategies have been utilised for several decades, but now demand-side management is widely implemented by DR programmes and demand-side marketplaces. Demand-side optimization challenges in Smart Grids are DR, energy conservation, energy efficiency, and managing power losses in the power grid (Fadlullah & Kato, 2015). The supply and demand optimisation problem is traditionally handled by the DSM, a concept for influencing electricity use by affecting load shape changes (Gellings, 1985). DSM includes energy efficiency aiming to use less energy to perform the same tasks, permanent demand reduction, or DR using any method to reduce, flatten, or transfer the demand. The forms of the load shape objectives are peak clipping, valley filling, load shifting, strategic conservation, strategic load growth (Gellings, 1984), and flexible load shape (Gellings, 1985).

The classic demand management techniques are peak clipping, valley filling, and load shifting. Peak clipping cuts the peak loads, valley filling builds the off-peak loads, and load shifting moves demand from peak to off-peak periods. Load shifting means reducing electricity consumption. An increase in demand follows later when the electricity prices are lower. Strategic conservation involves a decrease in energy sales, usually involving changes in usage patterns. Strategic load growth targets an increase in energy sales, which may involve a higher market share of loads obtained by competing fuels in transportation by the EVs or in heating by heat pumps, as an example. Flexible load shape relates to planning reliability criteria. The load shape can be flexible if customers are offered options for variations in the quality of service they are willing to allow as an example in exchange for various incentives. (Gellings, 1985)

The emergence and evolution of DR programmes are essential considering energy efficiency, supply reliability, and cost savings. The customer's energy consumption pattern can be modified according to the variations in electricity prices or the system's reliability compromise via DR programmes. The development of DR programmes aims to motivate also residential and small commercial customers to shift their load from peak hours to off-peak hours, thus providing flexibility via DSM. Traditionally, residential and small commercial consumers have bought electricity at a flat or fixed price that does not vary dynamically with the changes in supply and demand or the wholesale market prices.

The options for the DR programmes are the price-based programmes (PBP) and the incentive-based programmes (IBP). The PBP programmes base on dynamic pricing, where the customers are motivated by variable electricity prices, which depend on the real-time cost of electricity. In the IBP, customers are motivated to curtail their demand during peak hours against their incentives. The customers receive participation credits (a credit note or a discount rate) for their engagement. The PBP include the time-of-use (TOU), critical peak pricing (CPP), extreme day CPP (ED-CPP), extreme day pricing (EDP), and real-time pricing (RTP) programmes. The IBP include classical (load control) and market-based programmes. The classical IBP splits into the direct load control (DLC) and interruptible/curtailable load programmes. In the market-based IBP, customers are compensated according to the load reduction amount. The market-based IBP has demand bidding (DB), emergency DR, capacity market (CM), and AS markets programmes. (Albadi & El-Saadany, 2008, 2007; Sharma et al., 2020)

Chapter 6 addresses load control and DR marketplaces in the Sundom Smart Grid study cases.

4.4 Ancillary services and reserves

The aim of ASs is to support the reliable electricity supply and the transmission system operation. The demand and supply must be balanced constantly in the transmission system by ensuring that frequency, voltage, and power remain within certain limits. The adjustments and corrections in the power grid are provided by the ASs, including frequency stability support, power balance, voltage control, supply restoration, and system management (Chuang & Schwaegerl, 2009), as presented in Table 3. This thesis focuses on frequency stability, power balance and voltage control ASs, which are explained below.

Table 3. Ancillary services.

Ancillary Service Type	Means
Frequency stability support	Frequency control of power, regulation, and operating reserves
Power balance	Scheduling and dispatching of balancing energy
Voltage control	Tap-changer control Reactive power control
Supply restoration	Black start capability Island operation
System management	Power quality assurance operation Asset management

Frequency stability support services apply to normal operations of the grid in power system balancing and disturbance situations (power plant outages) or unexpected events (an unforeseen increase in consumption). The services supporting the power balance in the network aim to avoid foreseeable potential grid congestion or bottlenecks. Voltage support services ensure the quality and safety of electricity. Power factor correction aims to adjust the relationship between active and reactive power to stabilise voltage within the operational range. Supply restoration services use power plants (for example, hydroelectric or gas) able to offer automatic black-start without external energy supply after a power outage. (Kraftwerke, 2020)

The means to control the power system's frequency and power balance are generally upward regulation with a reserve that can increase electricity generation or reduce electricity consumption, and downward regulation with a reserve that can reduce electricity generation or increase electricity consumption. Operating reserves can be provided from the part-load operated and the standing but fast-starting power plants, controllable loads, wind power plants' downregulation, and energy storages (Chuang & Schwaegerl, 2009). These operating reserves are divided into the following (Denholm et al., 2019):

1) Frequency-responsive reserves, activated automatically by frequency changes
2) Regulating Reserves
3) Contingency Reserves
4) Ramping Reserves
5) The normal operation provided by energy and capacity

The time association of frequency regulation and operating reserves for the frequency stability support AS in Europe is illustrated in Figure 19 that was created based on Chuang & Schwaegerl (2009), Dattaray et al. (2019), ENTSO-E (2013), Fingrid (2018), Kaushal & Van Hertem (2019), Tamrakar et al. (2017), TUT et al. (2020), Yap et al. (2019), and You et al. (2017).

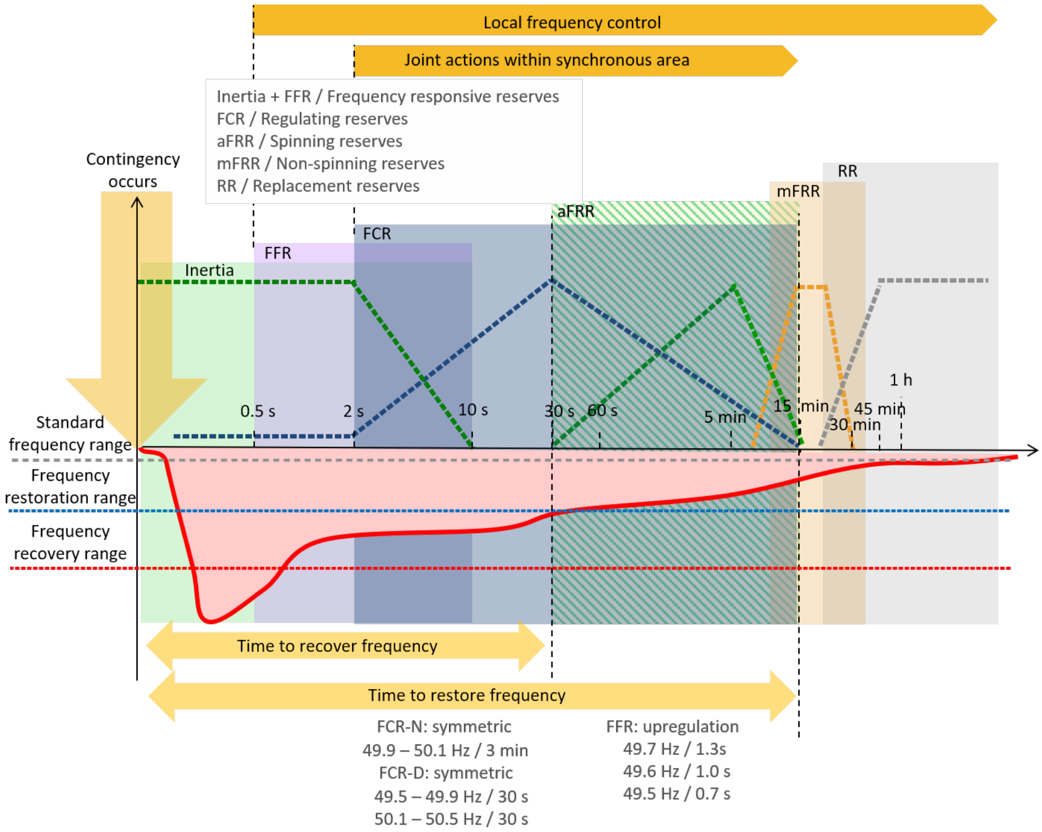


Figure 19. Time association of frequency regulation and operating reserves.

Various and random deviations in generation and load or disturbances can cause a frequency deviation in the power system to which the power system's primary control must react by the involved generators. The power equilibrium is immediately restored with the primary control by maintaining the system frequency within the permissible limits. If the frequency still exceeds the limits, additional measures outside the scope of primary control, such as automatic load-shedding, are executed to maintain interconnected operation. When the balance is restored, the system frequency stabilises and remains at a quasi-steady-state (restoration range) differing from the frequency set-point value. Then, the secondary control manages the remaining deviations (after 15 – 30 s), restoring power in cross-border exchanges to set-point values and the system frequency to its set-point value and completed (after 15 min). If the demand exceeds generation continuously, actions must be made to restore the balance despite the reserve capacity. The tertiary control replaces the secondary control reserve to restore a sufficient secondary control band by standby supplies and contractual load variation (load shedding). (ENTSO-E, 2004; Hodel et al., 2019)

The primary control is the frequency containment process (FCP), and the secondary control is the frequency restoration process (FRP) (Yap et al., 2019). The power systems' frequency control is based on the harmonised services across Europe. Frequency containment reserves (FCR) aim to maintain the frequency as close as possible to 50 Hz. Further, FCR reserves are divided according to the normal operation (FCR-N) and disturbance situation (FCR-D) reserves. Next, the frequency restoration reserves (FRR), realised automatically (aFRR) or manually (mFRR), aims to free activated FCR to take care of the subsequent frequency deviation and to restore frequency to the normal range. Further, the RRs release the activated FRRs back to a ready state for new disturbances. In the future, low inertia situations are to be managed faster than the FCR operates with the fast frequency reserves (FFR) (Fernández-Muñoz et al., 2020). FFR is procured only for low inertia situations, coping with a fast drop in frequency after the dimensioning failure. (TUT et al., 2020)

Electricity markets are developing for integrating DER and DR, aiding to maintain the flexibility and reliability of power systems. However, a review of AS marketplaces is excluded from this thesis since they relate to the economic perspective.

Voltage control at a grid node can be performed by adjusting reactive power. The voltage is raised by feeding in and reduced by intaking of reactive power. TSOs specifies reference voltages for the generation units and the distribution networks in the transmission grid connection points. The controlled reactive power exchange allows the voltage at the connection point to be settled to specified reference limits. Power plants directly connected to the transmission grid are obligated to participate in voltage support actively. Distribution grids are participating partially active in the voltage support (EU, 2016).

AS provided from DG (or BESS) can be voltage control, regulation, load following, spinning reserve, supplemental reserve (non-spinning), backup supply, harmonic compensation, network stability, seamless transfer, and peak shaving (Campbell, 2005). In developing power systems, ASs provided by DERs can be carried out for both transmission (system-wide) and distribution system level. The distribution system level AS is called local AS in this research. ASs to the transmission grid can be the frequency response, voltage/reactive power control, and smoothing of fluctuating power, and the local ASs can be reactive power control, smoothing of fluctuating power, harmonic mitigation, and fault-clearing and fault ride-through

(FRT) capability (Demoulias et al., 2018; Oureilidis et al., 2020)(Oureilidis et al., 2020). Microgrids provide an excellent option for AS operations (Laaksonen et al., 2021).

The next section focuses on a study case of local AS provided by a large-scale DG unit. A coordinated reactive power ADNM scheme is developed for the DSO to manage power flow at distribution/transmission network POI.

4.5 Reactive power control with the distributed energy resources for local ancillary services

Future distribution networks must operate according to the ADN operational targets, even independently as a microgrid. One essential goal is to provide local and system-wide AS by DERs. A potential local AS is the reactive power control by the power electronics connected DER. This section presents a case study of the DER units offering local AS for the Sundom Smart Grid. The Sundom Smart Grid is a local smart grid pilot in Finland, Vaasa, located in a suburban/rural area, offering a novel research platform to develop ADN solutions.

Figure 20 outlines the Sundom smart grid. The primary substation connects the 110 kV and the 21 kV grids, and the secondary substations connect 0.4 kV LV distribution networks to the power system. A 3.6 MW WT is connected to the MV bus with its own short feeder, and a 33.6 kW PV unit is located in the LV grid. Around 2500 metering points are consisting of residential and small commercial electricity users. The peak power was about 8 MW in 2018 and is increasing as housing in the area grows. The DG units, electric vehicles (EVs) and BESS, are assumed to increase at the customer premises. Customers use the electric heating systems, which can be direct, partially storing, storing, or heat pumps. Also, other energy sources are used for heating.

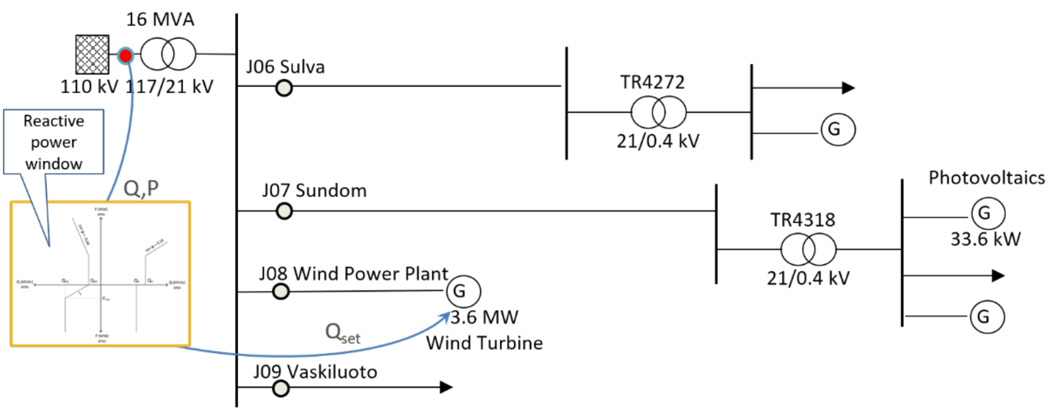


Figure 20. Outline of the Sundom Smart Grid.

Publication III presents the different requirements for reactive power flow between the distribution and transmission grids considered for the Sundom Smart Grid. The "future reactive power window" for the Sundom Smart Grid is based on the requirements for reactive power management for the transmission grid-connected distribution systems (EU, 2016), conditions set by Finnish TSO, Fingrid (Fingrid, 2017), and non-detection-zone requirements for microgrids (Laaksonen & Hovila, 2017, 2016; Uebermasser et al., 2017). TSO's reactive power window specifies the volume of reactive power delivered or received through the distribution/transmission connection points without penalties or separate compensation.

The future reactive power window for the Sundom Smart Grid was utilised for a reactive power control scheme formulation. The TSO's requirements and the requirements for reliable islanding detection for the microgrids were considered. The future reactive power window for Sundom Smart Grid (Publication III, Figure 3) is updated in Figure 21 because of the revision of Fingrid's requirements (Fingrid, 2021) which relaxed requirements when feeding in active power. Also, estimating the peak power (or energy in one year) increase (forecast 2030) in Sundom is considered. In the active power consumption situation (P_{output}), the reactive power output limit QD and input limit QD_1 are applied. In the active power production situation (P_{input}), the reactive power output limit QG and input limit QG1 are applied. The QD_{min} is 2 MVAr in a transmission line connection and 4 MVAr in a substation connection. The QD_{max} is 50 MVAr.

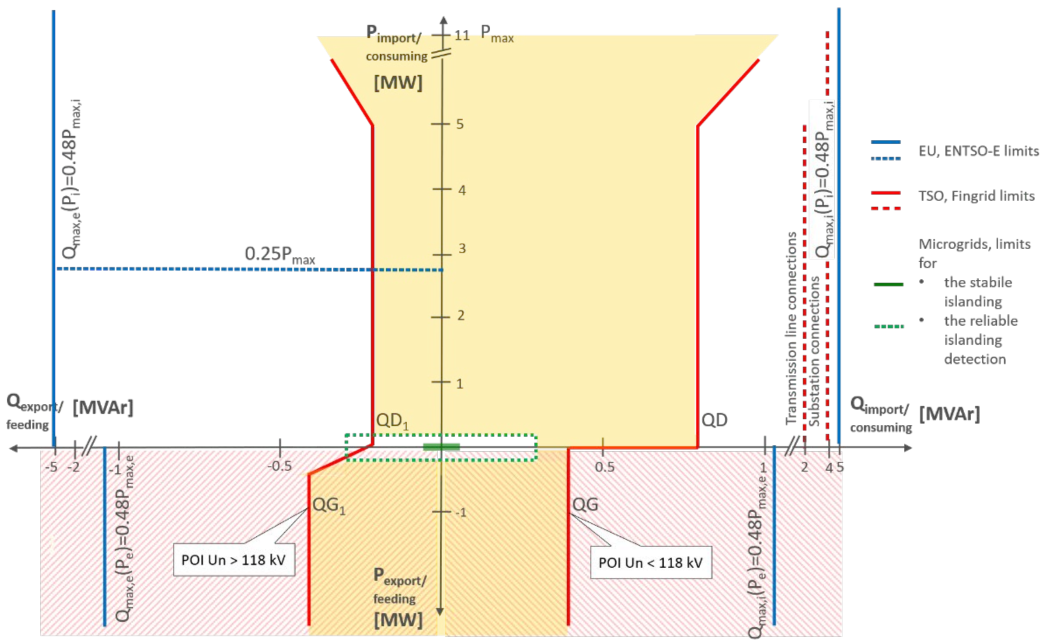


Figure 21. Future reactive power window for the Sundom Smart Grid.

The reactive power control algorithm for the WT's full-scale converter was developed to limit the reactive power flow at the POI, according to the yellow section in Figure 21. The algorithm used the one-year data generated based on one-month measurement data from the Sundom Smart Grid. The results show (Publication III, Figures 4 and 6) that a coordinated reactive power management scheme across the different voltage levels by utilising control of DG could benefit the voltage support AS and a microgrid reliable islanding.

Further research interests arose based on the results. More reliable results would be obtained through implementing one-year measurement data from both consumption and WT power generation. The cabling degree increases in the Sundom Smart Grid. Therefore, the adequacy of the WT converter's reactive power capacity should be verified. The number of PV units increases, so the PV inverters could be utilised in the reactive power management accordingly.

Publication IV (Prospects and Costs for Reactive Power Control in Sundom Smart Grid) presents feasibility case studies for reactive power management in the developing Sundom Smart Grid by utilising MV and LV network connected DER units, developed control algorithm (Publication III), and the nine-month one-hour average measurement data. The main challenge in reactive power flow management is low consumption time since the cables generate reactive power when they are lightly loaded. The simulations showed that coordinated reactive power management across the voltage levels utilising various DERs (PV and WT) is technically and economically significant for developing future distribution networks. The case studies demonstrated that the effect of the LV grid-connected PV units with 4000 m^2 of panels (or 40 units) and inverter power factor control ($\cos\phi$ = 0,8$_{ind}$), the PV inverters consumed reactive power was up to 250 kVAr, which is minimal considering the reactive power flow at the transmission and distribution networks POI. The panel area should increase notably to affect the reactive power flow at POI via the LV level PV units.

Further development of the reactive power flow management scheme is necessary. A coordinated operation with voltage control devices is needed. Therefore, they are included in the total management scheme. A possibility of active power control affecting reactive power control could be established using an energy storage system, through DR, or by limiting the generation from the WT and PV units. Modelling the LV distribution networks, energy storage systems, and DR actions and developing the active and reactive power control algorithms are essential for voltage control AS. The developed simulation model could be utilised in future studies of the Sundom Smart grid. More accurate results could be obtained by implementing one-year measured data. Further, modelling a 21 kV-side reactive power window is essential for reactive power control studies of the microgrids, in which more frequent measured data can be implemented. Adapting the offline models for the control algorithm and the power system for the real-time simulation platform builds a frame for HIL testing of the developed reactive power controller.

Publication III and IV provide the means for further studies of the voltage control AS provided by the Sundom Smart Grid or utility grid-connected microgrids. Publication IV has been cited in Hafezi & Laaksonen (2019), which presents a soft open point (SOP), the power electronic devices installed in the normally open points of the distribution networks, for the voltage control ASs. SOPs can provide active power flow control, reactive power compensation and voltage regulation in the network normal operating conditions, and fast fault isolation and supply restoration in the disturbances.

The management of the reactive power flow at POI of distribution and transmission networks has been topical. Retorta et al. (2020) presents a local market and a mechanism for managing reactive power flow according to the TSO's reactive power profile release, to which market agents (managing the DERs) can send bids. Stanković et al. (2021) presents a reactive power flexibility measure through flexibility coefficients based on the DSO capability and TSO desirability surfaces.

5 REALISING CONCEPTS FOR SMART GRIDS

This section focuses on the fourth research question: What kind of development and testing platforms are necessary for developing control functions for the microgrids or the active distribution networks?

New solutions for realising ADNs and ADNM scheme are being developed universally. An essential driver for the implementation of the microgrids is the more efficient DERs integration involving several stakeholders and actors. Hence, the control and protection of microgrids require novel technical solutions and applications. Standardisation is critical in developing multi-vendor ADN and microgrid systems where interoperability is mandatory, providing compliance of different and various vendors' solutions.

This section presents the development procedure of a reactive power control ADNM scheme from a control algorithm to a hardware controller for developing control solutions and related testing methods. First, however, the relationships among standardisation and product development and the simulation and testing methods are presented. Conclusively, this section discusses the significance of testing and piloting in living laboratories.

5.1 Standardised solutions

Innovations are achieved through the application of new technologies in the energy sector. New technology ensures performance improvements but brings uncertainties and risks in its capabilities, limitations, and development trajectory. Understanding the status of the maturity or the technology readiness level (TRL) is essential in making decisions about injections, development, and technology integration (Rose et al., 2017). The TRL scale (1-9) allows for assessing the maturity level of a particular technology and comparing different technologies' maturity (EC, 2021). The system readiness level (SRL) and integration readiness level (IRL) extends the TRL (Knaggs et al., 2017, 2015; Sauser et al., 2006).

Roughly divided, TRL 1-3 is academically driven knowledge development, TRL 4-7 is technology development in collaboration with academia and industry, and TRL 7-9 is industrial business development. Standardisation activities are essential for transforming innovations into products in markets. Analysis between research and standardisation (De Ipiña et al., 2015) and between product management and standardisation is crucial for sustainable technology transitions.

Figure 22 presents the six stages of the classic product life cycle: development, introduction, growth, maturity, saturation, and decline. Further, product portfolio analysis divides the products as question marks, stars, cash cows and dogs. Product management and strategic marketing can be carried out with portfolio-adequate positioning for products based on the classic product life-cycle curve (Reichmann, 1997). Figure 22 adds the impact of standardisation on product development, illustrating the product's lifetime cycle regarding the standardisation phases (Reilly et al., 2017).

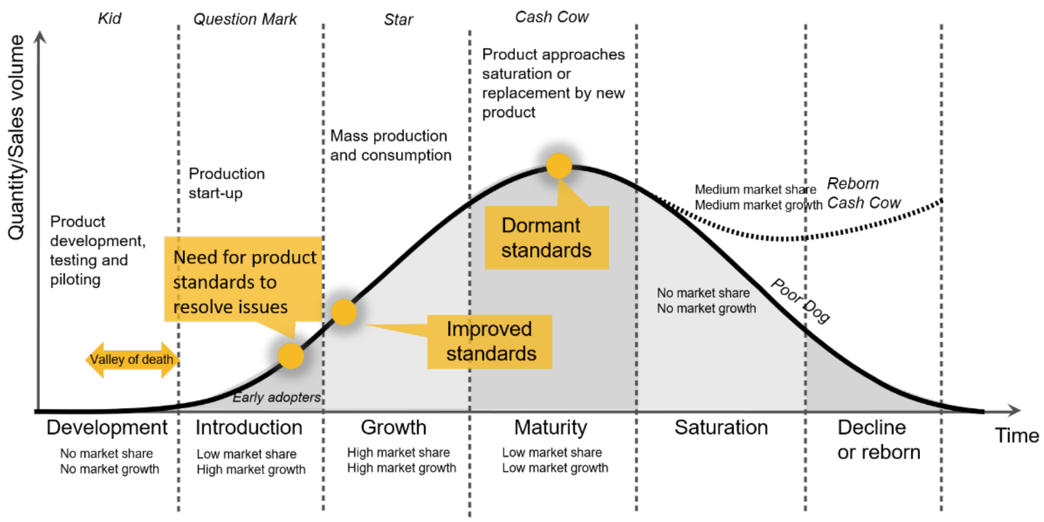


Figure 22. Product sales and standards cycle.

IEEE and IEC standards for the control and management of microgrids are developing. The following standards have been published.

- IEEE 2030.7: IEEE Standard for the Specification of Microgrid Controllers (IEEE, 2018a),
- IEEE 2030.8: IEEE Standard for the Testing of Microgrid Controllers (IEEE, 2018b),
- IEEE 2030.9: IEEE Recommended Practice for the Planning and Design of the Microgrid (IEEE, 2019),
- IEEE 1547-2018: IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces (IEEE, 2018c),
- 1547a-2020 - IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces--Amendment 1: To Provide More Flexibility for Adoption of Abnormal Operating Performance Category III (IEEE, 2020),

- IEC TS 62898-1: Microgrids – Part 1: Guidelines for microgrid projects planning and specification (IEC, 2017),
- IEC TS 62898-2: Microgrids – Part 2: Guidelines for operation (IEC, 2018),
- IEC TS 62898-3-1: Microgrids – Part 3-1: Technical requirements – Protection and dynamic control (IEC, 2020).

In the next few years, the following standards are coming:

- IEC TS 62898-3-2: Microgrids – Part 3-2: Technical requirements – Energy management systems (forecast 12-2022) (IEC, 2022a),
- IEC TS 62898-3-3: Microgrids - Part 3-3: Technical requirements – Self-regulation of dispatchable loads (forecast 2-2022) (IEC, 2022b)
- IEC TS 62898-3-4: Microgrids – Technical requirements – Monitoring and Control systems (forecast 8-2023) (IEC, 2023), and
- IEC TS 62898-4: Roadmap for decentralized electrical energy systems – Part 2: Microgrid use cases (forecast 11-2021) (IEC, 2021).

However, various vendor-defined microgrid controllers have already been developed and tested (Liu et al., 2016). The challenge of vendor-defined solutions can be that they might not meet interoperability and grid-code requirements.

The product development/standardisation phase curve indicates that microgrid controllers are partly in the stage of the "need for product standards to resolve issues." Despite this fact, the different solutions for microgrid management are becoming increasingly global. However, standards are emerging and developing. One concern is how to utilise and map the early-stage standardisation, different requirements and test cases with the functions and UCs when applying the microgrid concept in different applications.

5.2 Simulation and testing

(Upadhyayula et al., 2018) present the innovative technologies facing two valleys of death during their development from the basic principles observed (TRL 1) to the actual system proven in the operational environment (TRL 9) as presented in Figure 23. The first is the technology valley of death in TRL 5–6, which falls out when a validated concept does not yet show its potential for industrial mass production. Typically, innovations from TRL 1 through TRL 4 are granted, but moving to the TRL 5 stage is critical. After an innovation developed in academia enters the technology valley of death, poor commercialisation can be caused by the innovators failing to attract the attention of investors because of the lack of self-motivation, entrepreneurship culture, a structured framework for evaluating the developing technologies and overlooking the big picture. The second valley is the commercialisation valley of death during TRL 7, which can be caused by a lack of viability on a commercial scale for the piloted technology.

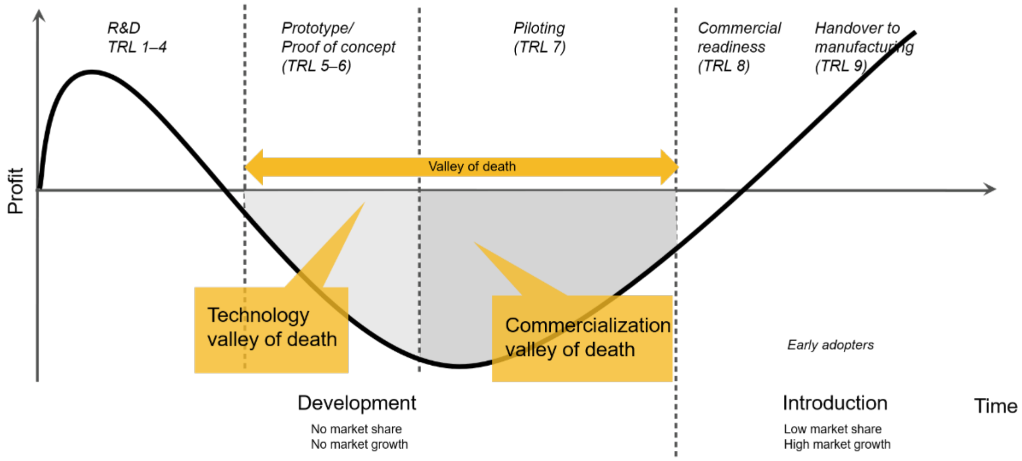


Figure 23. Technology and commercialisation valleys of death. Adapted from Upadhyayula et al. (2018).

This section focuses on the development of the evaluation methods, particularly by testing, of the emerging or improving technologies. The developed testing and evaluation procedures and the enhanced testing facilities are critical in aiding the successful progress in new technology development and convincing investors. Figure 24 presents the outline of the positioning for the different electrical engineering testing methods, according to testing method coverage and fidelity (Salcedo et al., 2019). The methods are traditional offline simulation, real-time simulation (SIL, CHIL, and power hardware-in-the-loop, PHIL), subscale system, power testbed and real power system. With the traditional offline simulations, coverage is easily well obtained, but fidelity or accuracy is poor. The fidelity is high with the real equipment/full system, but the tests only cover the particular case or system.

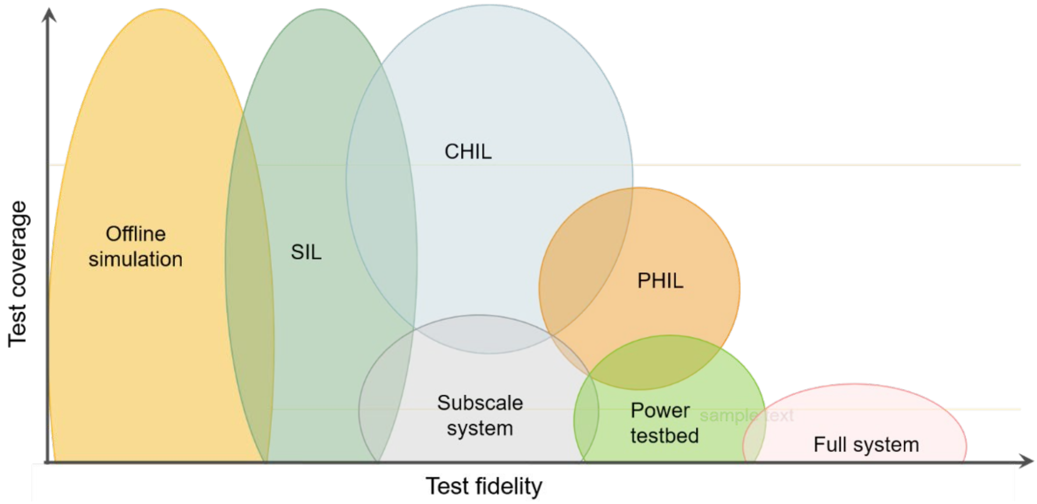


Figure 24. The coverage and fidelity of different testing methods.

The testing and validating environment for Smart Grid solutions, a near real-world development, stand as a critical requirement (GridWise Alliance, 2014) and attracts industry stakeholders (K. Sirviö, Kauhaniemi, Laaksonen, et al., 2020). At present, a great leap forward occurs with real-time simulation. Ibarra et al. (2017) present an overview of real-time simulation technologies, needs, and trends and a review of the applications in electric systems and used topologies and hardware. Also, an overview is introduced of the evolution of real-time simulators.

Figure 25 presents the utilisation of the different simulation methods along with the RDI projects. Traditional offline simulations are used for developing and testing a concept based on an initial idea. Next, real-time simulations are utilised for moving closer to practice, where SIL is the first stage for implementing and testing a developed control algorithm with real communications. The power system and the control algorithms are simulated in real-time, and the communication media and protocol are implemented. In CHIL simulations, the power system is simulated, and the control algorithm and the communications are implemented in real control equipment. The PHIL simulation setup implements interactions with real power devices and the simulated system through power amplifiers.

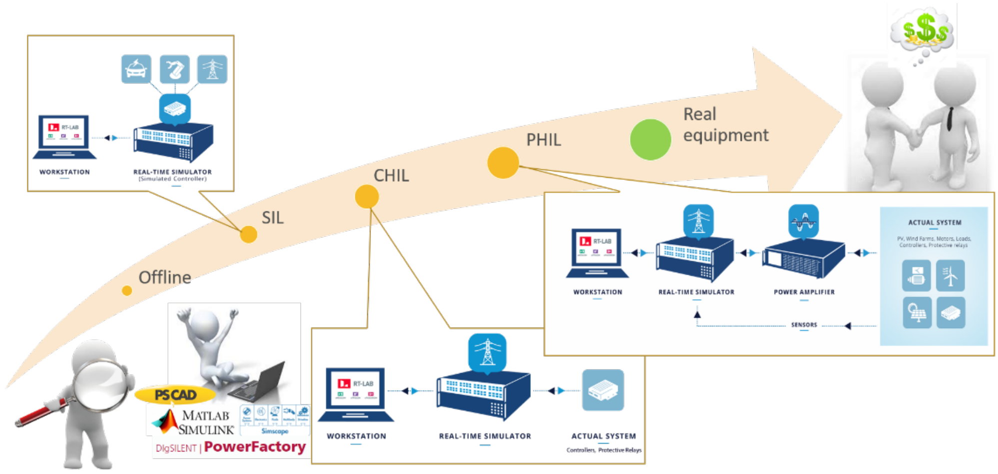


Figure 25. Simulation methods in research, development, and innovation. (K. Sirviö, Kauhaniemi, Laaksonen, et al., 2020)

Further, the power system simulation models can be divided into static and dynamic models. Static models are phasor or sequence models, including power flow modelling, fault level studies, and harmonic analysis. Dynamic models can be the root mean square (RMS) type, and they are common models for network planning and operations. EMT dynamic models are suitable for more detailed studies. They include information on the power system's individual phase voltages and currents in the time domain. The EMT models are favourable, for example, in inverter-based dynamics and controller interactions. For the Smart Grids, the increasing amount of DER and load modelling cause challenges in the ADNP. It is insufficient to have detailed information only on large-scale generation with the EMT simulations; enhanced knowledge is needed about the DER response in the power system. Therefore the RMS models of DERs need to be improved. (Badrzadeh et al., 2020)

Figure 26 presents the simulation types and the time scales of the various power system dynamics phenomena and controls (Bélanger et al., 2010; Milano, 2010; Sauer, 2011; Publication VIII). The division into dynamic and static models is not always unambiguous, therefore they are presented at the extremes and partly blending at the middle. The research in this thesis focused on power system transient stability, electromechanical transients on DER control and utilized the hybrid dynamic simulation (Badrzadeh et al., 2020) method, co-simulation of RMS and EMT.

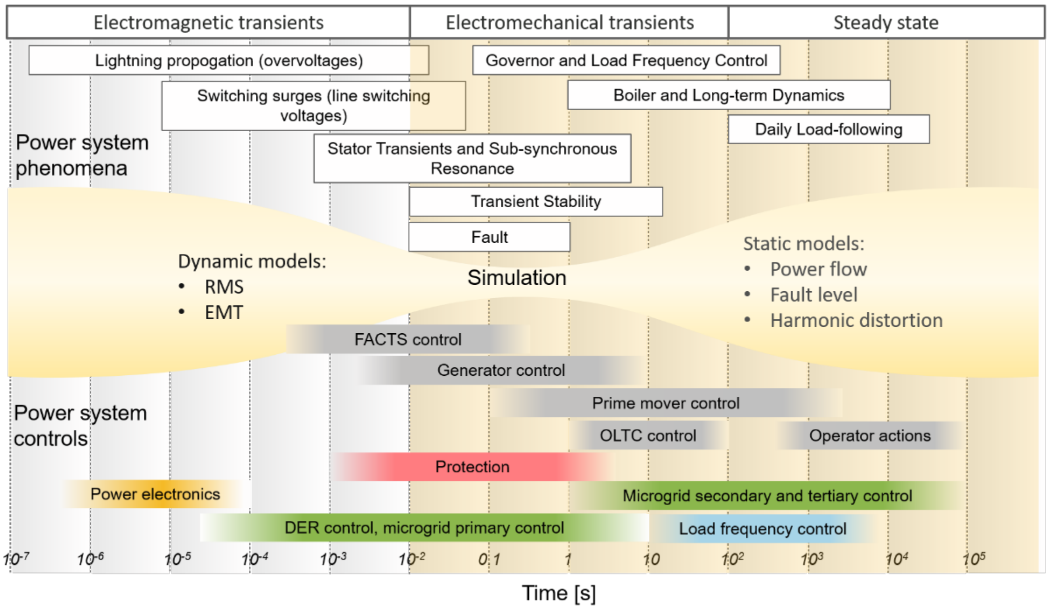


Figure 26. Simulation types and time scales of the power system dynamics and controls.

Naturally, the general power system and communications simulation tools (Badrzadeh et al., 2020) can be used for microgrid studies. In addition, particular microgrid simulation tools are commercially available as introduced in Mathur et al. (2017) to support the design and operation of the microgrids, aiding the decision-making of investments, investigating the microgrid's internal phenomena, and their reaction to the utility network and gain operational experiences in a virtual environment. Simulation over several microgrids (multi-microgrids) and distribution networks should be developed to support the RESs analysis into power system control.

Aiding microgrids and ADN concepts deployment, simulation tools for scenario building, analysing and designing them are developed mainly from the techno-economic perspective (Aalborg University, 2021; Homer Energy, 2021; XENDEE, 2021). However, institutional and geographical conditions can be included. In addition, Badrzadeh et al. (2020) presents a microgrid analysis platform as a methodology for developing business cases for microgrids. Stadler & Naslé (2019) presents a method and a tool for microgrid planning to create profitable microgrids to decrease the microgrid development cost. For successful microgrid planning, deployment, implementation, and operation, the authors describe the following high-level steps: 1) conceptual design, 2) technical design, 3) implementation and 4) operation and maintenance. A variety of tools are utilised in each step. The authors claim that the optimum would be one ultimate microgrid software that should combine single tools in one platform.

The emerging trends in developing power system simulation tools are high-performance computing, artificial intelligence (AI), and probabilistic modelling (Badrzadeh et al., 2020). In addition, the co-simulation method combines different models into the system-wide simulation, where the synchronization and interaction of different simulation time steps between the sub-simulators are managed. Close to practical implementation is PHIL setup, which can be extended by co-simulation as demonstrated in Syed et al. (2015) for ASs case studies. In the limelight is also the remote HIL (RHIL) systems development to connect different CHIL and PHIL laboratories, as for example a CHIL in microgrid controller testing (Prabakar et al., 2020).

5.3 The development procedure of a controller for the active distribution network management scheme

This section presents the development of a reactive power controller for DER providing local AS by constraining the reactive power flow between the TN and DN.

Publications V and VI present the development of a reactive power controller from a preliminary algorithm (presented in Publications III and IV) to a lightweight IED by utilising the Sundom Smart Grid network model and the measured data. The indications for improving the controller, the test setup, the real-time simulation, and the testing platform are discussed in the publications. The CHIL main development stages were:

1) the control algorithm and distribution network model development by the Simscape Power Systems offline simulation tool in the phasor mode,
2) adaptation of the distribution network model in the real-time ePHASORSIM solver,
3) adaptation of the control algorithm in the real-time eMEGASIM platform as SIL,
4) testing the SIL controller in the real-time OPAL-RT's co-simulation platform (ePHASORSIM + eMEGASIM),
5) implementation of the control algorithm to a microcontroller device, and
6) CHIL implementation tests.

Figure 27 presents the used real-time co-simulation system setup.

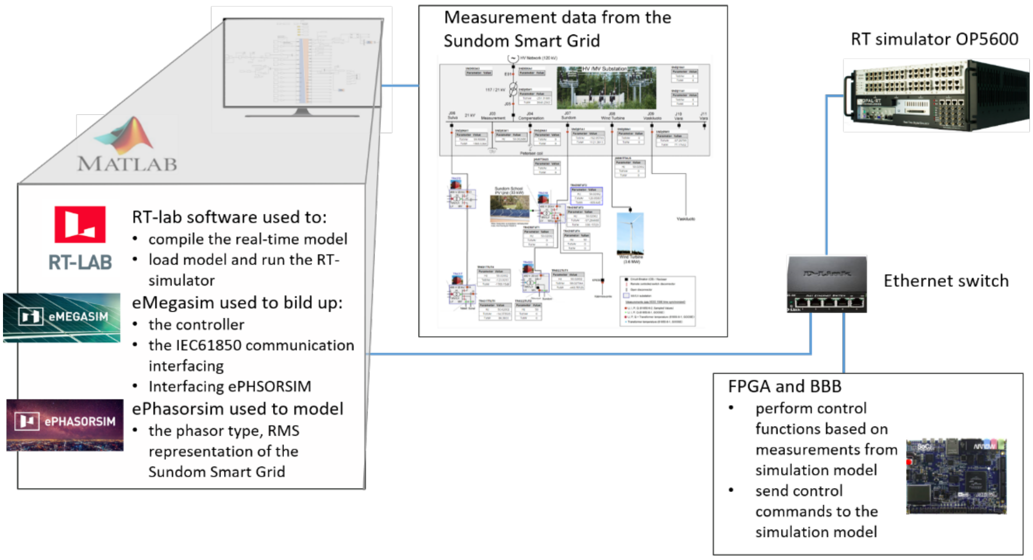


Figure 27. The outline of the real-time simulation platform. Adapted from (K. Sirviö, Mekkanen, et al., 2018).

Publication V presents various distribution network development scenarios of the Sundom Smart Grid to resolve the challenges because of the increased amount of reactive power injection from the DN to TN because of the network's cabling increases in the future. Whole year measurement data was utilised, and real-time simulation models of the network development scenarios were developed in eMEGASIM and ePHASORSIM. The paper suggests that the real-time simulation setup could be developed further. For long-term tests and simulation studies, a suitable coefficient for data reading cycle T_d could be defined to accelerate the simulation time reliable enough for one-year study cases, for example. Also, the controller could be improved, making it more intelligent, for instance, predictive. Offline and SIL test results comparison indicated the communication delay effects to the control. The SIL and CHIL test results comparison indicated the processing time of the hardware affecting the results.

Publication VI presents the performance of a reactive power control scheme on a lightweight IED. The development of the control solution and communication system based on open-source IEC 61850 and implemented on two hardware platforms, FPGA and BBB, for CHIL tests, is presented. The performance of the BBB and FPGA was evaluated through CHIL versus SIL test in terms of communication latency, processing time, and control action. The FPGA performed better than the BBB, and therefore, it could be more suitable, for example, for a microgrid (secondary level) controller.

Publication VII presents an accelerated real-time co-simulation method and testing platform for long-term simulations of power systems. Long-term simulations are needed to study, for instance, the potential weekly, monthly, or yearly usage of DERs providing different ASs. Therefore, real-time simulations or HIL tests should be accelerated for testing new algorithms in long-term case studies. Developing this kind of platform aims to aid the development and testing of the ADNM functions. The accelerated long-term simulations are developed and analysed with the Sundom Smart Grid study case. The reactive power controller and the power system model developed in Publications V and VI were utilised.

Publication VII suggests a procedure with the system presented in Figure 28. The ePHASORSIM solver emulates the power system with its simulation time step ts = 0.01. The reactive power window (RPW) controller presents the developed controller with its functioning time step T_c. T_d presents the data reading cycle for the loads and generation. The paper presents how to accelerate the long-term simulations by manipulating the input data reading cycle T_d. The behaviour of the reactive power controller in long-term simulations was studied by the offline simulations and the SIL and CHIL real-time tests by the following procedure.

> Step 1: The offline and real-time SIL simulations were executed for discovering the relevant time factors (including T_d) so that the offline and real-time results are equal.
>
> Step 2: When the accelerated SIL real-time results are closest possible to the offline results with only an effect of the communication time delay (T_d setting found), all relevant time factors for the real-time SIL simulations can be concluded.
>
> Step 3: Discovering and defining the T_d value, where SIL and CHIL real-time test results do not differ.

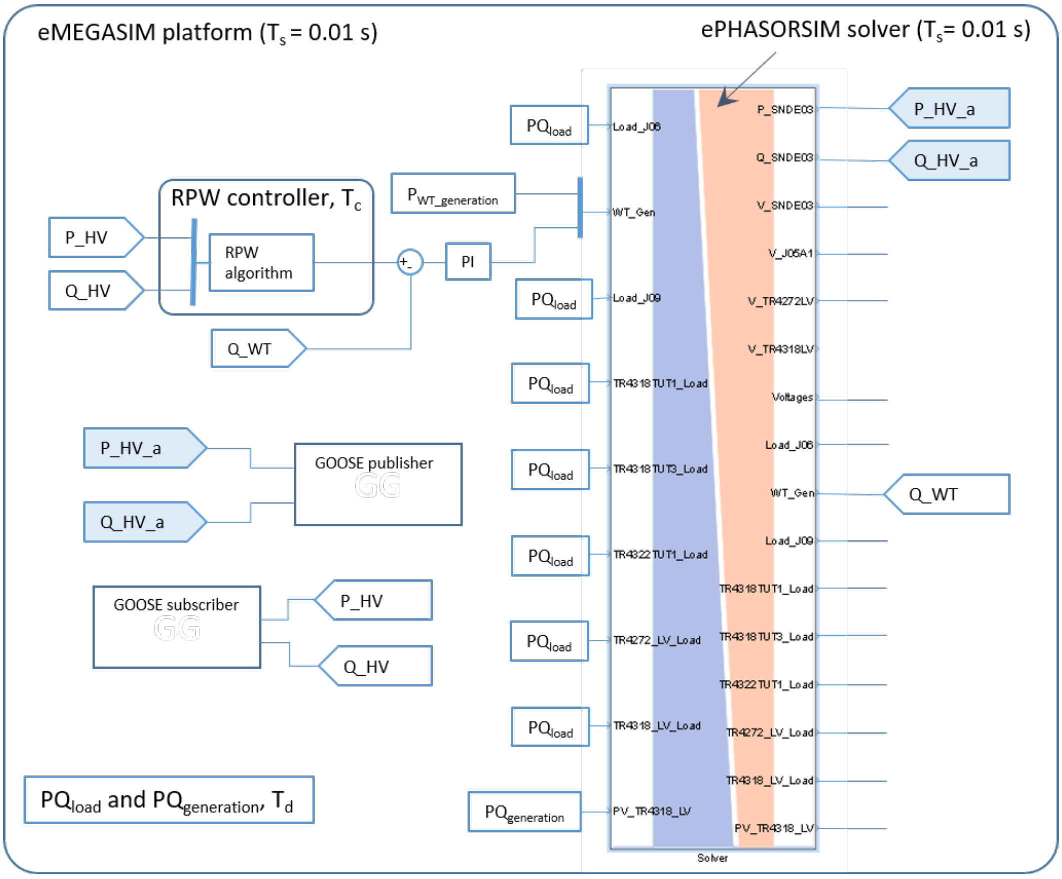


Figure 28. The emulated system and the controller (Publication VII).

The effects of the processed input data in the long-term simulations or tests affecting the results were demonstrated. In conclusion, it was shown that it is possible to find a data-reading cycle, coefficient T_d, to accelerate the long-term SIL and CHIL simulations/tests. The accelerated real-time co-simulation platform proved to be effective in one-year power flow control simulations. When T_d is equal or greater than a particular value, the simulation results do not differ. This defines the minimum data-reading cycle. The total real-time simulation time length is defined through the data-reading cycle. Further, based on the T_d result, a suitable PI controller can be derived for accelerated real-time tests preventing oscillations in the system with closed-loop control.

By considering the status of microgrid standardisation, standardised tests for microgrid control are needed (Joos et al., 2017). Though, the IEEE standard 2030.8 for testing microgrid controllers has been launched (IEEE, 2018b). Accelerated CHIL test methods are useful in testing the AS provision of microgrids since IEEE standard 2030.8 "does not address issues related to the power exchanges between the microgrid and the distribution network at the POI". The method developed in Publication VII can be utilised to define the test procedure for AS control development in microgrids. However, more detailed stability and technical analyses of the proposed approach is needed.

5.4 Development procedure utilising living laboratories

Piloting or field tests are crucial in Smart Grid deployment to test innovations in a real-life context with potential end-users. A living lab methodology based on co-creation focuses on the active and collaborative development of an artefact (product, interface, service, IoT solution) for the stakeholders, including users. Technical, societal, and economic challenges and benefits can be evaluated through a real-life environment. This thesis defines living labs following the definitions in Evans, P., Schuurman, D., Stahlbrost, A. and Vervoort (2017):

> **A living lab** is a multi-stakeholder organisation established to develop a co-creation platform for developing innovations that adhere to the open and user innovations and leverage real-life experiments with the stakeholders' benefit objectives.

In this context, living labs are the key platforms, the potential niches entering the regime level. Piloting in living labs gives real-life feedback and validates a developed concept or product before mass production, business applications, and sales. The stakeholders' co-creation within living labs has a socio-technical participatory aspect. For example, the field tests in a living lab encourage users to propose improvements for the technology being tested compared to a traditional field test, which aims to gather user feedback (Spohrer & Freund, 2012). The field tests can differ according to the phases of the living lab process, but generally, a field test can be defined (Coorevits et al., 2018):

> "**A field test** is a user study in which the interactions of test users with an innovation in the context of use are tested and evaluated."

The living lab process phases can be defined as 1) co-creation, 2) exploration, 3) experimentation phase, and 4) evaluation (Vicini et al., 2012). These process phases can be extended, producing eight working steps (Steen & van Bueren, 2017). The exploration phase can be described by implementing a concept to a solution. The experimentation phase can be described from concept to prototype putting the designed solution to the test in a real-life context to the greatest extent possible. The users face the solution for the first time. The evaluation phase is characterised by mature innovations focusing on market entry aspects. (Coorevits et al., 2018)

The development of a product needs research platforms and testbeds in its RDI phases; in product design, engineering, and prototyping. The real-life experiments and testing are traditionally at the end of the development process when the innovation has already reached a certain maturity level. The product features and settings are already close to actual usage. Interactions between the system, the user, and the environment can be diverse. If the scope needs to be changed, it can lead to high development costs or even a technological valley of death. Therefore, the real-life dynamics could be replicated in the early phases of the living lab project by simulations (usability lab, technology) or technology development. (Coorevits et al., 2018)

Hence, testing goes through the exploration, experimentation, and evaluation phases. The exploration phase can include trials in the laboratory. The experimentation phase can benefit from the SNM approach in the implementation of the innovation and its testing. The evaluation phase includes the final tests and customer validation, targeting for launching the solution.

Organising field tests in the early stages of innovation is challenging (Marez & Verleye, 2004). The degree of realism (physical location, test users, tasks, participants motivations) describes the test proximity to the actual use and context relevant to the assessment and aspects of use that are important enough to be present in the assessed configuration or evaluated setup (Coorevits & Jacobs, 2017). The components influencing the interactions with a system, should be considered in the simulation set-up development are 1) temporal, 2) physical, 3) technical/information, 4) social, and 5) task contexts (Coorevits et al., 2018).

HIL platforms combined with the models of living lab dynamics (such as co-simulation) can offer a means for early-stage learning in SNM. Integrating the actions of users in the power systems' technical simulations is essential for future scenario development and testing. This approach presents the socio-technical dynamics. For this reason, Publication II introduces a framework and a method to model the evolution of customers within the socio-technical dynamics of the electricity distribution networks.

The evaluation of appropriate simulations and testing methods, by accuracy and fidelity (Figure 24, p. 56), is essential when developing a living lab environment. Real-time simulation is of interest in technology development, but the HIL methods must be better known to various stakeholders, the potential collaborative partners in living labs (K. Sirviö, Kauhaniemi, Laaksonen, et al., 2020). As HIL technologies accelerate RDI, they enable new ideas to get faster in the piloting stage. Additionally, the measurements coming from living laboratories combine with the real-time simulations to provide safe product development testing in the laboratory in various scenarios flexibly.

Figure 29 presents an outline for using HIL methods together with a living laboratory. The development of Digital twins is essential for evaluating the power system and control models. This research utilised one-year measurement data from the Sundom Smart Grid to evaluate the power system modelled.

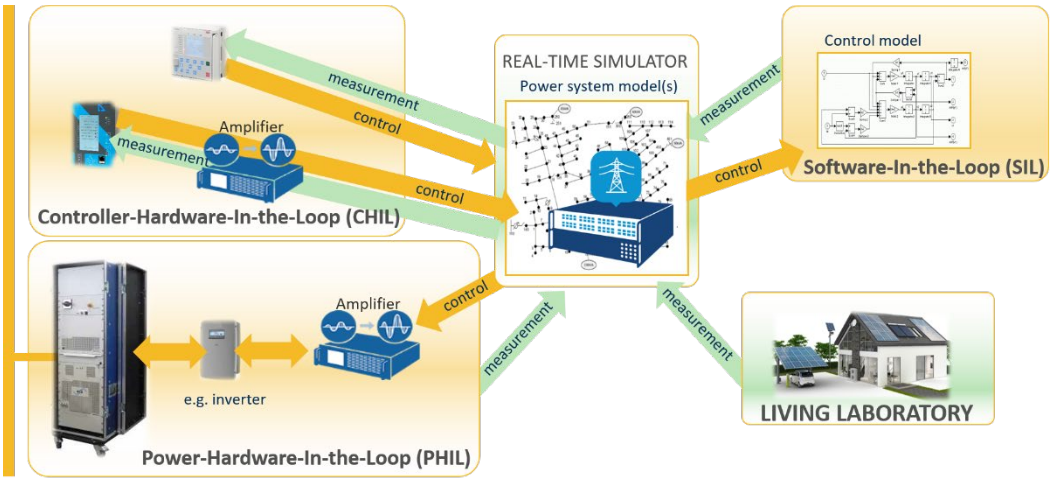


Figure 29. Real-time development and testing methods utilising living laboratories. Adapted from (K. Sirviö, Kauhaniemi, Laaksonen, et al., 2020).

In addition, Coorevits et al. (2018**)** define four types of field tests in living labs, characterised by their phase and degree of realism: concept (for example, proxy tests), mock-up (a scale or a full-size model of a design or a device), pilot, and go to markets to guide setting up field tests in the living lab process stages. The early-stage field tests are small-scale and closed. They need a higher degree of guidance, and they are qualitative. The later-stage field tests are large-scale and open, with limited to no guidance, and they are primarily quantitative.

Figure 30 presents the key elements of piloting within a living lab framework. Naturally, legislation and other regulations constantly influence the background in piloting and living labs. The figure intends to show the development stages (1-4), and basically, the actions by authorities and governments affect in all stages. The key elements are users, devices, intelligent networks, network operations, business applications, and exports, briefly introduced in the following description.

Besides considering the interactions between the users and devices, and their testing, intelligent networks must be assessed when planning a pilot in a living lab environment. The challenges of intelligent networks are grid modernisation (AI, Internet of Things, IoT), open architecture solutions, computing power increase, appropriate balance between security and investments. IoT development in the energy application domain is essential and identified (Brynskov et al., 2019) in security/cybersecurity, privacy, safety, and interoperability.

Network operations are the value creation procedures for the stakeholders with the appropriate methods. The Smart Grid operations include methods for the reliable, flexible, and efficient power flow and enable operations in the markets, with the ADNM scheme solutions (Figure 18, p. 43). By understanding the operations maturity, the windows of opportunity can be easier to notice. The maturity levels of the operations are described in Hui (2014) as reactive, informed, managed, automated, and predictive, defining the utility's ability and capacity to manage the data influx. Business applications can be solutions for ASs, DER, home area networks (HAN), advanced metering infrastructure (AMI), advanced utility control and management systems, smart EVs charging infrastructure. The exports of the Smart Grids technologies relate to the know-how, devices, and solutions.

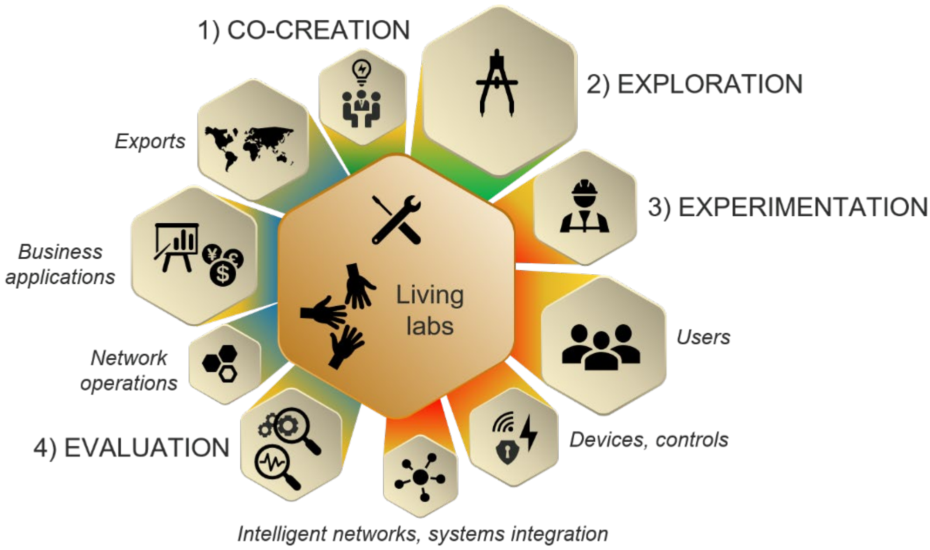


Figure 30. Key elements of piloting in living labs.

6 EVOLUTION OF THE ELECTRICITY DISTRIBUTION NETWORKS

This section focuses on the fifth and last research question: How the flexibility-utilisation-based network management evolves?

The operation of future ADNs and microgrids is complex because it involves several stakeholders and actors. Consequently, the control of a large number of different active and intelligent resources and devices can be challenging. The development of building blocks for Smart grids, the evolution of the distribution network infrastructure, and operation affect the distribution network management and control development.

A potential evolution path, a roadmap towards the ADN vision, is the basis for comprehending ADNM evolution. Chapter 3 considered the visions of energy and power systems, the evolution phases' definitions for the LV distribution networks, and the need to create joint roadmaps with stakeholders for developing the ADN roadmap. Chapter 4 discussed what ADNM essentially consists of and presented a flexibility case study of developing an ADNM scheme and a controller for the local ASs utilisation. Chapter 5 discussed the importance of developing standardised solutions, simulation and testing methods and environments for sustainably accelerating RDI. This chapter utilises these topics to form a holistic perception (operation and structure) of the electricity distribution networks' evolution and management and produce an outline of a sociotechnical roadmap.

First, energy transition in electricity distribution networks is discussed. After that, the socio-technical enablers and the challenges are discussed briefly in the electricity distribution network development. The issues of the developing microgrid management by an ADNM case study are presented. Next, the operations and structures of the evolving electricity distribution networks are presented of energy, power balance and protection management. Finally, an outline for a sociotechnical roadmap for the electricity distribution networks is created.

6.1 Energy transition in electricity distribution networks

The MLP framework in the energy and power system transition is increasingly becoming common. The concern of utilising the high-level energy system visions and the MLP framework to the electricity distribution level and practice reflects the importance of understanding large-scale socio-technical transitions through local conditions (Groves et al., 2021; Smith et al., 2010). Demonstration projects such as living laboratories should also be designed based on broad needs, values, history, and location. Energy system actors can rely on local or system-level visions (Groves et al., 2021).

Adapting the high-level international and national energy system visions and transition theories closer to practice can be viewed through electricity distribution networks. Understanding the development of the critical building blocks of future electricity distribution networks and the MLP's landscape, regime, and niche dynamics is the basis for the local-level scenario building. Local-level scenarios must be shaped in the societal, technical, and economic context too. Geels (2020) discusses MLP's micro-foundations and local models concerning actors that are under-developed.

The MLP framework is utilised for understanding and modelling the niches breakthrough to the power system regime in local energy systems (Ford et al., 2021), affected by the landscape level. For example, the microgrids' development is pressured by climate change and massive power outage concerns at the landscape level. The ongoing changes in other drivers like policies, processes, institutions, and interactions affect microgrids' development. Yu et al. (2018) highlight the microgrid development arguments and drivers, including policies and research investments, activities of system operators, various other stakeholders, and incentives. Ajaz & Bernell (2021) show that the adoption occurs through niches entering the regime level, where local boundary conditions, such as market structure development, can promote or hinder the niches break-in. In addition, the MLP framework has been utilised in energy storage technologies (Frey et al., 2020) and solar prosumers (Moser et al., 2021) as examples in Germany's energy transition and blockchain in Sweden's energy transition (Viktor & Nilsson, 2020)

Creating a holistic roadmap based on the MLP describes the electricity distribution development in a sociotechnical and practical manner. It is essential to understand that central to technologies and applications development are the requirements in the advanced architecture and functionality of various ADNM systems, like MMS, and the distribution management system (DMS), which aids the driving of the distribution grid and the optimisation of its assets (Fan & Borlase, 2009).

6.2 Aspects of the electricity distribution network development

The technical, economic, and social dynamics, the enablers and barriers, the opportunities and challenges, and the boundary conditions need to be identified for sustainable electricity distribution network development. These aspects give their characteristics for future network scenario building, road mapping, design, and network management. Technology is central in developing electricity distribution networks, along with the social and economic aspects. Because this thesis focuses on the socio-technical aspects of electricity distribution network evolution, the economic aspects are neglected in this section.

The fundamental socio-technical enablers in electricity distribution networks can be seen as (i) active customers and prosumers, (ii) DER integration and utilisation concepts and microgrid concept, design, and implementation in different applications, and (iii) DSOs roles.

i. Espe et al. (2018) review the prosumer communities. They point out several research gaps, which include prosumers' 1) objectives and motivations, 2) a deeper understanding of the prosumer roles in achieving sustainable prosumer community groups (PCGs), 3) the organising of PCGs, 4) the prosumer market design, 5) prosumer management, 6) provider-consumer relationships, 7) consumer engagement, and 8) social, economic, and technological aspects.

ii. This thesis focuses on DER utilisation through the ASs and the microgrid concept reviewed in Chapter 4.

iii. The DNOs' transformation to DSOs is an enabler of change (Western Power Distribution, 2020). The DNOs face challenges, including regulatory and organisational barriers, in addition to technical issues in integrating DERs into their networks (Johansson et al., 2020). A more detailed analysis of the DNO-DSO evolution is needed for the roadmap creation. DNO evolution towards DSO is discussed in Accenture Strategy (2016), Davarzani et al. (2021), Jenkins et al. (2015), and Western Power Distribution (2020). The evolving DSO roles are not the focus of this thesis, but they are partially initiated through the UC stories and the actor classifications in Publication IX, where other key actors of the evolving electricity distribution networks are classified also.

Social enablers and challenges are the dynamics to notice within stakeholders. Social acceptance in the market, socio-political, and community dimensions is critical in the transition pathways (Bolwig et al., 2020). Xiao Lin & Sovacool (2020) present the socio-technical drivers, benefits and barriers of the electric vehicle transition in Iceland through the MLP framework.

Challenges, which can be considered as research opportunities such as (i) ignoring risks (Osazuwa-Peters et al., 2021), (ii) complementarities and competition (Markard & Hoffmann, 2016), and (iii) a high trust in economic narratives that can cause underestimation of the technical obstacles (Renner & Giampietro, 2020). Further, Renner & Giampietro (2020) claim that the descriptive and prescriptive discussion of the energy transition in Europe seems to lack holistic (structural and functional) analyses.

F. Li et al. (2015) review the socio-technical energy transition (STET) models and claims that the quantitative energy models for possible futures tend to limit their scope to only the description of techno-economic factors. The political, social, and behavioural aspects are left exogenous. The STET models should include the following building blocks or domains: a) a techno-economic component with adequate detail, b) individual actors' conceptualisation and clustering of actors having the decision power, and c) transition pathway dynamics to evaluate the goals and compare different possible transition pathways. The authors recognised that compromises need to be made with the dimensions of domains and their overlapping areas. Most of the STET models were designed for a single sector, and specific national cases or they limited their innovations' consideration to revolutionary technologies rather than behavioural and lifestyle shifts.

Socio-technical scenarios (STSs) can be used as methodological tools to explore social and political feasibility (Geels et al., 2020). The authors propose "transition bottlenecks" as a methodological aid to communicate between the qualitative MLP-based dynamics analysis and the quantitative future pathways models. The methodological procedure is the following, and similarities can be found with this thesis research:

1. choosing of systems and countries (in sections 3.2 – 3.4),
2. baseline scenario development (in Section 3.5 and Chapter 4),
3. the conceptualisation of socio-technical understanding of transition pathways by combining aspects from transition pathway typologies (technologies in markets and social groups) (not included in this thesis),
4. pathways implementation into the models (not included in this thesis),
5. qualitative MLP-based analysis of the main innovations in the model-based scenarios (in Section 6.4),
6. the quantitative future scenarios (step 4) confrontation with the qualitative assessments of contemporary developments (step 5) (in Section 6.3),

7. qualitative socio-technical scenarios development aimed at articulating plausible actor-based storylines for the produced quantitative pathways (step 4) (in Section 6.4), and
8. policy implications discussions from the STSs and the model-based scenarios (not included in this thesis).

This thesis, in a way, follows this "transition bottleneck" methodological procedure by trying to indicate and define the opportunities, enablers and challenges in the energy transition in electricity distribution networks, especially in the distribution network and its management development.

6.3 Operation of the future electricity distribution networks

The operation and control of the ADNs and the microgrids is a complex task involving several stakeholders and actors. The stakeholders are considered system actors (or are affected by the operation of the system) having expectations, such as economic or social benefits. Further, actors can be personal roles and systems, devices, software, and events, which perform operations that change the system's state, for example.

Various scenarios should be modelled and analysed based on the electricity distribution evolution and the network's operational targets. The UC analysis helps to identify and analyse the network operations and functions and visualise the interactions between the network actors.

Publication VIII presents a comprehensive UC analysis for the microgrid concept. The UC modelling and analysis method and a tool (Enterprise Architect) were utilised for microgrid management analysis top-down, from an abstract/concept level closer to practice. First, the general microgrid functions were presented as HL-UCs defining the microgrid functions, regardless of the practical solution. Further down, PUCs were developed for the Sundom Smart Grid, and finally, TUCs of DR and overcurrent (OC) protection of the Sundom case study with real-time simulation. Regarding the different UC levels, the relationship between the concept and the functionality was emphasised with a microgrid management analysis case study. Figure 31 presents the UC analysis' method application.

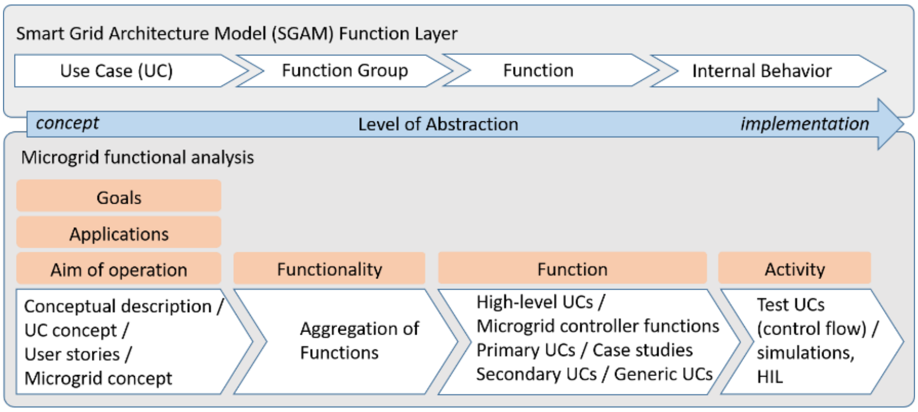


Figure 31. Functional analysis method for the microgrid concept. Adapted from (Publication VIII).

The TUCs were applied to the Sundom Smart Grid with measured data, including the previously developed a reactive power flow controller for the WT converter and the schematically developed DR controller for the household loads. These AS UCs were tested in the SIL co-simulation setup in the phasor and EMT platform with one-year measurement data. Also, protection case studies were analysed based on the CHIL test with the EMT platform.

The management system for the ADNs and microgrids is formed from different subsystems, that is, “a system of systems”, taking care of the operational targets. To recognise, analyse and realise the different levels of functions that can affect each other, a methodology for expressing the system's functions like those presented in Publication VIII is needed. For example, a case study can be developed to analyse residential customers who own the inverter-connected generation and controllable loads aiming to participate in different ASs. As demonstrated (TUCs) in Publication VIII, the customer’s ASs provision options can be both system-wide and local – DR programmes for the TSO and reactive power management for the DSO, controlled simultaneously by different stakeholders.

The potential entities can be detected by utilising this kind of functional analysis to develop or improve the concrete ADNM solutions. For applying the microgrid concept to the real case management system, the publication suggests that HL-UCs and PUCs should be specified, considering only the specific application requirements. TUCs for real-time simulations and testing is appropriate to prepare models, simulations and testing plans. Multi-objective control of microgrids puts pressure to develop management system test cases in a central, distributed, comprehensive, and dedicated manner, as shown in Publication VIII. In the future, different configurations regarding the depth of UCs needed, and a time-domain analysis should be used to examine various microgrid functions running in parallel.

This thesis defines the following terms for the ADNM, based on Publication VIII and Figure 18:

> A **technical concept** is an innovation described, planned or implemented. An ADN concept can be a microgrid or a VPP, for example. An ADNM high-level concept can be microgrid management or DR programmes.
>
> **Application** is a concept's real-life utilisation.
>
> **Operation** is the method by which a device or system performs its function. **ADN operation** refers to a concept(s) of multiple systems working together to achieve the operational target, which can be set economic, technical, or environmental. A high-level technical target can be improving power quality and power supply reliability, economic target to minimise operational cost, and environmental target to reduce carbon footprint. Power quality assurance and improvement refer to the functionalities to manage voltage amplitude and frequency. Power supply reliability refers to the functionalities to manage the failures in the power system, by asset and protection management, for example.
>
> **Functionality** is a set of functions implemented through the control and management systems. An ADNM functionality can be voltage regulation or active and reactive power control.
>
> **A function** is a multi-level term, which describes what an element does or for what it is used
>
> **A method** means a process by which a task is completed, whereas a procedure means a particular method for performing a task.

Publication IX presents a method for analysing the evolution of the distribution networks holistically. The analysis utilises the UML, and it consists of the dynamic descriptions of network operations and the static illustrations of the actors and their relationships. The dynamic descriptions are the systems' behavioural descriptions, the operational scenarios by UC stories and modelling. The static relationships among classified actors illustrate the network structure, the communications between the actors operating the system described by the class diagrams. A class diagram is the system's backbone and points out attributes (values), operations (the processes, which a class executes) of a particular class, generalisations, and constraints connecting the classes.

Four distribution network evolution phases: Traditional, Self-sufficient, Microgrid and Intelligent Microgrid Network were defined. Further, their operation and structure were modelled and analysed by a UML tool with the Sundom Smart Grid case study. The analysis is based on the network's normal state operation, which are energy management and power balance management and the network disturbance situations, which are OC fault situations. Publication IX presents the evolving network operations through the developed HL-UCs and PUCs by the UC descriptions and the evolving network structure through the classified actors and their associations with the class diagrams.

The generated method, graphical models of the ADNM schemes and the microgrid control functionalities in Publication IX can be applied for: a) scenario building in roadmap development, b) creating a common understanding of the distribution system operation, c) real-time simulations, d) management system development, and e) developing and analysing several parallel running control algorithms of distributed energy resources for ASs in the developing distribution networks, for example.

6.4 Roadmap creation for the electricity distribution network evolution

The ADN and ADNM development path towards the vision, the network's evolution through possible network scenarios can be presented as a roadmap. The question is how to produce joint and multidisciplinary roadmaps to various stakeholders' use to build confidence and trust in the scenarios. This thesis approaches this problem with holistic future distribution network scenarios and claims that for developing ADN scenarios:

- the possible futures have to be envisioned,
- the trends and drivers need to be recognised,
- the evolving actors have to be identified, and
- the ADN operations and functionalities, actors and their associations, need to be aligned and analysed.

UC modelling is a suitable method for multidisciplinary studies to describe and analyse the operation and structure of a system

Figure 32 collects the building blocks that are the key actors enabling the evolution of the electricity distribution network. It presents an outline of the building blocks for the creation of the socio-technical roadmap for the future electricity distribution networks based on Publications I – IX. The figure presents the evolution of the energy management from the Traditional phase to the Intelligent Microgrid Network phase. The figure presents energy management, power balance management and protection UCs from the Microgrid phase perspective.

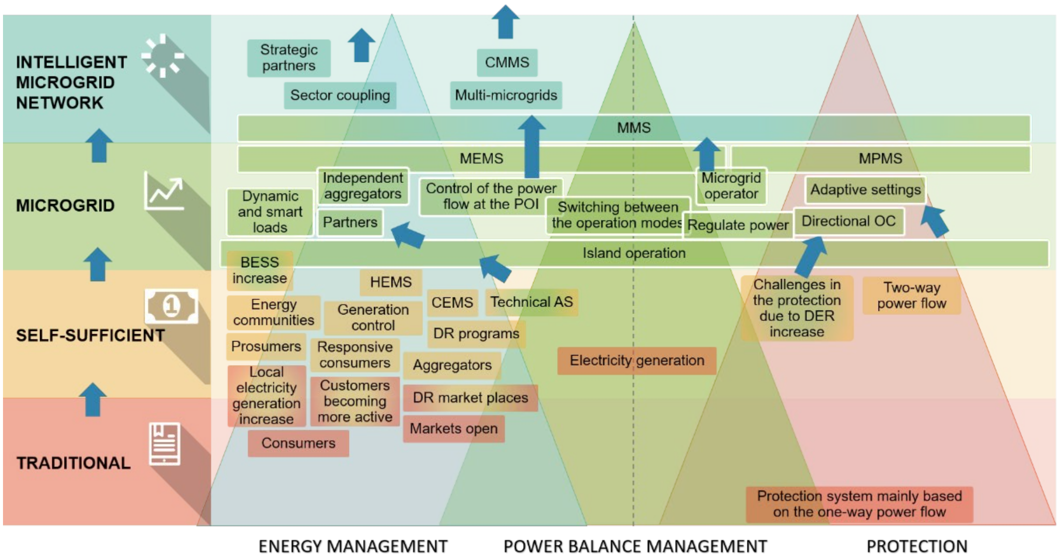


Figure 32. Outline of the building blocks for the socio-technical roadmap creation for the future electricity distribution networks.

Attempts to create roadmaps for the electricity distribution networks are starting to appear, and the following few examples are briefly summarised:

- Accenture Strategy (2016) presents a distribution network roadmap with utility actor definitions and business models define three strategic objectives: grid optimisation, regulatory and business model reform, and new customer model and services. This strategy roadmap can be found merely techno-economic and highlighting DER utilisation and piloting. Customer involvement is not present through living laboratories.
- The network transformation roadmap presented in Electricity Networks Association (2019b) gives the DSO boards and senior management guidelines to develop strategies and future plans. Programmes for the open network framework and the six constituent programmes are presented.
- Meeus (2020) analyses the past evolution of electricity markets in Europe and gives future directions and open questions.
- Johansson et al. (2020) recognise two distribution level pathways based on the survey of Swedish DSOs'. The challenge can be seen in DSOs preferring the DER assets under their direct control. The second pathway is described

by increased innovation and self-regulation at the microgrid level. It was found that DSOs prefer a business model where prosumers and microgrids are self-regulated according to the price signals instead of direct contracts.

- Laaksonen et al. (2021) describe a potential three-stage evolution path of the electricity distribution networks focusing on grids' flexibility by adaptive control and management methods and flexibility market schemes from a technological perspective. The power system readiness level (PSRL) is defined as consisting of (i) technology or solutions, (ii) customers, (iii) regulation, and (iv) market. This paper presents technical flexibility schemes evolution, a kind of a general level flexibility scheme's roadmap for the electricity distribution networks, which recognise regulatory and market aspects but lack socio-technical transition perspective.
- Campagna et al. (2020) present energy management concepts and recognises technical, technological, economic and social aspects for the evolution of Smart Grids, but no evolution phases or roadmap is presented.
- Davarzani et al., 2021 analyzed the piloting of DR schemes and community engagement. Consumer engagement and DSOs' understanding of customers' flexibility potential is essential in succeeding DR. Authors claim a need to model the comprehensive frameworks of participants' interaction in real-time environments, such as techno-economic DR control schemes.

The high-level roadmaps and storylines like Rogge et al. (2020) provide guidelines for local roadmap creation. The distribution side has to develop in line with power system technical challenges. The roadmaps presented by the high-level descriptions, the research purposes, and the utilizations of the dedicated stakeholders must be integrated socio-technically and economically.

However, creating a comprehensive roadmap for the technical, societal, and economic aspects of electricity distribution networks should start implementing the high-level visions locally. A prerequisite for anticipating and visioning tomorrow is a common understanding of today's facts. The facts and visions of the energy system transition were presented in Chapter 3. Chapter 4 presented the status of electricity distribution networks in system transition. Chapter 5 discussed and demonstrated a possible pathway for realizing the concepts for future Smart Grids. This section set a framework for developing a roadmap of the electricity distribution networks based on these chapters, considering megatrends and currently developed roadmaps.

This section and Publication IX leans on the idea from Hiltunen (2019) that anticipation of the future, scenario creation, is based on the facts summated by imagination. Further, the continuum for creating a scenario is making the future. The building blocks are: recognizing the facts of the present situation, a vision of a better future, a state of mind, and action. Megatrends should be separated from trends, and weak signals should be noted. A weak signal (Hiltunen, 2010) has low visibility meaning that nobody heard it before, or it can be a signal of a newly emerging issue. A sum of weak signals can be utilized to innovate. They can indicate possible development paths. Weak signals can be surprising. Therefore, they can break the "business-as-usual" thinking.

This thesis accepts ten megatrends from Hiltunen (2019), on which Figure 33 is based. The figure presents the occurring phenomena and outlines the trends and drivers within the megatrends from the environmental, social, regulatory, economic, and technological perspectives.

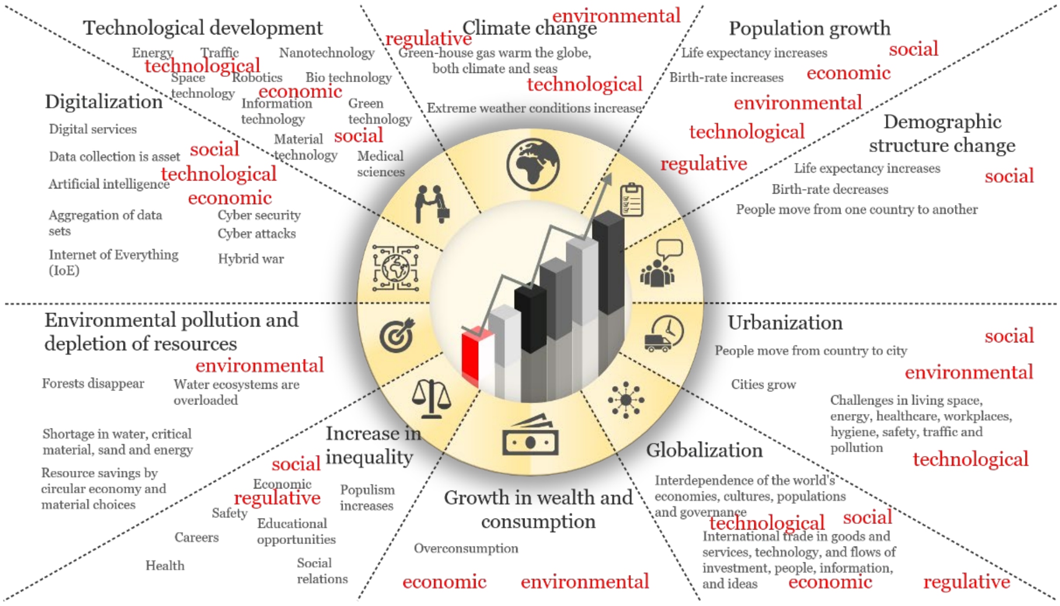


Figure 33. Megatrends.

This thesis respects these megatrends within a socio-technical approach to create the roadmap for the electricity distribution networks. Climate change is the primary megatrend in the energy transition. Technological development and digitalization are the enablers. Globalization standardizes the concepts and the solutions. The geographical location gives urbanization and demographic structural change special features. Behavioural aspects can be deduced from the perspective of population growth and age distribution, growth of wealth and consumption, and an increase in inequality. Environmental pollution and depletion of resources demand enhancements in the whole energy sector. More important than a single megatrend is understanding the larger whole to which it relates and how it links to other trends. The Finnish debate on future trends is well established through Sitra's megatrends (Dufva, 2020).

6.5 Method and a tool outline for co-creative road mapping

Models of network evolution and the roadmaps are needed to describe the energy system transition. Hirt et al. (2020) reviewed the linking models and socio-technical transition theories for energy and climate solutions in the co-evolution of society, technology, the economy, and the environment. The literature analysis identified that realism needs to be improved in models and theories. Integrative research should be redirected to provide more practical outcomes. Geels et al. (2016) suggest that interlinking the approaches of quantitative systems modelling, socio-technical analysis and initiative-based learning is an important strategy to guide future transitions. The 'bridging strategies' and dialogue between analytic approaches are productive in multidisciplinary transition studies, and the emergence of a modelling community within the transitions field is welcomed (McDowall & Geels, 2017).

Local-level models, as Nilsson et al. (2020) present, can combine an energy systems model with socio-technical systems analysis and a local action study by analysing the transition in residential heating systems in Sweden until 2050. The identified niche innovations are implemented as scenario options in the model. The local action study focuses on the community attitudes affecting the niches and regime level. The authors claim that linking these three approaches provides enriched insights into future energy system change.

The modelling of the energy system transition and how its building blocks interlink seems to be a comprehensive task in multidisciplinary systems modelling research. However, the issues are too complex to create a shared understanding of the transition path for the energy systems. To create a joint roadmap, for example, for the stakeholders' strategy development, a more simplified model is feasible.

Hofman et al. (2004) reviewed the forecasting, foresight, backcasting, technological road mapping and breakthrough scenario methods. The methods lack a co-evolutionary aspect, learning process, or actor interactions. Compared to other methods, the STSs, which is defined as a tool rather than a method, has two strong features: (i) they are based on a scientific theory on transitions and (ii) focus is on transition paths, roadmaps. A tool requires user skills to achieve the final outcome, whereas a method refers to a sequence of actions that automatically leads to an outcome. The main steps in scenario building are defined. This thesis follows these steps, but step 3 is ignored.

1) Vision identification
2) Empirical analysis of aspects and processes (trends, signals) affecting the vision
3) Trends and signals ranking by importance and uncertainty
4) Baseline scenario development and scoring of trends and signals most uncertain and having the primary effect
5) Scenarios development
6) Analysis

Technology road mapping (TRM) has been applied among diverse organizations to align an organization's strategic objectives with the technologies related to the products and businesses (de Alcantara & Martens, 2019). One cluster of the TRM approach utilisation is “Road-mapping”, in which the T-plan method (Phaal et al., 2003) is famous. T-plan is a method for creating technology roadmaps through workshops. The tentative roadmap in this thesis utilizes the T-plan methodology and framework. It extends it by transition and future scenario theories for developing a joint multidisciplinary roadmap for future electricity distribution networks. Figure 34 presents a roadmap outline for evolving electricity distribution networks to summarize the road map-related research in this thesis. The trends and drivers (environmental, social, regulative, economic, and technological), the solutions (concepts, pilots, and products), the process (SNM – learning via concepts) and the enablers (actors and infrastructure) are identified. For this roadmap outline, Publication VIII and IX were utilized (the future scenario building theories and different levels of storytelling with the UML tool). For creating an illustrative and easily customizable roadmap description, a roadmap template was created based on utilizing the T-plan method. In the template, only topics in this thesis are presented.

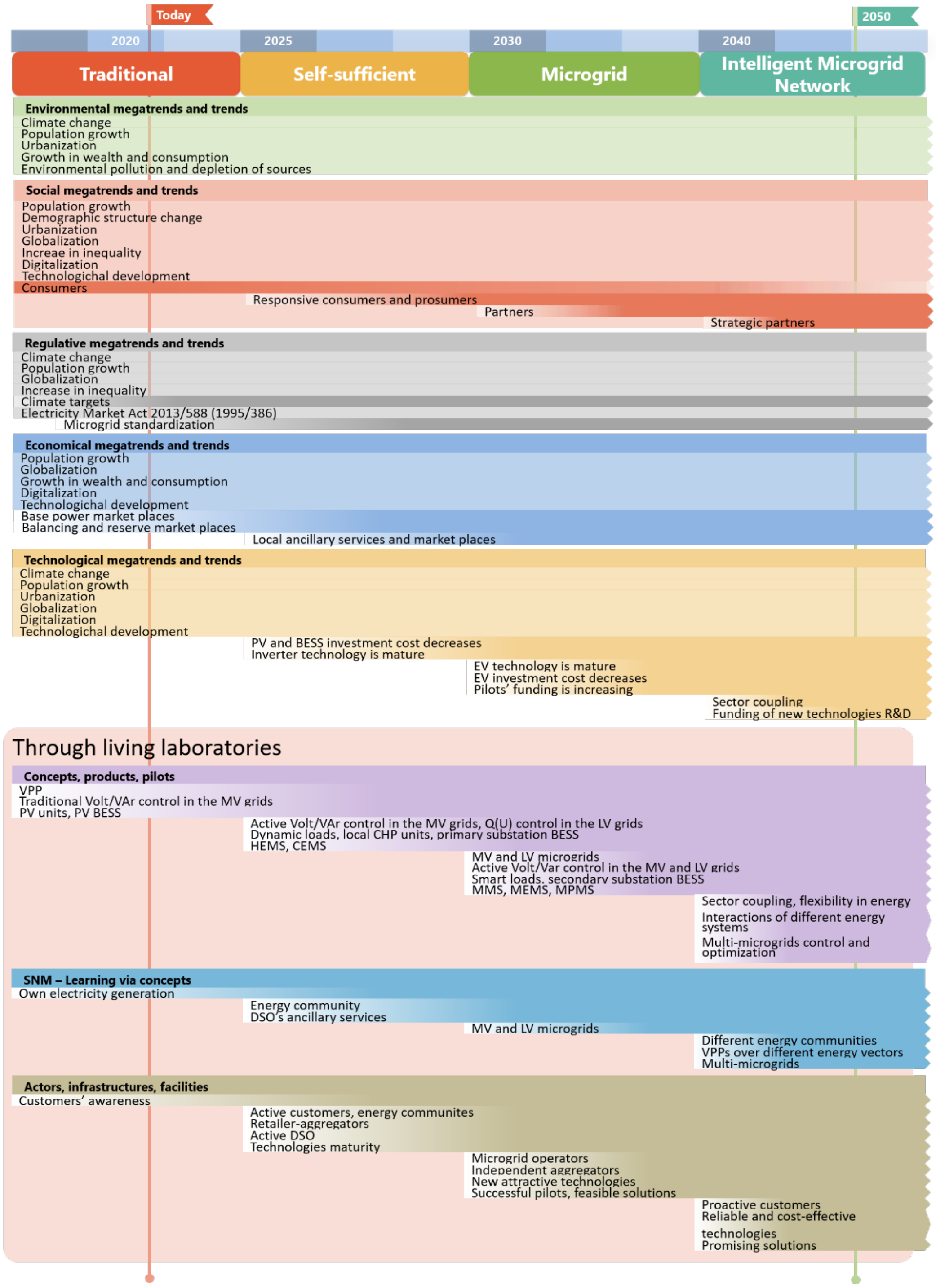


Figure 34. Socio-technical roadmap outline of the electricity distribution networks' evolution.

7 CONCLUSIONS

The energy transition is in progress, emphasising boosting development and sustainability in the energy sector. Promoting RDI assignments in collaborative platforms and joint playgrounds is essential for implementing novel solutions. Vision and roadmap building together with the stakeholders refer to TM. These numerators were considered in this thesis, forming a multidisciplinary approach. The framework is socio-technical, reflecting SNM and excluding the economic benefit consideration. Scenario building, the customers' social acceptance, co-simulation, HIL testing, technology maturity, and socio-technical road-mapping were reflected in the electricity distribution network development, focusing on providing AS. The importance of sustainable development of local test platforms in the laboratory, the real test environment or electricity distribution networks through living laboratories is highlighted.

7.1 Main research outcomes

The refined answers to the research questions RQ1 – RQ5 summarize the research.

RQ1: How low voltage distribution networks evolve towards the Smart Grids?

> Energy transition in the power system occurs in the generation, transmission, distribution, customers, markets, operations, and service provider domains. The low voltage distribution networks evolve through the DERs integration and utilization. The evolving LV distribution networks can be described through the operational scenarios in energy management, power balance management and protection.

RQ2: What are the key aspects of developing low voltage distribution networks?

> The evolution of the LV distribution networks occurs through the systemic change in the energy transition frameworks. The perspectives of the systemic change are socio-ecological, socio-economic, socio-technical, and action-oriented perspectives. In this research, the focus was on the socio-technical perspective of the evolution of the electricity distribution network. The key enablers identified are the social actors' evolution, focusing on the customers' evolution, the DER integration and utilization, integrating the new concepts, and the different ASs in the regulatory and legislative conditions. Besides, open ICT is the critical enabler in multi-vendor distribution network systems and the flexible structure enabler in integrating DER and related management systems.

RQ3: How distributed energy resources offer local ancillary services for developing the distribution networks?

> The different sizes and voltage levels connected DER units could be exploited at the local level, the DSOs' ASs. Active power control could be utilized for congestion management and reactive power control for power flow and voltage level management in the first place. Microgrids could be considered DERs when they offer themselves as a local ASs' source. The tailor-made but standardized AS control solutions are needed because of the variations of the electricity distribution networks and their operation. Object-oriented systems provide fundamentally open data models to be utilized in the development of control and management solutions.

RQ4: What kind of development and testing platforms are necessary to develop control functions for the microgrids or the active distribution networks?

> Different simulations and testing platforms have their purposes and benefits in developing new concepts for the control and management systems. The real-time HIL simulations and testing platforms accelerate the RDI. The development of real-time co-simulations and HIL testing platforms is essential because the case studies and tests close to practice provide an efficient step in the concept development before piloting them. As shown in this research, DER control, based on the standard IEC 61850 with the GOOSE protocol, for the local ASs was proven to be suitable to develop, implement, and test in the real-time co-simulation CHIL test platform developed (by utilizing the standard microcontroller hardware) for the Sundom Smart Grid test network.

RQ5: How the flexibility utilisation-based distribution network management evolves?

> The future ADNs evolve through the integration and utilization of DERs for the implementation of various concepts where the requirements and need of several stakeholders and actors must be met. A high-level and local-level system understanding is the key enabler for successful management concept realization. The dynamic descriptions of the electricity distribution network operations and the static descriptions of the network management structures were developed for roadmap creation, illustrating both operation and structure. Further, they were utilized for the socio-technical roadmap development.

The research was conducted through the previously presented research questions and publications. The research findings are the following.

- Evolution phases can be defined for the electricity distribution networks basing on the increase of the DERs and the utilisation of the social actors, particularly the evolution of customers.
- For accelerating and creating sustainable RDIs in future electricity distribution networks, different stakeholders should be involved in the whole development path via the SNM. Collecting the stakeholders on one platform and creating collaborative roadmap(s) increase learning over different disciplines.
- Future electricity distribution networks vary, and they might have different operational goals. An operational goal can relate to technological, economic, or environmental and/or social matters affected. The desired operation is provided by a set of functions forming the required functionality. For example, the operational goal for a community microgrid can be self-sufficiency and cost minimization. This target is economic. The operational target of a DSO's microgrid can be reducing congestion in the distribution network. This target is primarily technological. In both cases, the required functionalities are achieved with flexible DER control via the MMS coordination. The functions of DER units can be load, generation, and Volt/VAr control.
- The abstract level or generally higher-level concept is defined as HL-UCs describing the high-level functions. The concept's HL-UCs should apply to every case. However, lower-level UCs or functions closer to practical implementation are dedicated and must be defined to analyze simultaneously running controls for different stakeholders.
- Different real-time co-simulation platforms need to be developed to integrate functionalities by the various systems (actors) and their operations over different time frames for ADN development. Further, a testing method for long-term real-time simulations for evaluating ASs control and management schemes need to be established.

7.2 Contributions

The contributions of this thesis to science are definitions, frameworks, methods, procedures, and schemes/solutions explained in the following.

Definitions:

- The research defined the general level evolution phases of the electricity distribution networks regardless of the region. The phases are Traditional, Self-sufficient, Microgrid, and Intelligent Microgrid Network. In this research, a case example representing a suburban area in Northern countries was examined.
- The distribution network evolution phases relate to the definition of the customer evolution phases in general: Consumer, Responsive Consumer, Prosumer, Partner, and Strategic Partner. These customer evolution phases are defined for the framework level and not for segmentation.
- The definition of function, functionality, and operation related to the electricity distribution network management was sharpened. The formation of the definitions was generated with the help of the microgrid concept. In other cases, the contents depend on the concept.

Frameworks, methods, and procedures:

- A framework was set for developing a socio-technical roadmap of the customer evolution in evolving electricity distribution networks by combining MLP and SNM. Further, a method to develop a socio-technical roadmap by utilizing UML design was created. MLP and SNM frameworks are popular for describing a systemic change. UML as a method is well known and universally used for describing a system's structure and operation. UML tools are also key implements utilized in Smart Grid standardization. This research combined MLP, SNM and UML, aiming to create a method for moving forward from a framework creating a roadmap that could be utilized easily further down to the more practical level.
- A method was developed for conducting a functional analysis of microgrids from the concept level to practice by utilizing the different levels of UCs, from HL-UCs to TUCs. The functional analysis utilises an object-oriented design by a UML method with the UC and activity diagrams describing the system's behaviour. The functional analysis was conducted from the concept level down to the simulation case studies showing the use and purpose of different levels of UC modelling. The case studies were selected to demonstrate the functionalities in different time-domain and investigate

the effects of functions running in parallel. This method aims to describe the behaviour of the system that could be tested and sharpened for different levels of power system operation, for example, for frequency control and Volt/VAr methods.

- A framework was established for developing a roadmap of the electricity distribution network evolution in energy management, power balance management, and protection. A method was created that combines and analyses the operational scenarios and structural descriptions within the framework by utilizing UML design, generating the related management architecture schemes. This framework bases on the general level definitions in first publications extending and particularising the contents by relying on the exemplary distribution network for creating a method to generate management architecture schemes in an evolutionary manner. The UML method is generally used for management system development.
- A procedure was established to develop a lightweight IED based on IEC 61850 GOOSE protocol from a control algorithm to the BBB and FPGA microcontroller platforms. The procedure consists of the development of a reactive power control algorithm, the real-time co-simulation platform, the implementation of the developed control algorithm in controller hardware, and the testing of the CHIL system. The implementation part is only briefly explained since it was the second author's contribution.
- A method was developed for accelerating the long-term real-time simulations, and a method was established for testing a controller in the accelerated real-time simulations. The aim was to present the developed method's potential and related issues for accelerated real-time simulations. Hence a more detailed stability analysis of the proposed control method and detailed technical analysis of the proposed approach should be done.

Solutions:

- A reactive power controller was developed for a DER unit to avoid the DSO’s reactive power and energy penalties to the TSO. The controller algorithm is functioning based on the measurements, but a predictive control could be more useful.
- Management architecture schemes were formed for the evolving electricity distribution networks for energy and power balance management and OC protection UCs with UML tools. A combined scheme of these UCs was analysed, especially for the Microgrid phase. The schemes were developed based on the case example distribution network, a suburban rural area in the Northern countries.

- A socio-technical roadmap outline was developed, and a tool proposed for the future electricity distribution network or intelligent microgrids network analysing trends, concepts, and actors. The created roadmap template utilizes the T-plan method that is efficient for creating technology roadmaps through workshops. Workshop is a typical practice to bring different actors and stakeholders together.

The created electricity distribution networks' evolution path can help develop the desired concepts, functionalities, and requirements. The developed schemes could activate the stakeholders of network users, systems development, and service businesses. The management architecture schemes could be utilized for management system development.

The real-time simulation method for accelerating the long-term case studies and the test grid in the co-simulation platform could be utilized for control algorithm development for the TSO's and DSOs' ASs.

7.3 Future research

This research produces potential research topics and raises further questions. The future electricity distribution networks' system analysis could be exploited for the application and the communications' development for the electricity distribution networks.

1. Analysis of the dissimilar electricity distribution networks through their evolution phases:

   The desired functionalities and UCs related to energy management, voltage and frequency control for power balance management, and protection and outage management could be differentiated among dissimilar electricity distribution networks by questionnaires, interviews, and testing. The questionnaires and the interviews could be directed to the defined stakeholders for testing the relevance of the ADN functionalities based on the functions defined in this thesis and Publications II, IX. Simulations and testing, according to the defined TUCs, could be carried out with a co-simulation platform. The functions can be studied in more detail by the activities that an object of an actor class could perform and the events that change the object's state. The results could be presented by state diagrams, which help analyse a single object's behaviour in multiple UCs. A state diagram describes all possible states, which an object can transfer and how the functions aligned to an object can change its state. Even the types of events can be classified like the measurement or the alarm types.

The actors of the electricity distribution network system are, in fact, roles, which a user of the system has. A system user can have several roles, as a protection device can provide various protection functions, act as a measuring or an alarming actor. The actors defined in this thesis summary and in Publications I, II, and IX can be studied further by their fundamental roles and the roles they might afford added value to other actors, system's operators or stakeholders. As a result, the analysis of the actors by functionalities could be produced, and the operation of the dissimilar electricity distribution networks by their evolution phases could be utilised for the total management system description and development.

2. The description of the electricity distribution networks' management system along with the communication system design requirements in the different evolution phases:

   Based on the analysis of the electricity distribution network operations and actors, the management functions could be represented with sequence diagrams, which illustrates the collaboration between the objects related to a single UC clarifying the events' sequence. The sequence diagrams help explore the behaviour of several objects in a process. Alternatively, a state diagram or a state chart is valuable when investigating a single object's behaviour in multiple UCs. The created diagrams (UC, class, state and sequence) could be analysed interlinked.

   The developed UCs, diagrams and analysis might indicate the redundancies and lacking items or aspects in developing an electricity distribution network management system. For example, gaps in actors' activities, classifications of objects or associations of the classes. A suitable communication network hierarchy, media, and protocols could be discovered by analysing an object-oriented electricity distribution network operation model. Optimal system design and communication requirements could be presented.

   The actors' information flows could be analysed, including the amount, priorities, and criticality of the data sent or received. A general co-simulation model of the data transmission could be built to define the data transfer requirements for measurements, control events, and protection.

3. Accelerated CHIL testing methods for testing microgrids' ASs provision:

The developed method in Publication VII can be further developed. For example, more detailed stability and technical analysis of the proposed approach is needed. Also, the testing method of various controllers' interactions must be developed.

4. The following methods and tools for joint road mapping in co-creation:

   Extended T-plan method of workshopping to produce the stakeholders' joint roadmap.

   Holistic futures scenario building and storytelling methods including quantitative models (for example as Chapter 3), and qualitative local models (for example as Chapters 4 -6) of transitions.

   UML method and a tool for visualising and holistically analysing the multidisciplinary system.

5. Road-mapping methodology presented in this thesis to be evaluated in the living lab development process.

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Evolution Phases for Low Voltage Distribution Network Management

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***Abstract*—It is necessary for the low voltage distribution networks to develop to meet the operation targets of Smart Grids. Therefore, the evolution phases of low voltage distribution networks are introduced. The operational scenarios are described mainly by the use case studies for each evolution phase, which illustrate the evolving operations between the actors in different domains. Alternatively a use case gives a picture of the system from a certain point of view. This approach gives a base for further studies to improve the low voltage distribution network management. A use case studied thoroughly could indicate the redundancies as well as deficiencies in the system design and the sum of the all use cases is the overall picture of the system. These could be exploited for the development of the communication means and system as well as the management functions and applications.**

***Index Terms*— Distributed Power Generation, Power System Management, Power System Control, Smart Grids.**

I. Introduction

The Smart Grid can be divided into the groups of actors as Bulk generation, Transmission, Distribution and Customer, which are connected together from the energy- and the communication flow point of views. In addition the actors in the field from Market, Operations and Service providers are interlinked to them by communications. These actor groups are named as Domains, where the actors perform different applications. Actors comprise of devices, systems, programs and stakeholders for the applications; like home automation, energy generation and storage as well as energy management for performing the applications. The actors in a particular domain interact typically with actors in other domains e.g. a distribution company in the Distribution domain is included in the Operations domain as in the distribution management system (DMS) or in the Customer domain as in smart energy meters. [1]

Also, the Smart Grids roadmaps [2], [3] present the central and local energy productions, customers, energy storages, distribution system operators (DSOs) amongst other actors, which are interlinked together in real time for applications in different power distribution and management processes. The real-time and transparent communication between the actors as well as local automation affords events to be exploited in several applications and in multilevel functions of distribution automation (DA) [4].

Traditionally DA is applied within a hierarchical control including different levels of power distribution, which are divided horizontally from bottom to top. The levels are low voltage (LV) network, medium voltage (MV) network, bay, station, control (or network) and enterprise (or utility) [4],[5]. Also the power distribution is divided into the primary power distribution processes up to the station level and into the management processes up to the enterprise level. The *management processes* are composed vertically and they include:

- distribution network safety and protection management,
- network normal operation and control management,
- asset management, and
- business management [6].

This describes the management of the distribution system on market terms. However, the LV distribution networks consists mostly of passive components at present [5] and therefore in future LV distribution networks have to be developed towards networks which are capable to operate as an integrated part of the Smart Grids.

This paper presents a roadmap for development of the LV distribution networks with four evolution phases, which are based on earlier concept development in Energy Village project [7]. The evolution phases are named here as Traditional Network, Self-sufficiency in Electric Energy, Microgrid and Intelligent Network of Microgrids. The evolution is studied here considering the operations for safety and protection management as well as the management of the network normal operation. The asset and business management processes are excluded.

The operations of the LV distribution network in each evolution phase are described by use cases based on Unified Modeling Language (UML), which represent different operating scenarios between the actors [8]. The use cases presented in this paper describe operations of the energy

This work was carried out in the Smart Grids and Energy Markets (SGEM) research program coordinated by CLEEN Ltd. with funding from the Finnish Funding Agency for Technology and Innovation, Tekes.

distribution related to the traditional network operation management. In addition the operations in disturbance situations related to the safety and protection management are studied.

II. Evolution Phases

The Traditional Network describes the state of the art of the LV distribution networks comprising the Finnish or the European system. The networks, which are Self-sufficient in Electric Energy, are introduced when the amount of the distributed generation (DG) mostly exceeds the demand of electric energy. Next the Microgrid phase describes the LV distribution networks capable of transferring to operate in island mode as well as capable of reconnecting to the national grid both in network normal operating state and in disturbance situations. The Intelligent Network of Microgrids is the phase, where several advanced and different types of microgrids are operated dynamically together to meet the operational targets of the Smart Grids. In this paper all evolution phases are represented generally, and in addition Traditional Network and Microgrid phases are described by the energy distribution use cases as well as by the use cases of disturbance situations covering the outage management. Some event types are introduced in every evolution phase. Finally the main use case of the Intelligent Networks of Microgrids phase is illustrated.

A. Traditional Network

In traditional networks the electric energy is produced centrally and delivered one-way to the consumer loads. The structure of the network is hierarchical and the network is operated radially. Backup supply is arranged by open ring connections. Some local micro-generation like photovoltaics (PV) or wind turbines can appear, but in negligible amount.

The energy distribution use cases consist of functions for the management of energy balance and consumed energy in this evolution phase as the Fig. 1 presents. The main functions are control of loads, monitoring of the network status in the secondary substation and measurements of consumed energy for billing. The actors are the energy retailer, DSOs' data and information systems, the components, devices or equipment in the distribution network, consumers, controllable passive loads, micro-generation units and smart energy meters.

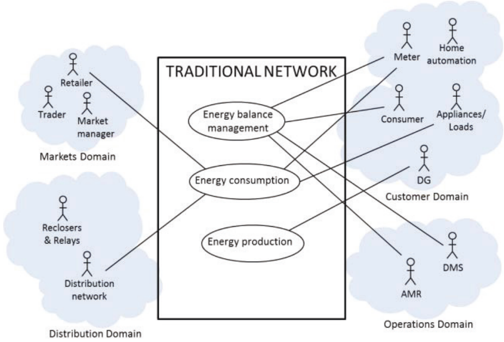

Figure 1. The energy distribution use cases of Traditional network.

The use cases of the disturbance situations of the network describe *the protection and the outage management*. The main protection functions in LV distribution network are short-circuit- and overcurrent protection. In addition, the micro-generation units are disconnected in a fault situation by the loss-of-mains (LOM) protection devices. The main functions of the outage management are the alarms, the fault location, the fault isolation and the supply restoration [5] during a fault condition in the supplying MV feeder or in the LV distribution network. A fault is "alarmed" by customer calls, located based on customer calls and finally discovered by the maintenance staff sent in the place. In addition some smart energy meters are exploited for alarming about the blackout. The actors are the DSOs' personnel at the control center, network control system (NCS), DMS, protection devices (PDs), smart energy meters, maintenance staff and the consumers. The Fig. 2 presents the operational scenarios i.e. use cases of the disturbance situations, which are a fault in the MV feeder and a fault in the LV main line.

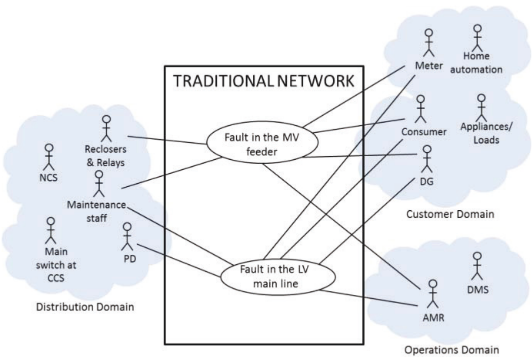

Figure 2. The use cases of the disturbance situations of Traditional network.

The main events that occur in Traditional Networks are:

- short-circuit and overcurrent *protection* provided by fusible devices,
- *measurements* of consumed energy provided by smart energy meters as well as measurements of current, voltage, power flow and power quality at the distribution transformer,
- *remote control* of passive loads provided by smart energy meters or by corresponding devices, and
- *alarms* for the DSO about the supply outages by customer calls or by smart energy meters.

B. Self-sufficient in Electric Energy

In this evolution phase there is an increase both in micro- and small-scale generation because consumers aim at self-sufficiency in energy by producing the major part of the energy locally or regionally. Local production, mainly PV units or wind turbines, is micro-generation type. Energy villages or cooperative societies are formed to produce energy regionally by means of a small-scale energy generation unit, like a combined heat and power (CHP) unit. Because of the large amount of grid-connected DG units, the number of home automation systems for the energy management increases as well as the voltage monitoring at least in the secondary substations. Management of the voltage level in the distribution network put pressure on DSOs to control DG units and loads, which calls for a role of distributed energy resources (DER) operator i.e. DER aggregator [9]. Because in the current regime DSOs cannot participate in electricity markets, the electricity retailers can act as retailer-aggregators [9] in this phase. The retailer-aggregator sends the price signal to the customers to be exploited for decision about the production and the consumption of the energy.

The increased amount of grid-connected DG units may result in false operation of the protection functions in the network such as nuisance trippings and increased delays [10]. Because of bidirectional fault currents in the networks, a false trip can occur in adjacent healthy feeders causing unnecessary disconnections. Increased operation delays in protection may also occur, for example, in a fault situation, where the DG unit reduces the fault current fed by the main grid. However, during utility grid power outages, all DG units have to be disconnected, precisely when these on-site sources could offer the greatest value to both generation owners and society.

The energy distribution use cases presented in the Fig. 3 contain management of energy balance and consumed energy in the Traditional Network phase but in addition the local and the regional energy production is significant. Demand response functions are applied for economical usage of electricity. The integration of the automated meter reading (AMR) system to the DMS is developed further, which offers ability to monitor the LV distribution network. The actors are as in the Traditional phase, but the consumers begin to act more like customers as well as a cooperative society is an increasing customer type. In addition consumers' home automation systems or automation systems for the DG units are the actors at the Self-sufficiency in Electric Energy phase.

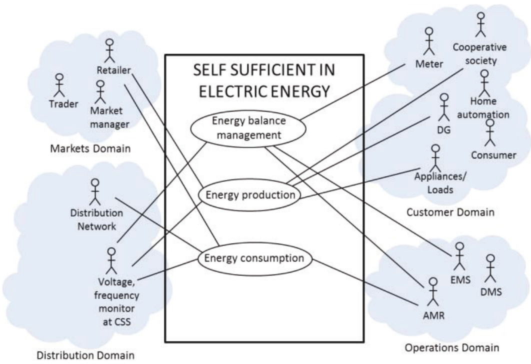

Figure 3. The energy distribution use cases of Self Sufficien in Electric Energy.

The use cases of the disturbance situations represent the operational scenarios in fault situations like in Traditional phase, but the outage management process is developed further based on the technology provided by the smart energy meters. Both the regional and the local DG units are disconnected from the utility grid in a fault situation by the LOM protection devices.

The main event types are *protection*, *measurements* and *remote control* as in Traditional Network phase. In addition the *local control* of dynamic load type of EVs as well as *monitoring and remote control* of the status of the regional CHP unit are the events in this phase of evolution.

C. *Microgrid*

The Microgrid evolution phase comes out, when the installed amount and the capacity of DG units challenges the protection and the voltage control in the LV distribution network. At the same time customers become more active because of the opportunities to manage the electric energy usage by the smart energy meters, by the DG units and by the increased amount of modern home automation systems. A prosumer consortium microgrid is formed within a single customer or multiple customers [11] belonging to a secondary substation area where consumers aim to minimize electricity bills. DSO influences the operation passively by requirements and charges [11].

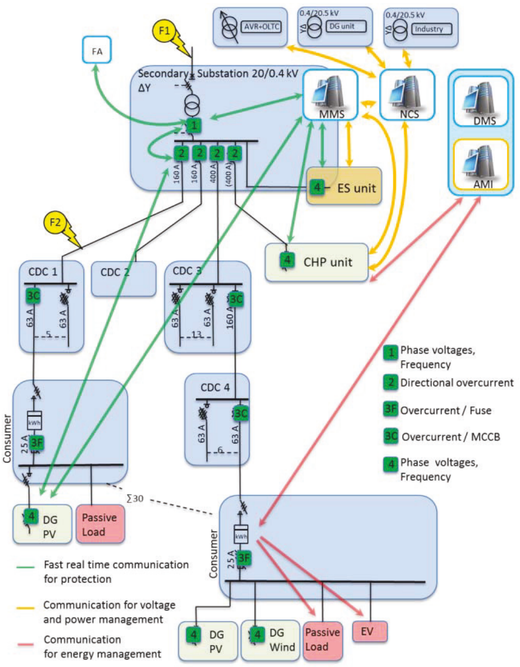

Figure 4. The Microgrid.

The microgrid presented in Fig. 4 comprises of a microgrid interconnection device, a central energy storage (ES) unit, micro- and small-scale generation units and customer loads [12]. The DG units are controlled by a central management system i.e. a microgrid management system (MMS), by home automation systems and by smart energy meters. The MMS also coordinates a sophisticated protection system, where the protection devices are capable to perform adaptive protection functions [13]. Grid topology is open ring and it can be changed by remote controllable protection or switching devices. In the figure also two fault cases, F1 and F2, are introduced to be used later in this paper with the uses cases of disturbance situations. F1 represents a permanent fault in the supplying MV feeder, which necessitates the transition to island mode. F2 represents a fault in the LV feeder.

Microgrids have two main operation modes, which are the normal operation parallel with the utility grid and the island operation; in addition to this the system can also be in blackout state after system collapse. Furthermore, there are transient modes between the different modes of operation or the blackout of the system. The transient modes are the transition to island operation, the synchronized re-connection to the utility grid, the system collapse and the blackstart. The Fig. 5 presents the transitions between the main as well as the transient modes of operation in Microgrids. In addition if the transition to the island operation is unstable, the system might collapse and a blackout takes place. Thereafter the service restoration is performed by way of the blackstart strategy in which all the DG units are firstly disconnected and thereafter reconnected in a controlled way.

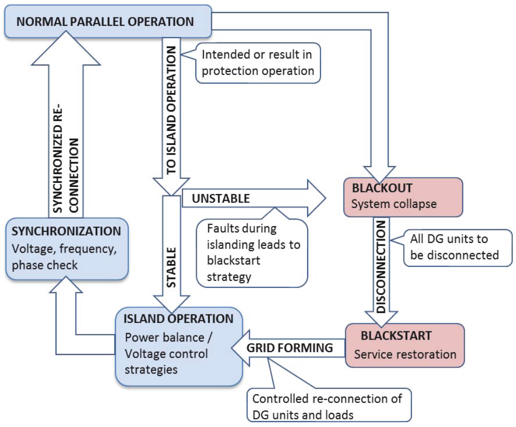

Figure 5. The operation modes of Microgrids.

The energy distribution use cases include functions for *energy balance management*. In addition to this the functions for *power balance management* in island operation become significant.

The energy balance management use case within a Microgrid includes functions like energy management, generation and load management and system efficiency monitoring. The energy management system may receive weather forecast data in order to predict the available amount of DG for the near future. One of the new actors is the microgrid operator (e.g. prosumer consortium microgrid), who can sell or buy energy as an energy depending on the capability of DG units with regard to cost as well as the current market prices. Other new actors are MMS, the microgrid interconnection equipment, sophisticated protection devices, and ancillary service providers i.e. aggregators. An aggregator helps consumers to take part in activities for demand response (DR), but can also utilize DR for own purposes like managing the power balance in the energy markets [9] by frequency controlled reserves.

The power balance management use case defines how the steady state and dynamic power balance is managed by maintaining stable voltage and frequency both in grid connected and islanded mode of operation. The balance between load, generation and ES has to be achieved either with the MMS, which controls the power balance and the level of the voltage locally within a microgrid zone [13], or without central management and a communication infrastructure by local controllers [14] of the DG units.

The use cases of the disturbance situations describe the functions of protection and outage management both in the parallel and in the island operated microgrid. The outage management consists of the alarming and the fault location performed by the smart energy meters or by the MMS, the fault isolation by protection devices and remote controllable disconnectors and finally supply restoration either manually or remotely. The new actors in both operation modes of the microgrid are the MMS, the microgrid interconnection equipment, sophisticated protection devices and feeder automation (FA), which are utilized for the critical LV feeders. The main operational scenarios of a microgrid in disturbance situations are represented in the Fig. 6 and briefly introduced in the following.

Fault F1 leading transition to island operation use case describes the situation, where a lack of supply occurs as a result of a faulted MV feeder. After the unsuccessful delayed reclosing the MV breaker operates and the supply voltage collapses, which the main switching device of the microgrid detects. The automated transfer function to the island operation is performed by the device, which is named in this paper as the microgrid (MG) switch. In addition uncritical loads are dispatched by the MMS.

Adaptive protection use case describes the situation, when the microgrid operates in the island mode and the protection system is adapted to the changes of grid topology, to the amount of the DG connected as well as to the level of the voltage. The type, the status and the short circuit feeding capacity of DGs, the voltage level and the LV feeder current are the information utilized for fault calculations performed by the MMS.

Fault F2 in the island operating microgrid use case describes the situation, where a fault occurs in the microgrid during the island operation. The LV feeder protection device detects a fault in the LV main line and sends a blocking signal to the other feeder protection devices and a disconnecting command for the DG units. After a specified time delay (e.g. 20 ms), the faulted line is disconnected, while the healthy part of the microgrid remains operating normally.

Reconnection of the LV line after F2 use case describes the situation, where fault F2 is cleared and the LV feeder is reconnected during the island operation of the microgrid. The supply restoration is performed by the protection device of the LV feeder, which checks the protection settings from the MMS and after adoption of the settings; the line is switched on by the protection device.

Fault F1 cleared leading to the transition to parallel operation use case describes the situation where the supply voltage recovers to the MV feeding line after the fault F1 is cleared and so the microgrid returns to the parallel operation with the utility grid. After the clearance of the F1, the DMS sends a reconnecting command to MMS. MMS monitors then the voltage and frequency differences measured by MG and takes suitable control actions to enable necessary condition for synchronization. After the permission from the MMS, the MG switch performs the synchronized reconnection. After the reconnection, the MMS sends commands for LV feeder protection devices to adopt the protection settings of the parallel connected microgrid.

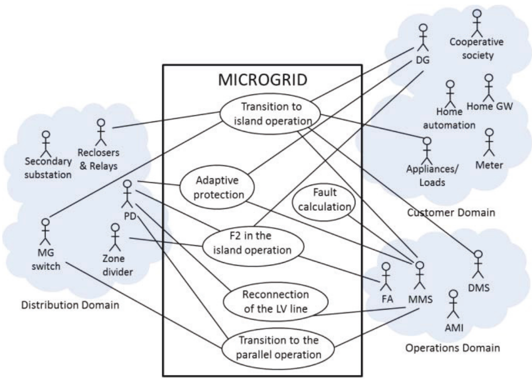

Figure 6. The use cases of the disturbance situations of Microgrids.

The main events of the Microgrid phase of the LV distribution network are the following:

- *remote control* of passive loads by smart energy meters or by MMS as well as remote control of active loads like EVs,
- short-circuit and overcurrent *protection* provided by the circuit breakers (CBs) with advanced protection functions with or without communication as well as by fusible devices in some places,
- *measurements* of energy consumption by the smart energy meters as well as measurements of the voltage in the essential nodes of the network by measurement units of CBs for example, and
- *alarms* for the DSO about the lack of the supply by the MMS, by the smart energy meters and by customer calls as well as alarms about the status change of the regional CHP unit.

The measurements such as voltage and status of the network are exploited further and increasingly for DMS applications like the load control, the load flow calculation and the state estimation.

D. Intelligent Network of Microgrids

The Intelligent Network of Microgrids comes to the limelight, when the operation of microgrids interests different stakeholders like DSOs, DG owners, DG operators, energy suppliers and increasingly also customers. The Intelligent Network of Microgrids is operated as an integrated energy system [2], [15], where electricity and heating are managed as integrated energy vectors of multiple energy systems and different stakeholders are involved in the scheduling of the optimal energy production.

The Intelligent Network of Microgrids is formed within several Microgrids controlled by the MMSs. The Microgrids operate according to the free market model [11], where the operation strategy of the LV distribution networks can be chosen flexibly from economical, technical, environmental or combined modes of various stakeholders in real-time between all the parties. Central MMSs (CMMSs) connects MMSs vertically to the SCADA system [12], [15], which supports the use of several Microgrids as a network of Microgrids. The CMMS behave as an energy retailer, which is responsible for local balance, import and export control, maintenance of technical performance and monitoring of the emission level [11]. The level and the quality of voltage are controlled locally by a single MMS.

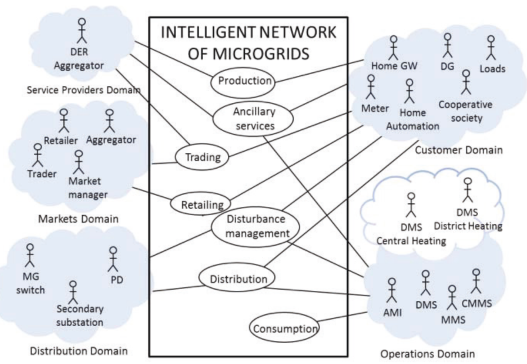

Figure 7. The main use cases of the Intelligent Network of Microgrids.

The main use cases are the operational scenarios for the energy distribution, for the disturbance situations, for ancillary services as well as for retailing, trading, production and consumption of energy as shown in Fig. 7 above. New actors appear for ancillary services, which are required e.g. for DER which are powered by intermittent supply, like wind and solar, so that they operate according to the required performance criteria [9]. In addition different types of aggregators appear for DGs or small ESs. Also aggregators of DR can appear which is an independent organization or an existing market participant. A DR aggregator can be the retailer, which collects the demand flexibility of customers and provides the access to the energy markets by providing a link between the end-users and the buyers of the DR [9].

III. Results and Discussion

The results presented in this paper can assist to select specific use cases from evolving LV distribution networks for further studies in order to consider the operations in Smart Grids. A specific use case gives a picture of the LV distribution system in a certain point of view like protection or power balance management. Alternatively the sum of the use cases is the outer picture of the system. Further studies could indicate the redundancies as well as deficiencies in the development of, for example, a LV distribution management system.

The approach by the UML could take a stand on the activities performed by actors (role), classifications of objects e.g. roles as well as constrains and dependencies of the classes. A class diagram, which is the backbone of object oriented methods, would illustrate the static relationships between different objects. Thereafter a sequence diagram would illustrate the dynamic relationships related to a single use case. It is useful when studying the behavior of several objects. Alternatively when investigating the behavior of a single object in multiple use cases, a state diagram or a state chart would be valuable.

These diagrams and their analyses could be exploited for the development of management system, the communication means and system as well as the new devices, equipments and applications needed for the LV distribution networks representing the different evolution phases.

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CIRED Workshop - Ljubljana, 7-8 June 2018
Paper 234

SOCIO-TECHNICAL MODELLING OF CUSTOMER ROLES IN DEVELOPING LOW VOLTAGE DISTRIBUTION NETWORKS

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ABSTRACT

The transition of low voltage (LV) distribution networks towards more intelligent and smart microgrids is dependent on both technical and behavioral factors, thus forming a socio-technical systems change. Socio-technical aspects need to be taken into account when developing concepts and models to establish and manage successful niche experiments. This paper presents a new framework to model actor (customer) evolution and engagement in the process of developing smart LV Microgrid distribution networks as socio-technical systems. The framework is based on combining the Multi-level perspective (MLP) and the Strategic niche management (SNM) approach with the Unified Modeling Language (UML) tool. Customer engagement is an essential element in SNM, wherefore understanding their and other actors' different development paths is invaluable to uncover the dynamics of the Microgrid transition in the societal and the technical contexts. The proposed framework could be applied to other key actors such as DSOs and energy retailers. The benefit of the models created by the developed framework is the articulation of expectations and visions as well as building up the networks in the SNM.

INTRODUCTION

Understanding and managing energy transition processes such as the microgrid evolution, calls for a multi-level perspective (MLP) approach. The MLP approach claims that technological change needs to be seen as one component of a broader set of institutional, behavioral and cultural changes that co-evolve [1], [2]. Thus, transitions are processes happening in socio-technical systems and involve technologies, actors and institutions that interact through niches, regimes and landscapes over long periods of time [3]. Niches form the micro-level, where the new innovations and experiments emerge [1]; they are models of the relationships between the functions, roles and actors of novel systems. The regime level is the "ruling system" supported by practices and institutionally stabilized systems (e.g. the current distribution system) where the new niche innovations (e.g. microgrids) are trying to enter. The regime and niche levels receive pressure from the landscape, macro-level, which includes demographic trends, political ideologies, societal values and macroeconomic patterns [4]. In the case of microgrid evolution, the early phases are according to the MLP approach niche experiments. In Strategic Niche Management (SNM) framework the first step is the articulation of expectations and visions, second one is building up the network of actors, third comes voicing and shaping by case studies and pilots and last step is learning from the pilots. After successful learning, niche experiments are complete for adaptation at the regime level [3].

A recent literature review [5] indicates that the main stream of smart grid research focus more on the general electric systems than the customers. Still, the socio-economic features are crucial for understanding the feasibility of Smart Grids and also have an impact on the development of the technologies.

The MLP approach opens an opportunity to test different methods for transition management [4]. In this paper the Unified Modelling Language (UML) tool is used to capture customer evolution in association with the other key actors (services and technologies) in the microgrid evolution phases, linking it also to the SNM discussion. Special focus is on explaining customer roles in the different LV development phases, as customer engagement is a fundamental driver of smart grid initiatives [5], [6] and [7]. Identifying customer segments such as early adopters and prosumers [6], understanding their needs and providing the right solutions e.g. products and services are of key importance for the future development of microgrids.

SOCIO-TECHNICAL EVOLUTION OF MICROGRIDS

Defining the concept

Decentralized energy systems suggest a paradigm shift in the way energy is produced, delivered and consumed [5]. In this paper we propose a new framework model for analyzing the transition of the developing low voltage (LV) distribution networks towards Smart Grids by different levels of system analysis as described above. This is done by combining the MLP [4], [8] and SNM [3] approach with the UML tool as a new framework model to better capture the systemic co-evolution of electricity consumers and technology [6], [9].

Evolution theory of LV distribution networks

To understand customers in the context of evolution phases this model was built up as follows. The evolution of LV distribution networks can be defined by four evolution phases in sub-urban areas (e.g. niche experiments), which are Traditional Network, Self-sufficient in Electric Energy, Microgrid and finally Intelligent Network of Microgrids phase. The Traditional Network describes the state of the art of the LV distribution networks, Self-sufficient in Electric Energy are introduced when the amount of the distributed generation (DG) mostly exceeds the demand of electric energy. The microgrids are formed within a secondary substation area for a solution to operate as an islanded network in addition to the parallel operation with the utility grid. Multiple microgrids interlinked together are introduced as the Intelligent Network of Microgrids, where the operation of microgrids interests various stakeholders and the operation strategy of the network can be flexibly chosen from economical, technical, environmental or combined modes. [10]

These evolution phases was developed based on the the use cases, which illustrate the different operating scenarios between the actors operating the system [11]. The actors in the model can be the above-presented key elements in their fundamental relevance (customers, service providers and technology) but also their roles. Thus, actors also comprise of systems, programs and stakeholders for the applications (like network monitoring and control, protection, energy generation and -storage, energy management and home automation).

Customers

The dissemination of socio-economic features (e.g. customers, services, providers and pricing) is crucial to demonstrate the benefits of smart grids (microgrids) to overcome associated barriers [5]. Customers can be both consumers and producers (i.e. prosumers) in future microgrid systems [7]. Especially, these prosumers are expected to have a much more active role in future electricity markets [12] – [14]. Still, apart from a small group of forerunners who actively seek new solutions, most customers' choices are an outcome of habits and practices (routines), enabled by the existing infra-structure and institutional structures [13], [14]. The evolution of microgrid customers is still in its infancy and for the 'normal' customers to accept and support the transition to microgrids, service providers (aggregators, DSOs i.e. Distribution System Operators, energy companies) and policy makers must communicate the benefits effectively [14]. As the number of consumer engagement projects in Europe is increasing [6] the key findings pinpoint the importance of understanding consumer response to the information about energy consumption and source, dynamic pricing and other incentives. Especially, from a business/developers/ technical perspective exploring consumption profiles and consumer segmentation are pivotal to be able to provide correct information and services [5], [16].

ANALYSIS SPECIFYING POSSIBLE CUSTOMER ROLES

Customer evolution in the developing LV distribution networks influenced by the technical and the social dynamics is presented in the Fig. 1. Referring on the research presented in [10], [13], [17] – [19] the technical and social dynamics of the distributed energy system is adapted to the developing LV distribution network system. In addition to this interaction, customer evolution is mapped to the system by classifying customers with UML technique according to the four evolution phases of the system. The classified customers are Consumer, Responsive Consumer, Prosumer, Partner and Strategic Partner.

In the first phase the customer is classified into the user class. A user exists in the present system, and it has its own value of the connection capacity, tariff type, demand profile and the amount of passive loads. A user can consume electricity. The main actors a user interacts with are DSO, energy retailer, smart energy meter and customer grid. When the boom of DG appears, the Consumers evolve. Exchange value becomes important as well as social and ethical issues.

In the self-sufficient of electric energy phase a consumer has assigned some amount of passive loads to DR markets, and to do so, started to use building automation system (BAS) and home energy management system (HEMS). The contract participating to demand response (DR) markets is made with a DR aggregator. Consumers make individual choices regarding price, product attributes, services and values. The Prosumer differs from the consumer profile by producing electricity (own generation and storage unit) and selling the excess to the market. The prosumer can also buy this service from an aggregator or other business.

The Partners of microgrids are the key operating actors. A partner has also dynamic loads like V2G (Vehicle-to-Grid) type of electric vehicles. Because of the enhanced control and electricity distribution system of the Microgrids, a partner can participate also to the ancillary service markets. The importance of cooperatives or other types of cooperation between different actors grows.

The last phase in customer evolution is the Strategic partners, who participate in the Intelligent Network of Microgrids. A strategic partner operates as one actor in a dynamically operated network of microgrids and has a more strategic role as a system actor. In the Intelligent Network of Microgrids, the operation mode can be selected based on economical, technical, environmental or combined modes of various stakeholders in real-time between all the parties. This also means that several operation modes can be selected in strategic partners' premises.

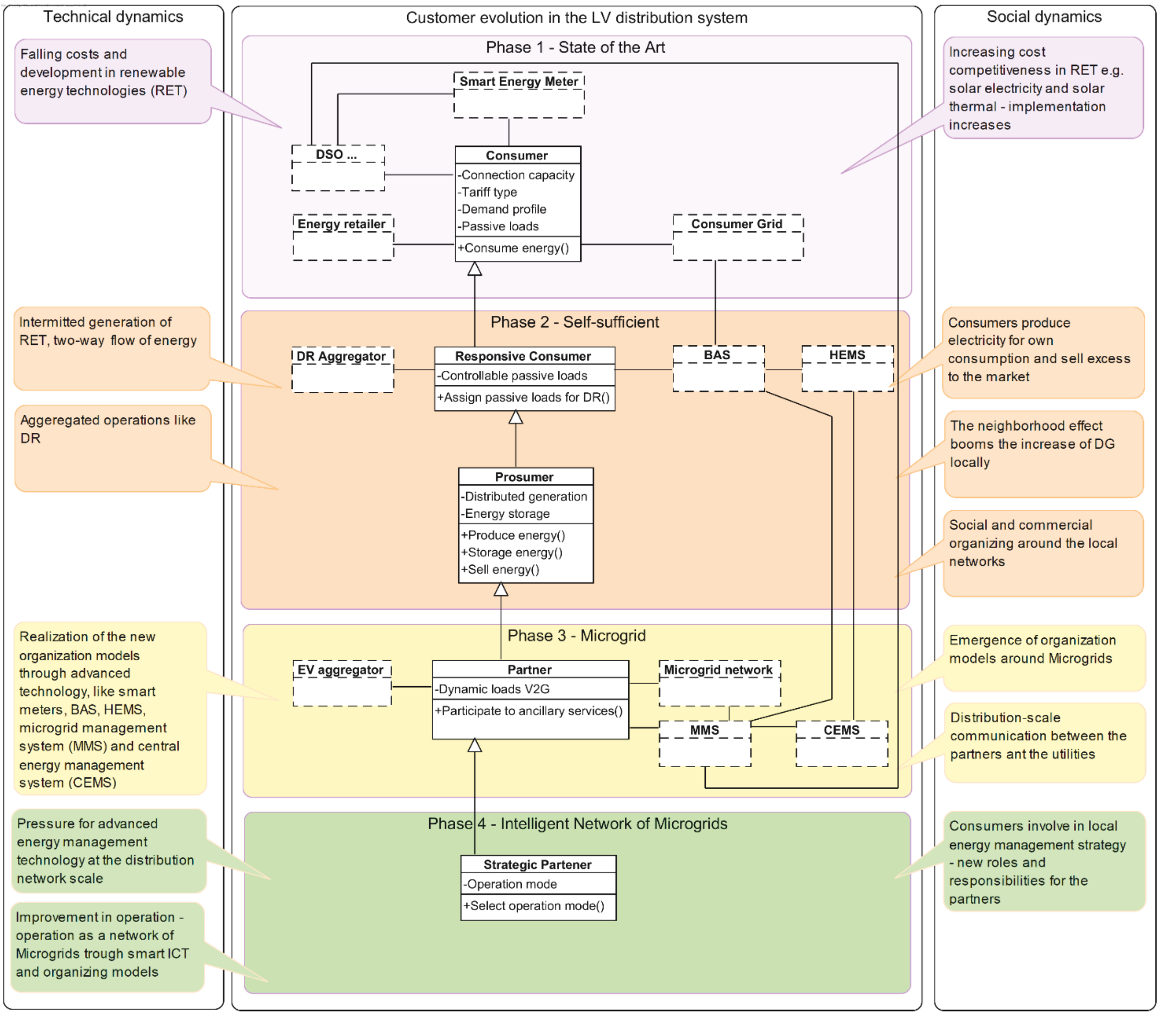

Figure 1. Customer evolution in the developing LV distribution system based on UML class diagram modelling.

The Fig. 1 presents the technology and the socio-economic aspects integrated to the customer evolution; also the associations or connections between the main actors and the customers are presented. This is the first step to illustrate the relationships of the key actors in a socio-technical manner.

CONCLUSIONS AND DISCUSSION

In this paper we have introduced a new framework to harness the full potential of developing smart grid markets. Consequently, there is a need for specific niche experiments (or so called living labs) to design, test, learn, and to validate social and technical functions that enable the microgrid evolution. This comprises how customers use and perceive the new systems, and which kinds of services are needed to further the evolution phases. We propose that using the UML tool, we can visualize and describe important interactions derived from using the MLP approach, and with special focus on SNM. This opens new horizons to develop a truly socio-technical understanding about microgrid transitions and the needed practices. Importantly it creates new understanding about how to enable microgrid experiments or living labs development. We suggest that the UML is a tool to create a system level understanding of both the existing system and it evolution paths.

As the result in this paper, the classifications of the evolving customers are introduced in the four evolution phases of LV distribution networks. This result can be exploited in the SNM for understanding the development path of the customer and its related actors in the dynamics of the societal and the technical environment. This framework could be applied to other key actors, at the very least to DSOs and to energy retailers, which affect strongly to customer engagement [6]. The benefit of the models created by the developed framework is articulation of expectations and visions as well as building up the networks in the SNM projects, like developing Microgrid concepts.

Furthermore the analysis can be applied to the Smart Grid Architecture Model (SGAM) framework -tool, which includes a methodology about the development of use cases, reference architectures, communication technologies as well as data- and information models [20]. The 3D SGAM -model represents "the functional information data flows between the main domains and integrate several systems and subsystem architectures [21]".

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CIRED Workshop - Ljubljana, 7-8 June 2018
Paper 080

ACTIVE NETWORK MANAGEMENT SCHEME FOR REACTIVE POWER CONTROL

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ABSTRACT

In the future new options to provide needed technical ancillary services locally and system-wide by distributed energy resources (DER) are needed. One ancillary service which DER could provide is the reactive power management when microgrid is operated in utility grid-connected mode. In this paper different requirements for reactive power flow between distribution and transmission grids were considered in Sundom Smart Grid (SSG) and the measured data from SSG was used for developing a concept for reactive power management. Based on these different requirements "Future Reactive Power Window" was formulated for SSG which was the basis for control scheme formulation. The simulations showed that coordinated reactive power management scheme across different voltage levels by utilizing control of distributed generation could be very beneficial to the voltage support ancillary service.

INTRODUCTION

Due to extensive integration of distributed generation (DG) units different options to provide needed technical ancillary services locally and system-wide are needed in future Smart Grids. Solutions for the coordinated management of ancillary services across different voltage levels and for the benefit of different stakeholders has yet to be studied [1]–[3]. Sundom Smart Grid, Innovation Cell Finland in DeCAS project[1], offers a novel platform for the development of ancillary service solutions for future grids across different voltage levels.

Different requirements for reactive power flow have been studied in this paper. EU sets grid code requirements. Further local transmission system operator (TSO), Fingrid set requirements for reactive power flow by "Reactive Power Window". In addition, reliable and islanding detection and possibility to make stable transition to island operation set requirements for control of reactive power flow.

Reactive power flow across different voltage levels was studied in this paper. First the SSG and the requirements for the reactive power management are presented. Thereafter the simulation model is described and the study cases are presented. Finally, conclusions and future research questions are presented.

1 This work was carried out in Demonstration of Coordinated Ancillary Services (DeCAS) research project coordinated by (http://www.decas-project.eu). This project has received funding in the framework of the joint programming initiative ERA-Net Smart Grids Plus, with support from the EU's Horizon 2020 research and innovation program.

SUNDOM SMART GRID

Sundom Smart Grid is the innovation cell of Finland in DeCAS project. Sundom Smart Grid is a pilot living lab of ABB, Vaasan Sähköverkko (Distribution System Operator, DSO), Elisa (communications) and University of Vaasa [4]. The overview of the system is presented in Figure 1. Real-time measurements are gathered from the MV distribution network on-line, from all four feeders at one HV/MV substation as well as from three MV/LV sub-stations. There is 20 measurement points totally in Sundom Smart Grid. The measured data is IEC61850 stream (IEEE1588 time synchronized, IEC61850-9-2) with current and voltage measurements. The sampling is 80 samples per a cycle, which is 4000 samples/s. In addition power, frequency, RMS voltages, currents etc. measurements comes by GOOSE messages. Measured data is collected to servers to provide data also for future research themes. In this project the data was received and utilised via Grafana web interface developed by Jubic. The data attributes downloaded were instMag.f (GOOSE-type) from the selected measurement points.

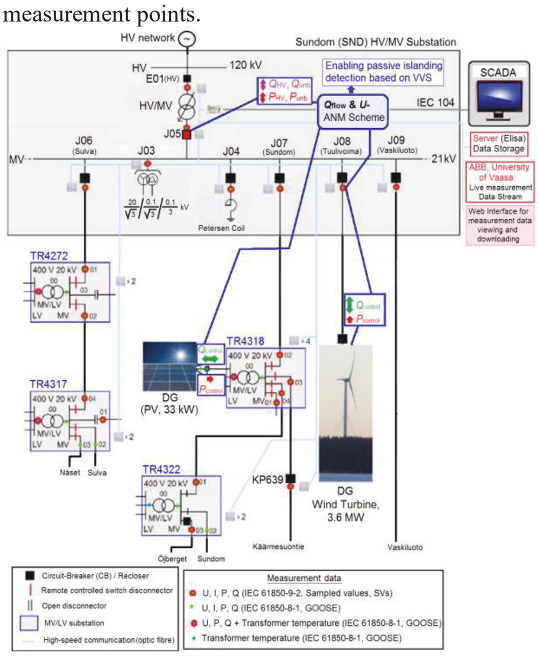

Fig. 1. One-line diagram of Sundom Smart Grid living lab.

PRINCIPLES FOR REACTIVE POWER MANAGEMENT OF FUTURE SUNDOM SMART GRID

Reactive power management for SSG should be observed by the present conditions set by Finnish TSO, Fingrid, which entered into force beginning of 2017. Reactive power window gives the limits for the hourly consumed or produced reactive power regarding to consumed or produced active power (Q_i,P_i) without fees. Exceeding points (Q_m,P_m) are billed, which is illustrated in Figure 2.[5]

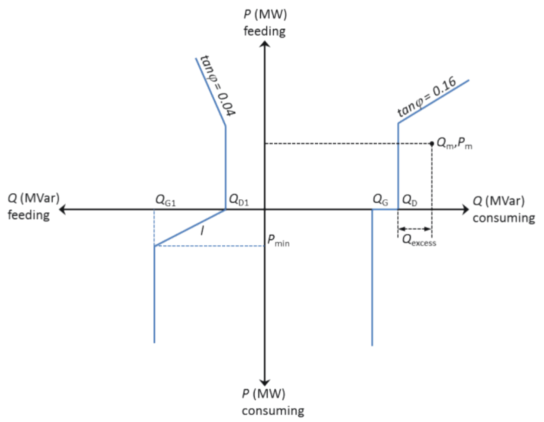

Fig. 2. Fingrid's reactive power window. Applied from [5].

In future, when considering microgrids the requirements for reliable islanding detection should be taken in account. Active and reactive power flows should be managed the way they don't reach Non Detecting Zone (NDZ). On the same principle a zone for stable transition to intended island operation has to be adopted. [6] – [8]

In addition, if the requirements for new installations need to be considered, the Network Code of Demand Connection sets requirements of reactive power management for the transmission connected distribution systems. Reactive power should not exceed 48 % of maximum capacity to import or export of active power (P_{max}). TSO may also require that it is not allowed to export reactive power in the situation where reactive power import is below $0.25P_{max}$. [9]

Figure 3 presents and combines TSO and microgrid requirements as active and reactive power operation limits for future SSG, also the EU requirements for demand connection are illustrated on the background. Limits for the maximum active power is based on the measured data the year 2016, when $P_{max,import}$ was 8.3 MW and $P_{max,export}$ was 1.975 MW. Limits a for reliable islanding detection as well as limit b for stable transition to island operation was implemented based on simulations [10].

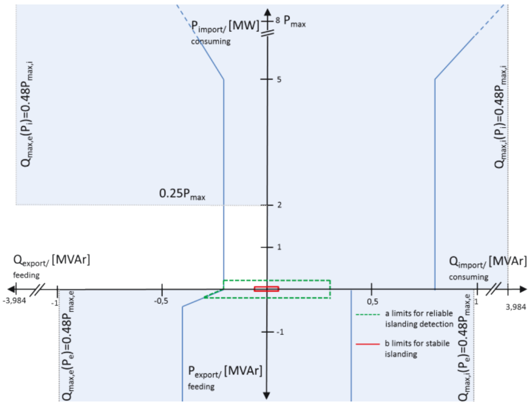

Fig. 3. Active and reactive power operation limits for future SSG.

SIMULATION MODEL

The simulation model of SSG was created with Matlab/SimscapePowerSystems. The model is developed from "One-Year Simulation in One Minute" model [11], which simulates one year P and Q flow based on hourly data. The main grid was modelled as a three-phase source with phase-to-phase voltage of 134.585 kV (the highest voltage based on primary transformer tap positions). U_n of the primary transformer was 117/21 kV and S_n was 16 MVA. On load tap changer (OLTC) was not modelled because using an OLTC model of a transformer caused the simulation speed to slow down too much.

Four feeders were modelled, where three of them J06, J07 and J09 load profiles were generated from the real system measurements. The data was diffused and available only for some months, so the consumption data model was generated based on the data in May 2017 and using "Typical load profiles" (TLP) [12] to extend it for the whole year. One feeder, J08, was solely for 3.6 MW wind turbine. The wind turbine was 3.6 MW PMG synchronous generator type and the converter was a full power IGCT type [13]. Wind data was generated by combining data from Klemettilä weather station [14] near Sundom and data available from Tuuliatlas [15].

One distribution transformer TR4318 and its LV network were modelled including a 33.6 kWp PV system. Solar irradiation data was generated from classic database of Photovoltaic Geographical Information System (PVGIS) [16], which was obtained hourly profiles of solar irradiance estimates on a fixed plane [W/m^2].

STUDY CASES

In Basic Case the present situation of the reactive power flow in the Sundom Smart Grid was presented. Power factor of the WG converter was set 0.97_{ind} based on the measurements May 2017. The reactive power window at TSO (110 kV) side is presented in Fig. 4. The "reactive power window" at DSO (21 kV) side was ~ 70 kVAr more consuming because of the effect of the primary transformer inductance.

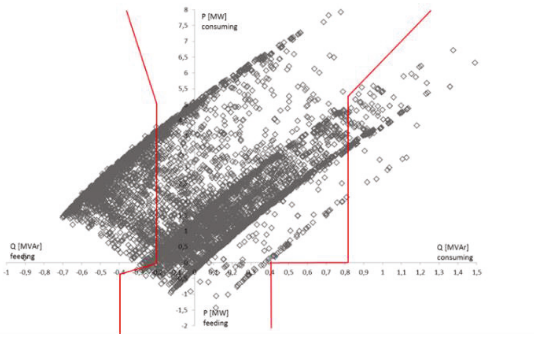

Fig. 4. Reactive power window at 110 kV side in Basic Case.

In Microgrid Case the TSO's requirements of reactive power window and in addition, NDZ requirement of Q ± 50 kVAr to enable islanding detection was studied. In this case the idea was to develop a control algorithm for wind turbine converter. The developed algorithm is presented in Fig. 5. The action was check if (Q_i, P_i) were out of the window at the primary transformer primary side or in the NDZ area at the primary transformer secondary side. If the point was out of the window, the algorithm drove Q_{set} = ± 50 kVAr depending on the direction. If the point was in the NZD, the algorithm drove $Q_{set} = Q_i \pm 50$ kVAr depending on the direction of Q_i. If the point was inside the window and out of NDZ no control action was done. The reactive power window is presented in Fig. 6.

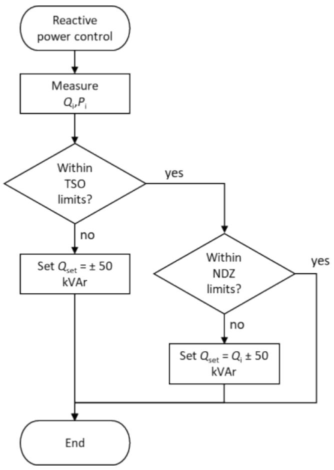

Fig. 5. Control algorithm for reactive power control in Microgrid Case.

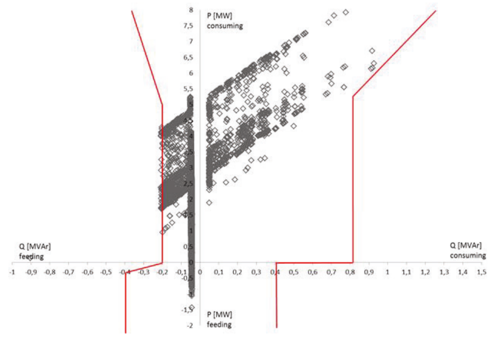

Fig. 6. Reactive power window in Microgrid Case.

CONCLUSIONS

Based on the simulations the reactive power management in SSG could be implemented by controlling the converter of the WG unit. In future when cabling degree will increase the adequacy of the converter reactive power consumption capability should be investigated. In addition if the amount of photovoltaics (PV) would increase, the possibility to utilize PV inverters for reactive power management should be studied.

Considering the requirements for microgrids and the reliable islanding detection by reactive power management, the control algorithm for reactive power of the WG converter was developed. In addition the means of active power control should be studied, which could be developed by means of an energy storage system, by demand response actions or by limiting distributed power generation.

The simulation model can be developed further for the future studies. By implementing one year measured data (consumption and power generation) to the model more accurate model would be obtained. For control studies of the technical ancillary services a shorter period of time with the measured data could be implemented.

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Prospects and Costs for Reactive Power Control in Sundom Smart Grid

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***Abstract*—New options to provide the technical ancillary services locally and system-wide by distributed energy resources (DER) are needed in the future. Sundom Smart Grid (SSG), local smart grid pilot in Vaasa, offers a novel research platform to develop protection and control solutions for future distribution networks. In this study, an ancillary service solution for reactive power management was studied by utilizing measured data and available MV and LV network connected DER units. Different requirements for reactive power flow between distribution and transmission network were considered in the studies. Based on these requirements "Future Reactive Power Window" was formulated for SSG. The reactive power flow across voltage levels in different cases was studied by simulations. Simulations showed that a coordinated reactive power management scheme across different voltage levels is very important from the technical and the economical point of view for development of future distribution networks.**

Keywords—Smart Grid, Microgrid, Active Network Management, Reactive Power Control

I. Introduction

Options for ancillary services are one main focus on the development of Smart Grids, which is a result but also a possibility due to massive implementation of distributed generation (DG) units. The integration of DG units is well studied, but solutions for the coordinated management of ancillary services across different voltage levels and for the benefit of different stakeholders have not been that much in focus [1]–[3]. Sundom Smart Grid, Innovation Cell Finland in DeCAS project, enables the development of ancillary service solutions for future grids over traditional boundaries from the high voltage level until to the LV level.

In this paper different requirements for reactive power flow have been studied. EU sets grid code requirements, for example, for connection of demand and generators. Further local TSO set requirements for active power flow dependent reactive power flow (P_{flow} and Q_{flow}) by "Reactive Power Window". In addition, reliable and future-proof islanding detection as well as possibility to make stable transition to islanded operation sets requirements for reactive power flow control.

In this paper the reactive power flow (Q) across different voltage levels is studied by the developed simulation models.

This work was carried out in Demonstration of Coordinated Ancillary Services (DeCAS) research project coordinated by (http://www.decas-project.eu). This project has received funding in the framework of the joint programming initiative ERA-Net Smart Grids Plus, with support from the EU's Horizon 2020 research and innovation program.

Eight of these cases in which the effects of Q control were investigated are presented in the following sections. Section II presents the SSG and the requirements for the Q management. Then in Sections III-V the used simulation model is described and eight study cases and reactive power fee comparisons are presented. Finally summary from simulations, conclusions and future research questions are presented in Section V.

II. Living Lab Sundom Smart Grid

SSG is a pilot living lab jointly created by ABB, Vaasan Sähköverkko (DSO), Elisa (communications) and University of Vaasa [4]. The overview of the system is presented in Fig. 1. Real-time measurements are gathered from the MV distribution network on-line, from all four feeders at a HV/MV substation as well as from three MV/LV substations comprising 20 measurement points totally. The measured data is IEC 61850 stream with current and voltage measurements. The sampling rate is 80 samples per a cycle, which is 4000 samples/s. In addition power, frequency, RMS voltages, currents etc. measurements are received by GOOSE messages. The data is collected to servers for providing data also for future research.

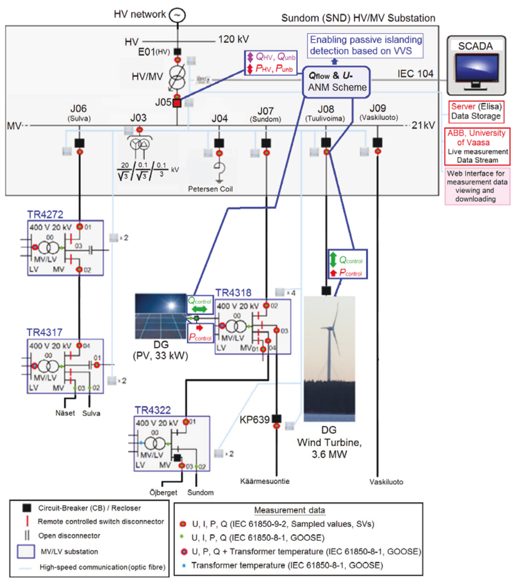

Fig. 1. On-line diagram of Sundom Smart Grid living lab.

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III. Objectives of Reactive Power Management

In this study the Q management was considered by the means of primary local control method, which target is to manage *reactive* power flow within voltage and thermal current limits. The secondary local control method designed to manage *active* power flow within voltage and thermal current limits. The secondary control method can is used if voltage and thermal limits or stable transition to island operation cannot be achieved with primary control. [5], [6]

A. Reactive Power Window of Transmission System Operator

The reactive power window settled by Fingrid, TSO in Finland, presented in Fig. 2 is specifying the reactive power Q that is allowed to be delivered or received from the main grid without fees. The limits are set according to whether active power P is produced or consumed in the customers' connection point of the main grid.

The measured points are hourly average values of power, and the reviewing period is 12 months. The points out of the window (Q_m,P_m) are invoiced, but the 50 largest excesses of the Q limits within one month are not noticed. In addition, the reactive energy fee is defined.[7]

B. EU Regulation

EU commission regulation Network Code of Demand Connection set requirements of reactive power management for the transmission connected distribution systems, and it should be applied to new distribution systems to provide demand response (DR) services to relevant system operators and relevant TSOs. The requirements should not apply to existing distribution systems. The requirements also should not apply to new or existing demand facilities connected at the distribution level unless they provide DR services to relevant system operators and relevant TSOs. However, the requirements should apply in case the relevant regulatory authority or EU member state decides otherwise.[8]

TSO may require DSOs to actively control the exchange of reactive power. Secondly a DSO may require the TSO to consider utilizing the distribution network for reactive power management. The actual reactive power range should not exceed 48 % of maximum capacity to import or export of active power (P_{max}), which means when importing (consuming) reactive power $cos\varphi_{max}$ = 0,9$_{ind}$, and when exporting (producing) reactive power $cos\varphi_{max}$ = 0,9$_{cap}$. In addition TSO may require that it is not allowed to export reactive power in the situation where active power import is below 0,25P_{max}. In Fig. 3 is presented these requirements outlined for SSG, and it is based on 8 MW peak power. [8]

In addition, requirements for grid connection of generators [9] set requirements for reactive power management for voltage stability purposes for new installations.

C. Microgrids

In addition to the above, when considering reliable islanding detection for Microgrids, Q_{flow} and P_{flow} have to be managed in a way that the magnitudes are not in NDZ (Non Detection Zone). Also at the situation when the network is able to transfer to the island operation, a zone for stable transition has to be adopted. [5], [6], [10]

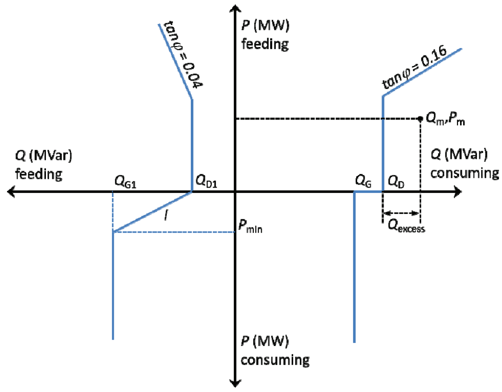


Fig. 2. Fingrid's reactive power window. Applied from [7].

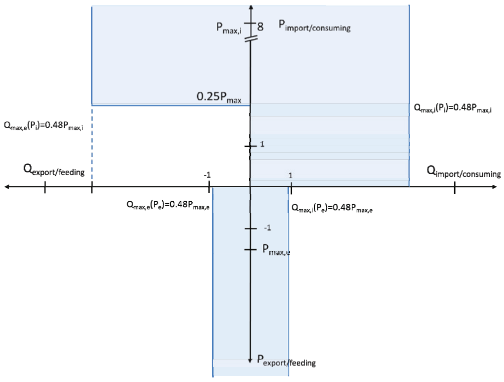


Fig. 3. Requirements set in Network code of demand connection applied for SSG.

Based on studies and PSCAD simulations [11] there are limits for Microgrids. The a-limits enable the reliable islanding detection in every situation considering the limits for NDZ when using e.g. VVS (Voltage Vector Shift) based loss-of-mains protection. In the blind spot area the system is too close to power balance situation for detecting islanding based on a change of VVS. The limits for SSG should be Q_a ± 50 kVAr and P_a ± 30 kW. The b-limits enables the distribution system to transfer to island operation in a way the frequency and voltage stability is possible to maintain after islanding. The limits for SSG should be Q_b ± 300 kVAr and P_b ± 150 kW. These limits are presented in Fig. 4.

D. Reactive Power Management for Future Sundom Smart Grid

The operation limits for reactive power management for SSG in the future could be observed by the previously presented limitations. The "Future Reactive Power Window" could look like the limits presented in Fig. 4. The TSO requirements and the requirements for Microgrids are combined, in addition on the back-ground there is the EU requirements. Limits for the max. active power is based on the measured data the year 2016, when $P_{max,import}$ was 8,3 MW and $P_{max,export}$ was 1,975 MW.

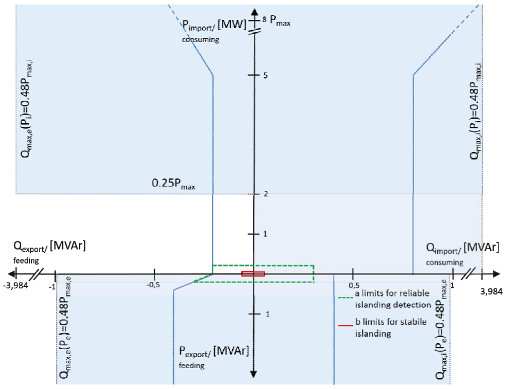


Fig. 4. Active and reactive power operation limits for future SSG.

The observation point according to [7] is 110 kV side of the primary transformer, but the potential point for islanding is the 21 kV side. This means that the distribution network the primary transformer is supplying is the area for which the limits a and b are defined. In some other case these limits could be set for a MV feeder or for a secondary transformer i.e. in the point where an intended islanding operation is desired. Voltage and thermal current limits have to be fulfilled at every network point. This can be based on the measurements or on estimated values.

In this study, Fingrid's reactive power window was considered for reactive power management by the different use cases. A control algorithm was developed for managing Q_{flow}. Moreover, a control algorithm was developed providing Q control for the reliable islanding detection and for the stable transition to intended island operation.

IV. The Simulation Model

The simulation model, presented in Fig. 5, was developed with Matlab/Simscape Power System. The model is based on "One-Year Simulation in One Minute" model [12], which simulates in phasor simulation mode one year P and Q flows based on hourly load and generation data.

A. Main Grid and Primary Transformer

The main grid was modelled as a three-phase source with phase-to-phase voltage of 134.585 kV (the highest voltage based on primary transformer tap positions). Short circuit level was 100 MVA and base voltage 110 kV. The U_n of the primary transformer was 117/21 kV and S_n was 16 MVA. On load tap changer (OLTC) was not modelled because using an OLTC model of a transformer caused the simulation speed to slow down too much.

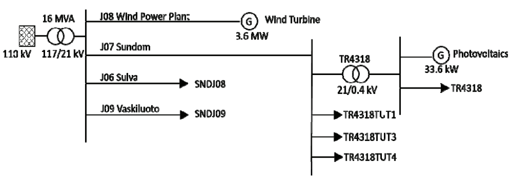


Fig. 5. The network structure of the simulation model.

TABLE I. Line Lengths in Sundom Smart Grid

Feeder	Overhead [m]	Cable [m]	Sum [m]	Cabling degree
J06 Sulva	25246	7938	33184	23,9 %
J06 Sulva 2028	0	40756	40756	100,0 %
J07 Sundom	12950	10199	23149	44,1 %
J07 Sundom 2028	8200	16372	24572	66,6 %
J08 Wind	0	733	733	100,0 %
J09 Vaskiluoto	5913	1122	7035	15,9 %
J09 Vaskiluoto 2028	3340	4467	7807	57,2 %
Total 2018	**44109**	**19992**	**64101**	**31,2 %**
Total 2028	**11540**	**62328**	**73868**	**84,4 %**

TABLE II. Distribution of the Electricity Users in Sundom Smart Grid

Feeder	Group 1	Group 2	Group 3
J06 Sulva	39,5 %	44,1 %	16,4 %
J07 Sundom	29,0 %	47,5 %	23,5 %
J09 Vaskiluoto	1,3 %	5,2 %	93,5 %

B. Lines

The overhead lines and the cables were modelled, presented in Table 1, by considering lengths of different conductor types. In future it is planned to increase cabling degree, which is also shown in the table as year 2028.

C. Load

The loads in feeders J06, J07 and J09 were modelled so one can be selected to be either constant power load or dynamic load, but only the constant power loads were considered. Since the consumption data available from the real system measurements was diffused and available only for some months, a consumption data model was generated based on the data in May 2017 and using "Typical load profiles" (TLP) [13] to extend it for the whole year.

TLP customers in Finland are classified as user groups 1…3. Group 1 includes household customers, which electricity consumption is 10 MWh/year at highest. Group 2 includes household customers, which electricity consumption is above 10 MWh/year. Group 3 includes others, like cottages. The distribution of the electricity users as user groups in SSG is presented in Table 2. [13]

The load profiles were generated for feeders SNDJ06 Sulva and SNDJ09 Vaskiluoto. Feeder SNDJ07 Sundom was modelled in more details. In addition one year data AMR measurements from the LV side of the distribution transformer TR4318 was utilized for load modelling on the LV side.

D. Wind Power Plant

The wind turbine was 3.6 MW PMG synchronous generator type and the converter was a full power IGCT type [14]. The wind generator (WG) was modelled as an ideal WG or a controlled power source. Wind data was generated by combining data from Klemettilä weather station [15] near Sundom and data available from Tuuliatlas [16]. Wind measurements at Klemettilä weather station are available at 27 m high, but the turbine hub is 90/125 m high, so the wind speed data is tuned according to Tuuliatlas data. Power varies as a function of the wind speed.

E. Distribution Transformer

One distribution transformer TR4318 and its LV network were modelled including a 33.6 kWp PV system. The nominal voltage of the distribution transformer was 21/0.4 kV and the nominal power was 315 kVA.

F. Photovoltaic System

Solar irradiation data was generated from classic database of Photovoltaic Geographical Information System (PVGIS) [17], which was obtained hourly profiles of solar irradiance estimates on a fixed plane [W/m^2].

V. Study Cases and Comparisons of Reactive Power Fees

Eight case studies were developed for investigating the P and Q flows. The first case represented the present situation in Sundom Smart Grid. With Case 2 and 3 the possibilities to consume reactive power were evaluated. Previous presents a situation where a shunt reactor was added to 21 kV bus and the latter a situation where the WG converter consumed Q at full power. Case 4 represented a situation where both the WG unit and the PV unit are consuming Q according to constant power factor. By Case 5 it was demonstrated an ideal Q control, which fulfills the conditions for reactive power window whereas by Case 6 it was demonstrated control fulfilling conditions for reactive power window as well as conditions for Q control for Microgrid islanding detection. Case 7 demonstrated a situation where amount of PV panels were increased. Finally by Case 8 it was evaluated the effect of the increase of the cabling degree.

A. Case 1 – State of the Art

This simulation case indicated the present situation of the reactive power flow in the Sundom Smart Grid. Power factor of the WG converter was set $0{,}97_{ind}$ based on the measurements May 2017. The reactive power window at TSO (110 kV) side is presented in Fig. 6. The "reactive power window" at DSO (21 kV) side was ~ 70 kVAr more consuming because of the effect of the primary transformer inductance. The result of the simulation was that 3054 (Q, P) points were out of the window.

B. Case 2 – Shunt Reactor Added

A shunt reactor was dimensioned to the network when there was no reactive power consumption than loads. First in Case 2a it was simulated the situation that WG was not injecting or consuming reactive power ($cos\varphi = 1$). Then in Case 2b a shunt reactor ($L_{\pm} = 4$ H, $L_0 = 8$ H) was modelled to 20 kV bus. The result of Case 2a was that 6800 (Q, P) points were out of the window and 163 points in Case 2b respectively, which is presented in Fig. 7.

C. Case 3 – Consumption of Q at WG with Full Power

WG converter was set up to consume Q all the time at the full S_N and $cos\varphi = 0{,}95_{ind}$, which means $Q_{max} = 1{,}124$ MVAr. This simulation case indicated the potential of the WG converter to consume the reactive power of the network.

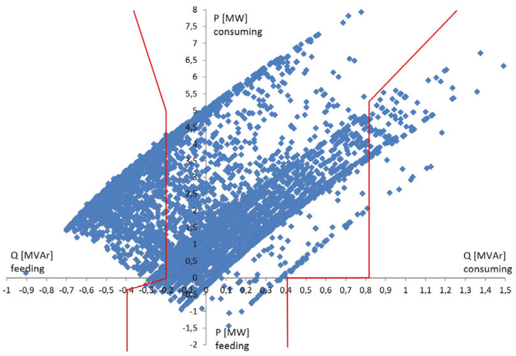


Fig. 6. Reactive power window at 110 kV side of the primary transformer in Case 1.

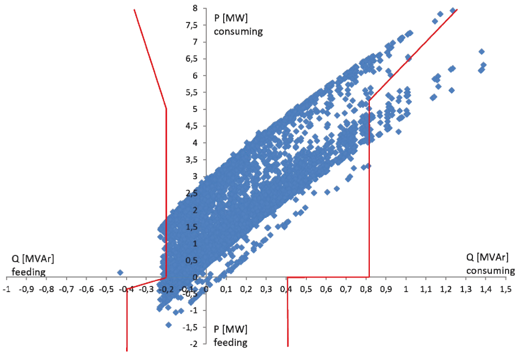


Fig. 7. Reactive power in Case 2b.

D. Case 4 – Consumption of Q at WG and PV According to Power Factor

WG converter was set up to consume Q according to P with $cos\varphi = 0{,}95_{ind}$ and PV inverter $cos\varphi = 0{,}95_{ind}$ respectively. The result of the simulation was that 3046 (Q, P) points were out of the window.

E. Case 5 – Ideal Control

WG converter was set up to consume reactive power according to the simulated reactive power (Q_{window}) at the primary transformer 110 kV side. In other words this control method was attempting to drive Q to zero i.e. $Q_{set} = -Q_{meas}$. The result of the simulation was that no (Q, P) points were out of the window.

F. Case 6 – Control Algorithm

The TSO's requirements of reactive power window and in addition NDZ requirement of $Q \pm 50$ kVAr to enable islanding detection was studied. In Case 6a the control algorithm was generated for "Reactive power Window" requirements, so the target value was $Q = 0$ if (Q_i, P_i) is out of the window otherwise no control. The result of the simulation was that 0 (Q, P) points were out of the window. The reactive power window is presented in Fig. 8.

In Case 6b the idea of the control algorithm action was check if (Q_i, P_i) were out of the window or in the NDZ area. If the point was out of the window, the algorithm drove Q_{set} = ±50 kVAr depending on the direction. If the point was in the NZD, the algorithm drove $Q_{set} = Q_i$ ±50 kVAr depending on the direction of Q_i. If the point was inside the window and out of NDZ no control action was done. The result of the simulation was that no (*Q, P*) points were out of the window. The reactive power window is presented in Fig. 9.

G. Case 7 – Increase of PV Systems

The amount of PV panels was increased from 300 m² to 4000 m² at the LV distribution network. In Case 7a the inverters were set up to consume Q at $\cos\varphi = 0{,}8_{ind}$ and the wind generator $\cos\varphi = 1$. In the Case 7b $\cos\varphi = 1$ both to the PV inverters and WG converter. The result of the simulation 7a was that 6147 (Q, P) points were out of the window and 6788 respectively in Case 7b.

H. Case 8 – cabling 2028

The effect of increased cabling was investigated according to Table 1. In Case 8a the WG converter was set up consume reactive power at $\cos\varphi = 0{,}95$. In Case 8b the WG converter was set up to consume *Q* at full power (compare to Case 3). The result of the simulation in Case 8a was that none of (*Q, P*) points were inside the window and in Case 8b 8697 points were out of the window.

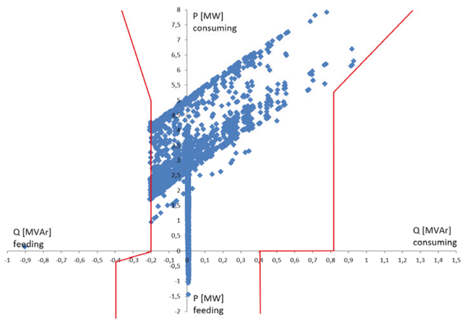


Fig. 8. Reactive power window in Case 6a.

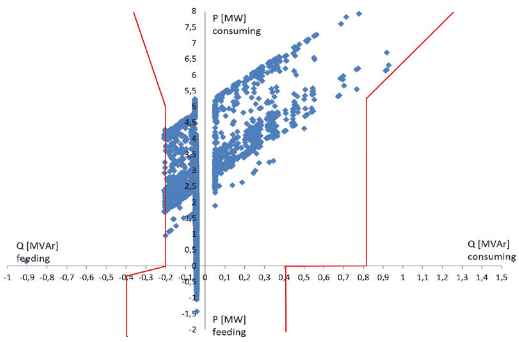
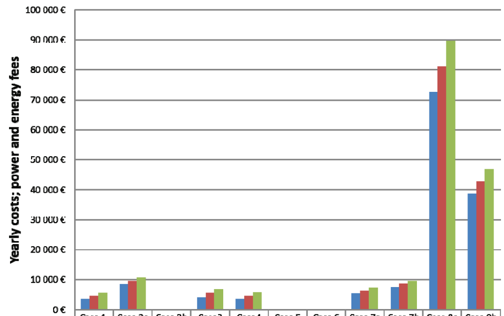


Fig. 9. Reactive power window in Case 6b.



	Case 1	Case 2a	Case 2b	Case3	Case4	Case 5	Case 6	Case 7a	Case 7b	Case 8a	Case 8b
2017 Total	3 563 €	8 449 €	31 €	4 142 €	3 558 €	0 €	0 €	5 421 €	7 548 €	72 584	[illegible]
2018 Total	4 593 €	9 601 €	58 €	5 526 €	4 647 €	0 €	0 €	6 376 €	8 588 €	81 135	42 747
2019 Total	5 626 €	10 757	85 €	6 914 €	5 739 €	0 €	0 €	7 334 €	9 630 €	89 711	46 875

Fig. 10. Yearly fees for reactive power flows in Sundom Smart Grid.

I. Reactive Power Fees in Different Cases

The yearly reactive power and energy fees according to the different case studies are presented in Fig. 10. In this study cost are considered to comprise of TSO fees only. There are unnecessary expenses caused by reactive power, which lead to potential saving opportunities with optimizing the *Q* control. Increasing the cabling degree in the future causes the fees rise significantly and the utilization of the *Q* control becomes even more essential. [18]

VI. Summary of the Simulations and Conclusions

Based on the simulations the *Q* control in SSG today could be implemented by controlling the converter of the WG unit. By comparing results of Case 3 and Case 8 it can be discovered that the *Q* control by the WG converter is inadequate in future because the lack of its potential to compensate the capacitive impedance of the increased amount of cables. However the increase of the *P* consumption in future is not taken in account, which will decrease the amount of capacitive *Q* formed by the cables. One solution for future SSG could be a shunt reactor installed to the MV bus and then control the *Q* by the WG converter so the requirements for *Q* control introduced in section III will be fulfilled. Naturally one WG unit more with a full scale converter like today could be one option.

Case 7 demonstrated the effect of the PV inverter to *Q* management. By comparing simulation results Case 2a and 7b it can be noticed that there is a slight positive effect to decrease the injecting of reactive power to the main grid. With 4000 m² of panels, the generated active power was up to 425 kW and consumed reactive power was up to 250 kVAr according to power factor control of the inverter ($\cos\varphi = 0{,}8_{ind}$). In order to affect the reactive power control by PV inverters at the LV level, the amount of the panels should increase notably.

Considering requirements for Microgrids and the reliable islanding detection by the management of Q_{flow} and P_{flow}, the control algorithm for *Q* of the WG converter was developed in Case 6b. In addition the *P* control should be studied in future studies, which could be established by utilising an energy storage system, by the means of demand response or by limiting power generation of the WG unit or the PV systems.

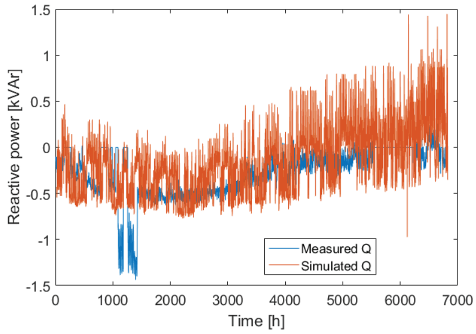


Fig. 11. Measured and simulated reactive power profiles at SNDJ05.

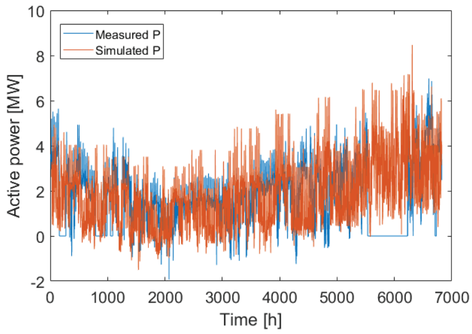


Fig. 12. Measured and simulated active power profiles at SNDJ05.

For evaluating the simulation results, the data available from SSG was gathered from 22nd April 2017 until 30th January 2018, which means about nine month data. Fig. 11 presents measured and simulated reactive power profiles on that time slot. Fig. 12 presents in turn active power profiles.

The generated simulation model could be utilized for the future studies. Different case studies could be implemented by the model. By implementing one year measured data (consumption and power generation) to the model more accurate model is obtained. Modelling an accurate ”Reactive Power Window” of 21 kV side for future SSG is essential for further studies of reactive power control.

For control studies the measured data could be implemented as shorter period of time. For the studies of ancillary services, modelling of LV distribution networks, energy storage system and demand response actions as well as developing control algorithms are essential. These all will provide the means of further research of ancillary services provided by SSG, but also Microgrid operations. Adapting the model for the real time simulator creates a frame for hardware in the loop testingevaluated

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Controller Development for Reactive Power Flow Management Between DSO and TSO Networks

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***Abstract*—In the future, new solutions for active and reactive power control related to the flexibility services offered by distributed energy resources (DER) will be needed even more. One ancillary service which DER could provide is the reactive power flow management between DSO and TSO networks. This research aims to develop a reactive power controller from a preliminary algorithm to a light-weight IED for a wind turbine converter. The purpose of the controller is to maintain the reactive power flow of a medium voltage network within the limit set by a transmission system operator. In his paper, the controller development stages are presented - starting from the preliminary algorithm development by Simscape Power Systems to real hardware and testing it by Controller-Hardware-In-the-Loop simulations. The operation of the controller is investigated in the different development stages of the power network. The outcome is the development suggestions of the real-time simulation platform, as well as the discussion of further improvement possibilities for the controller.**

Keywords—Control Systems, Microgrids, Power system simulation, Testing

I. Introduction

Due to extensive integration of renewable generation at all voltage levels (HV, MV, and LV) new solutions to provide the needed technical ancillary, i.e., flexibility services are required in the future at local (DSO) and system-wide (TSO) levels. Among others, one specific flexibility service which distribution grid connected DER could provide is the reactive power (*Q*) flow management between different voltage levels and between DSO/TSO networks. However, to avoid unwanted interactions between the needs of different stakeholders, transparent coordination, and cooperation between TSOs and DSOs become increasingly important. [1] [2] [3]

So far, different control and management functions of microgrids have been studied, simulated, and tested [4], [5]. Pilot cases for different types of microgrids have emerged with early-stage microgrid controllers with vendor-defined characteristics [6].

The impact of standardization of product development can be illustrated as a general cycle of product sales and standardization [7]. The status of IEEE and IEC standards for microgrids, and especially for the control and management of microgrids, is still mostly in the development phase [8] [9] [10] [11] [12] [13] [14] [15] [16] [17]. However, real-life microgrid management solutions and their implementations are increasing rapidly globally. Some standards for microgrids have been published, but the standardization of microgrid controllers is still under development. Based on the state of the standardization, and available products, it can be concluded that microgrid controllers are in the stage "need to resolve issues related to product standards" [7]. The current issues of microgrid controllers relate to interoperability of different systems and functions that might comprise of solutions from different vendors, which comprises a microgrid. [18] [19]

These standards above establish the requirements for the microgrid controller at the point of interconnection (POI) [8]. One requirement for microgrid controllers is to offer ancillary services (AS). One possibility can be seen due to the requirements of reactive power flow at the HV/MV connection point set by the TSO for the DSO [20]. These kinds of issues should be considered when developing and testing the operation of microgrids and the microgrid controller functions.

Due to these issues, this research aims at developing a microgrid controller function in grid-tied mode, the technical AS for reactive power (*Q*) control. The control techniques for reactive power compensation in microgrids are generally implemented by converters for power quality and power control by droop strategies. In grid-tied mode, the microgrids can be used for reactive power control, thus transforming its operation into static VAR compensation [21], [22]. Authors did not find any similar reactive power control algorithm for DER that presented the preliminary controller [1] and wanted to develop the controller further. The algorithm is developed according to the "Reactive Power Window" (RPW) set by Fingrid, the Finnish TSO [20] or EPV Alueverkko who owns the sub-transmission HV network. A precursor algorithm of reactive power management for future Sundom Smart Grid (SSG) has been developed by offline simulations in [1] and [23], but in this research, the algorithm is developed further to fulfill the real-time requirements. The control algorithm for technical AS, managing reactive power flow at TSO/DSO interface is developed during the first stage with traditional offline simulations and after that tested as software-in-the-loop (SIL), as well as controller-hardware-in-the-loop (CHIL) in the real-time simulation and test platform.

In Section II, the network development scenarios of Sundom Smart Grid as well as the preliminary reactive power control algorithm with the traditional offline simulations by Simscape Power Systems are presented. Section III presents the development of RPW controller operation within the SIL and CHIL simulations on the real-time simulation platform. The conclusions and discussions are presented in Section IV.

II. Reactive Power Control and Network Development Scenarios of Sundom Smart Grid

Sundom Smart Grid (SSG) is a unique living lab pilot that is established in an MV network. The primary substation and

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four secondary substations are equipped with modern IEDs with fiber optic connections to each IED. A cloud service is set up to collect the IEC 61850 sampled values (SV) and GOOSE measurements from the network at 20 points. The measured SV data stream carries current and voltage measurements. The sampling rate is 80 samples per cycle or 4000 samples/s. Also, power, frequency, RMS voltages and currents, and other measurements are received by GOOSE messages. The University of Vaasa's Smart Grid laboratory and the SSG are connected with a direct communication link and the data collection facilities are used in various research activities. The GOOSE measurement data from the SSG is utilized for this research.

Three different basic structures of the network are developed with Simscape, with topologies expected for the years 2018, 2028 and 2035. These network scenarios differ on the expected demand growth, the increase of photovoltaic (PV) units, and cabling changes throughout the distribution system. These issues are presented in numbers in Fig. 1, where the line lengths and types are presented by the feeders: J06 Sulva, J07 Sundom, J08 Wind, and J09 Vaskiluoto. Also, the loads and PV generation are presented by the feeders. The total column presents overhead lines and cabling lengths as well as power demand and generation in the years 2018, 2028 and 2035. The cabling changes in the distribution system provide reactive power given that the demand expected by 2028 and 2035 is below the natural loading of the feeders.

These basic scenarios are simulated by SPS in phasor mode at 50 Hz. Fig. 2 presents the network structure of the simulation model. The main grid is modeled as a three-phase voltage source with the phase-to-phase voltage of 134.585 kV (the highest voltage based on primary transformer tap positions). The U_n of the primary transformer is 117/21 kV, and S_n is 16 MVA. In the following paragraphs, the developed use cases are presented, which are also presented in Table 1.

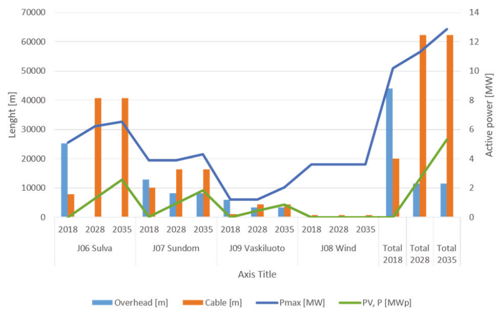

Fig. 1. The development of cabling, loads and generation in SSG.

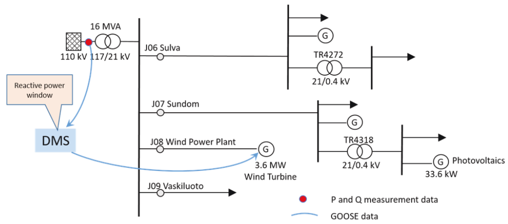

Fig. 2. Outline of the simulation model.

TABLE 1
The Simulation Scenarios

Scenario	Base network scenario	RPW control of WT	Shunt reactor 1.75 MVA
Status 2018	x		
Scenario 2018s1		x	
Scenario 2028s1	x		
Scenario 2028s2			x
Scenario 2028s3		x	x
Scenario 2035	x		

A. Situation 2018 and Scenario 2018s1

Situation 2018 is the base case presenting the current state. This use case aims at validating the simulation results and showing consistency with the real whole year measurements from the SSG. Hourly average values of active power generated from the measured GOOSE data over one year (1.5.2017 – 31.4.2018) are utilized in the model. The load profiles of the feeders J06 Sulva, J07 Sundom, and J09 Vaskiluoto are obtained from these measurements. In the same way, hourly average values of the measured active power generation of the 3.6 MW wind turbine (WT) are used as the generation data. Active power generation of the 33.6 kWp PV system at the Sundom school, connected to 0.4 kV, is modeled based on the estimation of solar irradiation data.

Based on the simulation results, the active power (P) flows of the simulation model are consistent with the measured data. The loads are modeled with a constant power factor to simplify the simulation. These power factors are estimated by calculating one-year power flows with different values of power factors. The best results are achieved by cosφ = 0.995 for all loads. The measured hourly reactive power according to active power (Q, P) values are presented in Fig. 3 and the simulated values in Fig. 4. It can be seen that the simulation results are in line with the measurements. Even though the results are slightly different because the OLTC was not modeled, the load types were not dynamic type, and the topology of the network is the same during the whole year simulation (which was different to reality). This is acceptable and actually better for the evaluation of the RPW controller actions at the TSO's limits. The results are more accurate compared to the previous studies [1] [23], where the whole year load flow has been estimated based on one month's measurement data.

B. Scenario 2018s2

In this scenario, the RPW control is implemented through the WT converter and presented in the simulation model outline (Fig. 2). The measurements of active and reactive power are fed into the RPW controller, and the controller gives the reactive power set point (Q_{set}) as output for the WT converter. Fig. 5 presents the result of the simulation when the Q_{set} is set to the opposite of the measured reactive power at HV connection point (Q_{HV}) value if the reactive power according to active power (Q, P) point, is out of the window, i.e., $Q_{set} = \pm Q_{HV}$. In other words, the RPW algorithm always requires the reactive power to be set to zero at the POI if the (Q, P) point is out of the window. It can be noticed from Fig. 5 that all the points out of the window are controlled to "zero", except in the situation where reactive power is highly inductive. This is due to the variation of the voltage. The flowchart of the RPW algorithm part is presented in Fig. 6.

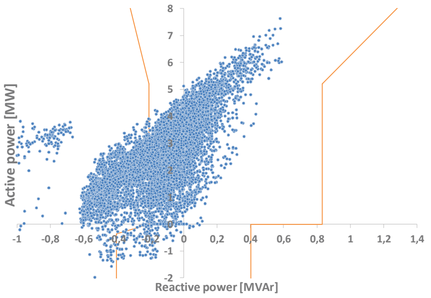

Fig. 3. Measured hourly active power as a function of measured reactive power in the TSO's reactive power window for the SSG.

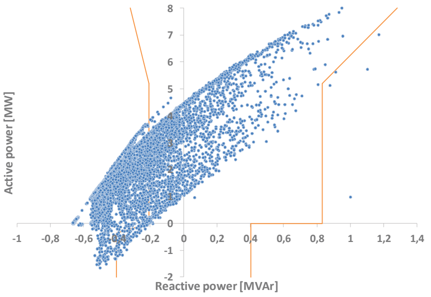

Fig. 4. Offline simulation, Simscape results of the Status 2018.

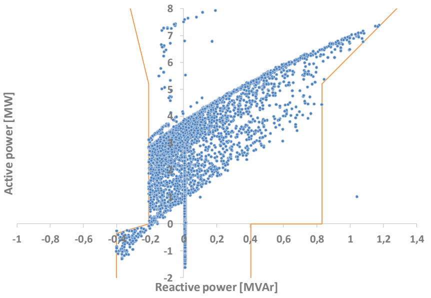

Fig. 5. Offline simulation, Simscape results of the Scenario 2018s2.

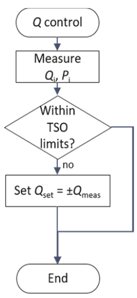

Fig. 6. Flowchart of the RPW control algorithm.

C. *Scenario 2028s1 and Scenario 2035s1*

In Scenario 2028s1, the grid is developed with increased cabling, loading, as well as the PV generation as presented in Fig. 1. The total cabling degree in the SSG will be increased from 20 km (31 %) up to 62 km (84 %) by the year 2028. The peak load is estimated to increase from 10 MW up to 11 MW. The PV generation increase is estimated to be up to 2.6 MWp in total at feeders J06, J07, and J09. In this scenario, the reactive power is all the time capacitive, and the TSO's limits are mostly exceeded.

In Scenario 2035s1, the grid is developed further with loading as well as the increase of the PV generation that is also presented in Fig. 1. The cabling situation is the same than in the year 2028. The peak load is estimated to increase up to 12.8 MW, and the PV generation is estimated to be up to 5.3 MWp in total. Compared to the Scenario 2028, the (Q, P) situation is quite the same.

III. Development of the RPW Controller Operation

Several types of scenarios are developed with Simscape, as presented in Table 1. The scenarios differ based on the control; in scenarios 2028, there is also a shunt reactor (SR) implemented to the MV bus. The same network scenarios are modeled with ePHASORSIM, and the SIL offline results are compared to the SPS simulations with the one-year load flow of the basic network without RPW control. After that, the RPW controller is modified for operating as closed-loop control during long-term simulations. In other words, the RPW controller is adapted for the real-time digital simulation platform and is improved.

A. *Scenario 2018s2*

The offline simulations by the real-time model(s) are performed for the SSG where the reactive power is controlled by the RPW controller as closed-loop. The controller includes the algorithm almost like the same as in the SPS model, but also, an I-controller is utilized to achieve stability of the controlled power system. Also, a hold/memory block is inserted to maintain the Q_{set} as long as the measured reactive and active power points (Q_{meas}, P_{meas}) stay inside the RPW.

The RPW control algorithm is also modified differing from the open loop model. Instead of controlling Q_{HV} to zero if the (Q_{meas}, P_{meas}) point is out of the window (as in Simscape model) the output of the algorithm Q_{set} is such that reactive power at the POI would be set to the RPW limits. This modification is necessary because when $Q_{set} = \pm Q_{HV}$ the reactive power at the WT converter is oscillating as well as at the 110 kV connection point.

Next, it is noticed that by controlling the reactive power exactly to the RPW limits at the POI gives the result that not all the points are inside the window. This happens because the controller is adaptive and measurements from HV connection points are lagging/delayed compared the output (Q_{set}) of the controller with one input data reading cycle T_d and one simulation step. In other words, the average hourly reactive power according to the average hourly active power (Q_{HVavg}, P_{HVavg}) points at the POI are calculated as hourly average values in which T_d is affecting (and the calculation was based on the T_s). Consequently, there are more points for calculating the hourly moving averages when $T_d = 1$. Since the $T_s = 0.01$ s, there are 100 measurement points within a simulated hour. In the situation $T_d = 0.1$ there are 10 measurement points within a simulated hour. Therefore by setting the RPW limits ± 50 kVAr tighter, except QD_I = 200 kVAr (the feed-in Q when consuming P) it is possible to imitate slightly and easily predictive control. Another option could be to develop an estimator, but this development work is left to the future. Now the active power of the WT is peaceful, and all the points are inside the window.

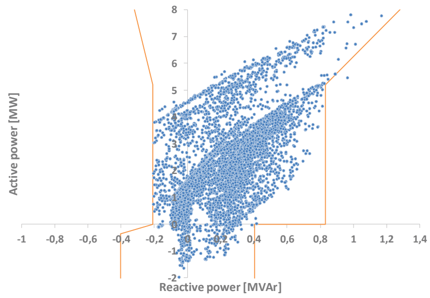

Fig. 7. SIL offline simulation of the Scenario 2018s2. RPW of the SSG when the input data is step function and $T_d = 0.1$.

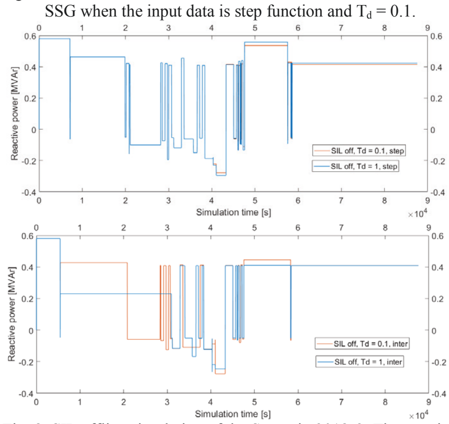

Fig. 8. SIL offline simulation of the Scenario 2018s2. The reactive power of the WT converter when the input data is either step function or interpolated as well as $T_d = 0.1$ or $T_d = 1$. The RPW controller is set up to the TSO limits ± 50 kVAr, except QD_1 = 200 kVAr.

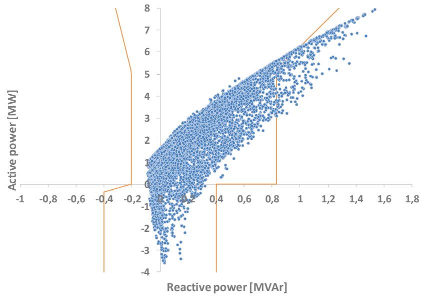

Fig. 9. Offline simulation of the Scenario 2028s2. RPW of the SSG when the input data was step function and $T_d = 0.1$.

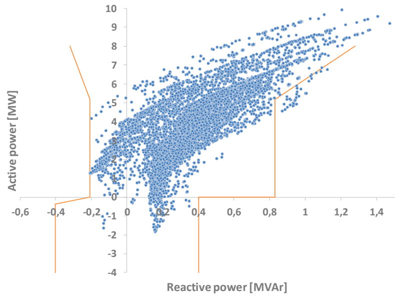

Fig. 10. SIL offline simulation of the Scenario 2028s4. RPW of the SSG when the input data is step function and $T_d = 0.1$. The RPW controller is set up to the TSO limits ± 50 kVAr, except QD_1 = 200

Furthermore, the RPW controller operation is tested with a different type of input data that either is a step function or interpolated. Fig. 8 presents simulation results, the reactive power window (with the tuned RPW controller), when the $T_d = 0.1$, and when the input data is a step function. The result is similar with interpolated data. The difference can be noticed against the results of the open loop simulations (Fig. 5). Fig. 8 presents, in turn, the reactive power of the WT converter when the RPW controller is set up to the TSO limits ± 50 kVAr, except QD_1 = 200 kVAr, and when the input data is either step function or interpolated as well as when $T_d = 0.1$ or $T_d = 1$. It can be noticed that there is a difference in the controlled reactive power depending on the input data; type and time step. The controller is calculating a new value for the Q_{set} in every simulation step (10 ms), so naturally, the Q_{set} differs between the simulations based on the step or interpolated data. Despite that, it can be noticed that the results are almost the same when the input data is step function or interpolated, but the number of the control actions for the converter is slightly less when the data is interpolated (that is closer to the real world measurement data). In the real world, $T_d = 1$ would represent measurement data coming from POI in every 36 s and $T_d = 0.1$ would represent every 360 s (6 min).

B. Scenario 2028s3

In this scenario, a 1.75 MVAr shunt reactor (SR) is applied for consuming the reactive power at the 20 kV bus. Fig. 9 presents the simulation results when the SR is applied. It can be noticed that almost all the points are inside the window. The RPW controller takes care of staying inside the RPW limits. This scenario is tested by the different variations of set-ups; the input data is either step function or interpolated, the SR is either constant Q or voltage-dependent, the limits for the RPW controller varies from TSO limits ±0, ±50 to ±100 kVAr. Fig. 10 presents results when the RPW limits are set according to the TSO limits ±50 kVAr, except QD_1 = 200 kVAr. By comparing the results the case TSO limits and the case TSO limits ± 50 kVAr, the latter gives slightly better results in the reactive power window (like in Scenario 2018s1), but much better results in the WT converter control point of view.

IV. Comparison of Tests

The SIL offline, SIL real-time, and CHIL tests are compared. The outline of the simulation platform is presented in Fig. 11. The presented use case is 2018s2, and the RPW controller set-up limits are TSO ± 50 kVAr, except QD_1 = 200 kVAr, and the data reading step T_d is 1. The hardware used is

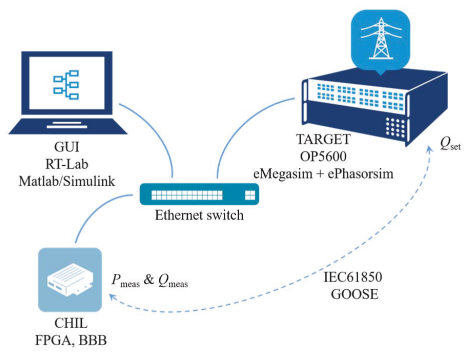

Fig. 11. The real-time simulation platform. [26]

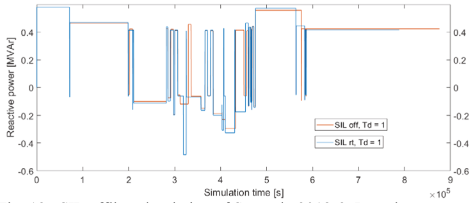

Fig. 12. SIL offline simulation of Scenario 2018s2. Reactive power of the WT converter when the input data is step function and Td = 1. The RPW controller is set up to the TSO limits ± 50 kVAr, except QD_1 = 200 kVAr.

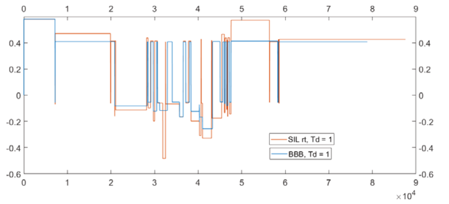

Fig. 13. SIL real-time simulation and CHIL test of Scenario 2018s2. Reactive power of the WT converter when the input data is step function and Td = 1. The RPW controller is set up to the TSO limits ± 50 kVAr, except QD_1 = 200 kVAr.

BeagleBoneBlack (BBB). Fig. 12 presents the results of SIL offline and SIL real-time simulations. There is a slight difference between the results that have to depend on communication delays that are affecting the control. Fig. 13 presents the comparison between SIL real-time and CHIL with BBB. It can be noticed that there is a difference caused by the processor/processing time of the used hardware.

V. Conclusion

In this research, the RPW controller was developed from a SIL controller to real hardware. The simulations bring into question that the RWP controller could be predictive to define the RPW limits simply according to the TSO's requirements. This development demonstrated that for long-term tests and simulation studies, a suitable coefficient for T_d could be defined to present, e.g., one-year study cases reliable enough. Also, the effect of the communication delay was demonstrated in real-time simulations and was compared to offline simulation results. Thus, in the CHIL tests, also the processing time of the hardware affected the results.

We propose that for the further development of an RPW controller a long-term real-time simulation platform or test set-up should be defined and developed in which a predictive RPW controller could be tested to take in account the communication delays and the processing time of the hardware in CHIL tests.

Acknowledgment

This simulation study has been performed using the ERIGrid Research Infrastructure and is part of a project that has received funding from the European Union's Horizon 2020 Research and Innovation Programme under the Grant Agreement No. 654113. The support of the European Research Infrastructure ERIGrid and its partner OFFIS e.V. is very much appreciated.

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Testing an IEC 61850-based Light-weighted Controller for Reactive Power Management in Smart Distribution Grids

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***Abstract*— Due to the large-scale integration of distributed energy resources (DER) new options for the local and system-wide technical ancillary services are needed. Reactive power control is one of such ancillary service provided by DERs. This paper aims to test the performance of a reactive power control scheme developed on a light-weight Intelligent Electronic Device (IED). The IEDs are implemented on a BeagleBoneBlack as well as on an FPGA. The test set-up is implemented by the Controller-Hardware-In-the-Loop platform. The simulation platform is OPAL-RT's eMEGASIM and ePHASORSIM. The results show the performance of the FPGA to be better than BeagleBoneBlack when comparing results of the Sofware-In-the-Loop simulations.**

Keywords—Control Systems, Microgrids, Power system simulation, Testing

I. INTRODUCTION

The electrical distribution systems have grown mainly with the increasing connection of decentralized energy sources and communication between their different components. Numerous studies have been conducted to identify how these components are controlled to support the management of the power grid, based on its real-time operation. In this context, some studies focus on the management of the reactive power capabilities of these sources to support local voltage throughout the distribution system [1] [2] [3] [4] and mainly to comply with reactive power distribution in-feed requirements imposed by grid codes [5]. Since actors are spread across the grid, Information and Communication Technology (ICT) plays a crucial role to coordinate and provide reactive power support. [6].

The latter brings new challenges in determining the performance of the distribution grid when having to consider both power system and communication phenomena and requires rigorous system testing under dynamic conditions [7]. The shift from offline modelling and simulation to hardware in the loop simulation allows the testing of both hardware and software planes under real-time conditions [8]. Techniques such as Controller-Hardware-In the-Loop (CHIL) are topics of research aligned on how these systems can be tested, with the advantage of a good fidelity which helps to study grid behavior of control mechanisms [9] [10] [11]. In CHIL, the hardware controller exchanges low powered analog signals with the real-time simulator. This has the benefit that different operational scenarios can be investigated under controlled experiments without harming any physical system. Also, the hardware controller can be programmed for parameter adjustment during the run time, which increases the flexibility of the test system and the simulation [12] [13]. Additionally, different communication protocols may be tested in CHIL to find out the optimal information exchange between hardware and software.

IEC 61850 is one of the popular automation protocol, due to the fast and reliable measurement rate provided by GOOSE over the Ethernet. In addition to reliable communication, the system and the controller can be modelled and automated using the IEC 61850 functions which map the measurements on the controller. Although IEC 61850 standards offers many benefits, recent works [14] [15] [16] [17] [18] [19] [20] [21] show that the major challenges facing the implementation of the IEC 61850 standard is the configuration task based on the available IED and system configuration tools within a multivendor environment. The recent works mentioned above are pilot projects that were used in the commercial IEDs in a designed laboratory platform and the commercial software configuration tools. Moreover, the commission task needs system support tools from the manufacturers. Therefore, research and development tasks can be more costly and time-consuming. However, in terms of accelerating research, development and relaxing the IEC 61850 implementations tasks, Light-Weight IEC 61850 IEDs can be used. Various open-source libraries are available that are based on C and Java solutions. These solutions automatically generate the low-level machine code required for the IEC 61850 implementation within different operating systems such as Linux, Windows, and macOS. Embedded open-source operating systems (Linux) running on the microcontroller and SoC kit are becoming increasingly popular in both industrial and academe domain since it is cost-effective and very flexible in its configuration.

This paper aims to present the implementation of a reactive power controller based on light-weight IEDs and test the performance. Section II presents the reactive power algorithm for Sundom Smart Grid. Section III presents the development process of the real-time simulation platform. More details about the Light-Weight IEC 61850 implementation is in section III B. Section IV presents the executed tests and experiments. Section V presents the round trip latency for GOOSE messages with the tested hardware. Finally, the conclusions are presented in Section VI.

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II. Reactive Power Control Algorithm for Sundom Smart Grid

An algorithm of reactive power management for future Sundom Smart Grid has been developed by offline simulations in [22], [23]. The case studies and this precursor algorithm has been developed with Simscape Power Systems. In this research, the algorithm is developed further for adapting it to the real-time simulation platform.

A. Sundom Smart Grid

Sundom Smart Grid (SSG) is a unique Smart Grid living laboratory pilot that is established in an MV network. The primary substation and four secondary substations are equipped with modern IEDs, and fiber optic connections are provided to each IED. A cloud service is set up to collect the IEC 61850 sampled values and GOOSE measurements from the network. A direct communication link from the site to the university's Smart Grid laboratory is also set up. The data collection facilities are used in various research activities.

At present SSG is facing challenges with the recently enacted requirements for Reactive Power Window (RPW) settled by the Finnish Transmission System Operator (TSO), Fingrid. RPW specifies the volume of reactive power that can be delivered to and received from the main grid without separate compensation. The output energy is calculated based on the hourly average (Q, P) for the previous 12 months. The fees are set to the points/situation that crosses the limits. A reactive power window for SSG that has been developed in [22] is presented in Fig 1. For this research, a whole year measurement data is available from SSG, and the situation is presented in Fig. 2.

B. Reactive power control

Reactive power management algorithm has been developed in [23] aiming to prevent the fees in SSG, and the paper presents the increasing fees estimated due to the increase in cabling during the years 2018, 2019 and 2020.

In this research, the reactive power window for future SSG [22] is utilized, and the reactive power control of SSG is implemented with the RPW algorithm for a 3.6 MW full-scale wind turbine (WT) converter. The outline of the simulation model is presented in Fig. 3. The RPW controller was developed further from the Simscape (phasor, continuous) model to the Simulink model fitting into the eMEGASIM real-time simulation platform.

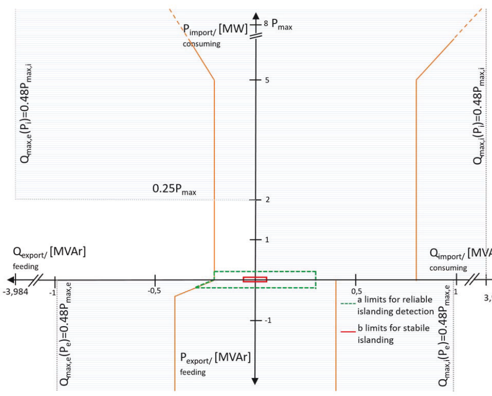

Fig. 1. Active and reactive power operation limits for future SSG. [22]

III. Development Process of the Real-time Co-Simulation Platform

The workflow of the development of the real-time con-simulation platform consisted of use case development, offline simulation model development, open-loop simulations, real-time model development and closed-loop simulations offline, IEC61850 communication implementation, the SIL tests as well as the CHIL tests. In the following, this development process is described in more details.

In the first phase, different use cases were developed about the evolving SSG for investigating the operation of the power system and validating it according to the measurements. After that, the RPW controller was developed. In the previous research [22] [23], the reactive power control has been implemented as an open-loop i.e. the first simulation results (control values) were the input to the second round and fed in to the RPW controller. This method was used because the direct closed-loop simulations did increase the simulation time greatly. The SSG and the controllers have been modeled in that case by Sismscape in phasor mode.

The results from the Simscape simulations showed the behavior of the power grid, which makes it possible to evaluate further the other interesting use cases for the real-time simulations. For the real-time modeling, particularly for the ePHASORSIM (the power system model) block, it was possible to import simulation models of the offline tools. The offline models were modeled and verified in PowerFactory and then converted to real-time models for ePHASORSIM simulation.

Based on Simscape results, the interesting use cases and the interesting moment of them (interesting hour) were selected to give the initial values of loads and generation as well as the voltage at the HV connection point for the PowerFactory model.

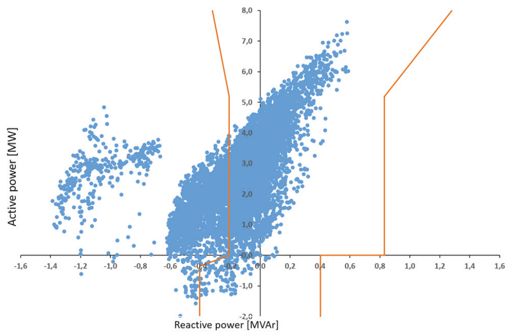

Fig. 2. Measured hourly active power as a function of measured reactive power in the TSO's reactive power window for the SSG.

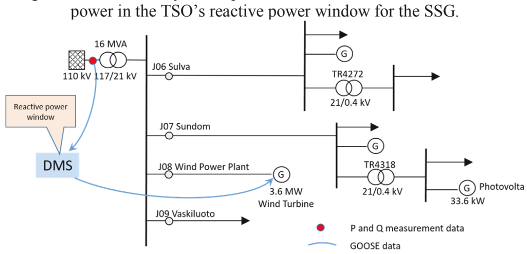

Fig. 3. Outline of the simulation model. [24]

A. Development of the real-time models

For the development of the real-time simulation model, the generated Excel file was imported into the ePHASORSIM block in the eMEGASIM model in OP5600 platform of OPAL-RT. The structure of the resulting model is outlined in Fig 4.

Further, the developed control algorithm, as well as the load (P_{load}) and the generation ($P_{generation}$) data from the Simscape blocks, were also imported to the eMEGASIM. After the real-time models for the basic cases Status 2018, Scenario 2028, as well as Scenario 2035, were built-up, the offline simulations by the real-time models were very efficiently performed for the one-year load flows compared to the Simscape simulations. For example simulating offline one year power flow (in phasor mode) of the basic case Status 2018 with processor Intel Xeon CPU E3-1505M v6 @ 3.00 GHz and installed RAM 32 GB took minimum 6 min (no scopes, no data to workbench) and maximum 14 min (with scopes and data to workbench) to perform the simulation with Simscape (variable step), Matlab r2017a and about 30 s with ePHASORSIM, Matlab r2015a respectively. Fig. 5 and 6 present offline results of RPW in the case Status 2018 with Simscape and ePHASORSIM, respectively. It can be noticed that the results of the offline simulations by the real-time models were consistent with the results from Simscape and hence to PowerFactory results.

Next, after the real-time models of the basic network structures were built up and working well, the RPW controller was tuned for the closed-loop simulations. The offline simulations were carried out after the controller was found to be working well. The closed-loop offline simulations for Scenario 2018 (RPW control) with ePHASORSIM, based on Matlab r2017a took about 6 min when several scopes, data to the workbench and average calculation blocks were applied, while Simscape open-loop simulations took 15 min + 15 min as previously explained. Further, when the real-time models were running well in offline mode, it was time to run the models in real-time. The results were consistent with the offline simulation results.

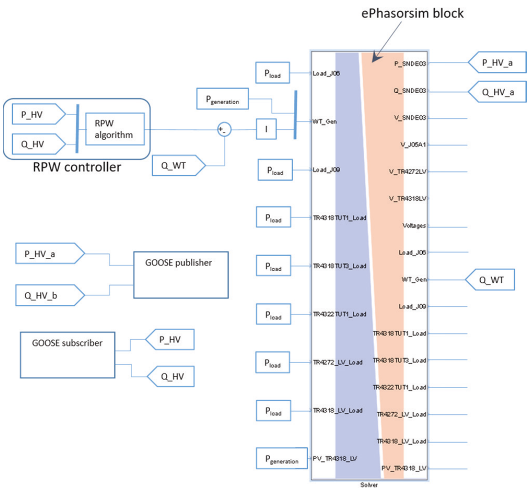

Fig. 4. The simulation architecture in SM_block for SIL of reactive power control in SSG Status 2018. [24]

After the real-time models were running well, the implementation of the communications to the real-time model for the SIL and the CHIL tests was the next phase. The IEC61850 GOOSE was implemented for sending the active power and reactive power measurement values (P_{meas}, Q_{meas}) from the point of interconnection to the RPW controller. This real-time co-simulation platform is presented in Fig. 7. Fig. 4 shows the GOOSE publisher block that was implemented in the real-time model for publishing (sending) the P and Q values from the target (OP5600 simulator), as well as the GOOSE subscriber block that was implemented for subscribing (receiving) the P and Q values from the Ethernet network.

In SIL case, the GOOSE publisher, as well as the subscriber block, were inside the model. For the publisher and the subscriber GOOSE blocks, one configuration file (*.icd) was developed by IEC 61850 ICD Designer tool that is a

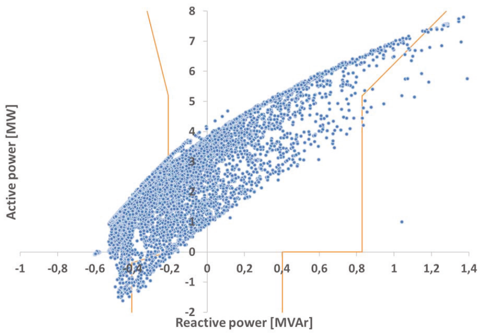

Fig. 5. RPW of the Status 2018 with Simscape.

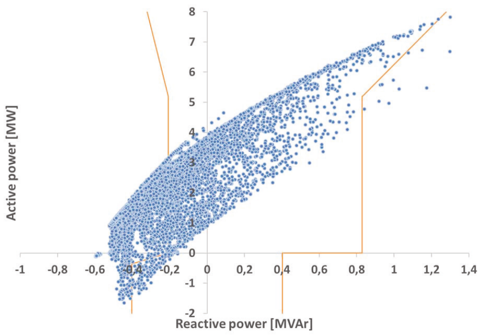

Fig. 6. RPW of the Status 2018 with ePHASORSIM.

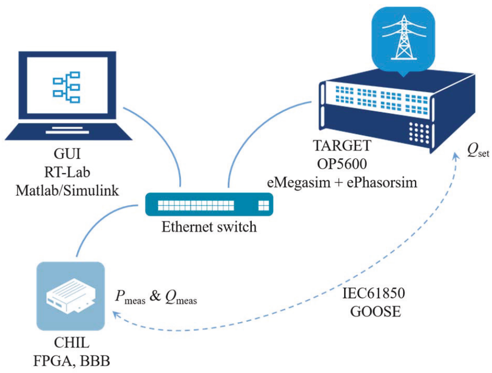

Fig. 7. The real-time co-simulation platform. [24]

software for configuring and modeling IEC 61850 clients and servers. The configuration file was created using a suitable set of Logical Devices (LDs) and Logical Nodes (LNs).

B. Implementation of the developed RPW control algorithm in controller hardware

Further, for the CHIL simulations, the Substation Configuration Description (SCD) file was developed and further adapted into two different hardware, namely to the BeagleBone Black (BBB) and the Field Programmable Gate Array (FPGA). The following paragraphs present implementation phases of the control algorithm to the hardware, where the developed C++ code included the RPW control algorithm, the GOOSE publisher and subscriber.

A "lightweight" implementation of IEC 61850-8-1 (mapping the IED data to GOOSE) that was done offered a practical approach for the CHIL by using the open-source library "libiec61850". Furthermore, the designed controller generated by this process can communicate with other IEC 61850 IEDs. The developed controller is flexible, and the files from the project C code can be generated from any valid SCD file. The generated C code files define the internal data model of an IED. This approach maximizes runtime performance and facilitates the use of relatively low-cost embedded devices and FPGA.

The procedure for designing the "lightweight" controller is presented in Fig. 8. In this study, the first step was designing an SCD (.icd) file that included the Logical Node (LN), data object (DO), and Data Attribute (DA) types as well as communication instances of the model.

For the second step, a C code representation of a model and their communication instances that are tailored to this model was automatically generated from the designed SCD file by the "libiec61850 model generator". According to the "model generator" process, each type of IED data model can be mapped directly to a C data structure, resulting in a hierarchy of C data structures. Besides, the generated C files must be accompanied by the platform-specific code to ensure consistency with IEC 61850.

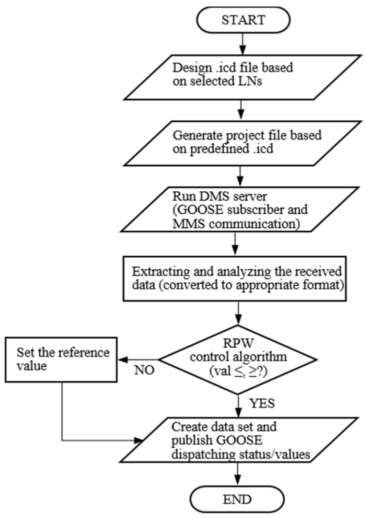

Fig. 8. The developed DMS internal processing. Applied from [25].

The third step was to define the parameters that are needed to be subscribed (in this case P_{meas} and Q_{meas}). Then to compile the design project file (or application file) to generate the execution file for running the project in the hardware under test.

The fourth step was about extracting the defined parameters (in this case P_{meas} and Q_{meas}) from the subscribing GOOSE message from the model. Next step describes the execution of the control algorithm in the hardware and based on the result, the new setpoint value (in this case Q_{set}) is published from the hardware under test back to the target (simulation model) via GOOSE.

The project was tested by the Advanced RISC Machines (ARM) processor-based microcontroller BBB as well as by the ARM processor-based SoC FPGA where both processor and FPGA architectures are integrated into a single device. Both are compatible with C and C++ compilers.

IV. Executed Tests and Experiments

For the real-time SIL and CHIL simulations, the simulation time step (T_s) was 0.01 s. The time factor (T_d) for reading data row from the input data (1 h average values) or the look-up table was set 0.1 s hence corresponding one-hour data. The data gathered to the real-time target were P_{HVavg}, Q_{HVavg}, P_{HV}, Q_{HV}, P_{WT}, Q_{WT} and the voltages 110 kV, 21 kV and 400 V. The CHIL tests were performed for the BBB as well as for the FPGA controller. From the IEC 61850 GOOSE messages, the packets traveling over the network were captured by Wireshark software that created .pcap files from the traffic between the controller in the test and the target.

A. Scenario 2018 with RPW control in SIL

In this case, Q_{set} for the RPW controller was according to the TSO limits ± 50 kVAr, except QD_1 = -200 kVAr. The reactive power of the WT converter is presented in Fig. 9 showing both the SIL offline and the real-time results.

When comparing the real-time results with the offline simulations, it can be noticed that there are slight differences in the controlled values. This is because of the delay from the communications that is obvious with real connections. The T_d factor was set tight to show the characteristics of the different hardware. However, in this study, one simulation step (10 ms) delay would represent 360 s delay in the real world.

B. Scenario 2018 with RPW control in CHIL

The comparison in Scenario 2018 was made between SIL real-time simulations, BBB, and FPGA. Fig. 10 presents the reactive power flow from the WT converter when T_d = 0.1. The comparison is made between SIL and BBB, between SIL and FPGA as well as between BBB and FPGA. In every case, differences can be noticed. This happened due to the different processing times of the hardware, which effect is presented in more detail in Fig. 11. After the first simulated hour, it can be noticed that the Q_{WT} have different values. The SIL controller calculates a new set value for the WT converter in every 10 ms (at the same time with the simulation time step) for the controller. The CHIL controller, in turn, calculates a new set point that is delayed with the round trip time, i.e. communication delays in Ethernet and processor calculation time step. This is analyzed in detail in section V.

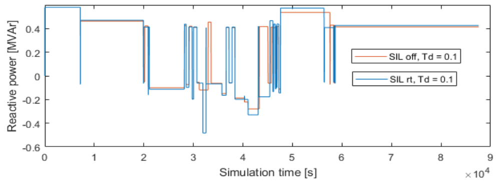

Fig. 9. SIL offline and SIL real-time simulation of the Scenario 2018. Reactive power of WT when $T_d = 0.1$. The RPW controller was set up to the TSO limits ± 50 kVAr, except QD_1 = 200 kVAr.

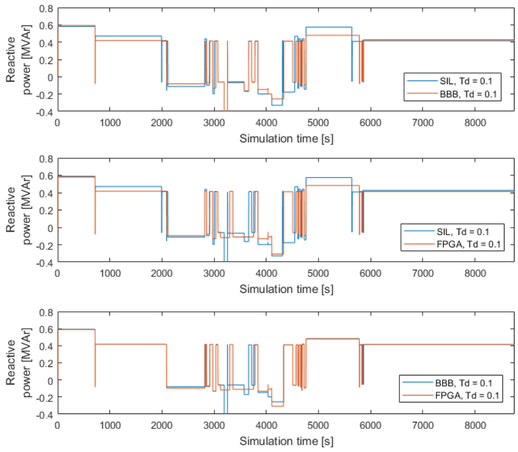

Fig. 10. Comparison of SIL real-time and CHIL test results in Scenario 2018/2. Reactive power of WT when $T_d = 0.1$. The RPW controller was set up to the TSO limits ± 50 kVAr, except QD_1 = 200 kVAr.

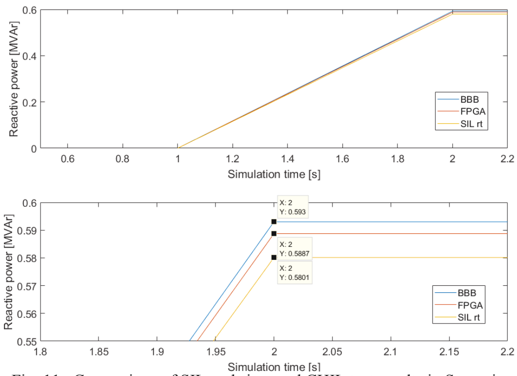

Fig. 11. Comparison of SIL real-time and CHIL test results in Scenario 2018. Reactive power of the WT.

V. THE ROUND TRIP GOOSE LATENCY

The round trip GOOSE latency was calculated for the overall completed tests. The main objective within this measuring task was to verify that the performance of the Device Under Test (DUT) for the publishing of the GOOSE messages was compliant with the IEC 61850 (not exceed 4ms). Moreover, to verify that the DUT had the ability to operate within the multi-vendor environment ensuring the interoperability concept.

For comparison of the round trip time of different devices, the instantaneous GOOSE round trip latency was measured for the tested lightweight IEDs. The GOOSE round trip

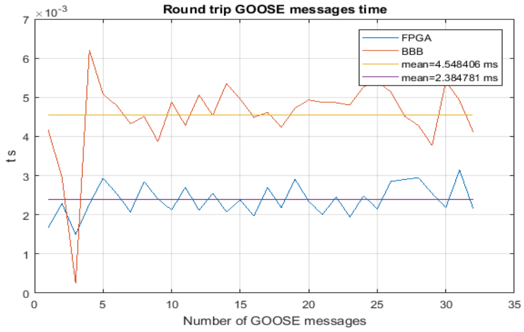

Fig. 12. The round trip GOOSE latency of BBB and FPGA.

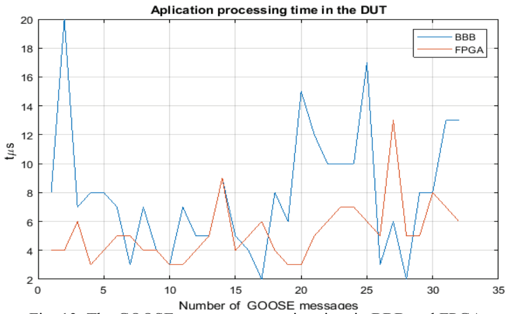

Fig. 13. The GOOSE message processing time in BBB and FPGA.

latency time includes seven individual times that may affect the connection channel performance as illustrated in (1). It starts from the real-time model running in the target that publishes GOOSE messages (Q_{HV} and P_{HV}), next there is the DUT that subscribes the message, computes the Q_{set} based on the RPW algorithm and then periodically publishes a GOOSE message containing magnitude Q_{set} for the simulated WT converter. This process was monitored by using a network protocol analyzer, Wireshark.

$$\bar{t}_{RTT} = \bar{t}_{out,Target} + \bar{t}_{net} + \bar{t}_{in,DUT} + \bar{t}_{app} + \bar{t}_{out,DUT} + \bar{t}_{net} + \bar{t}_{in,Target} \quad (1)$$

where

$\bar{t}_{RTT}$ the average round trip time,
$\bar{t}_{out,Target}$ the average time out from the target (client IED),
$\bar{t}_{net}$ the average time in Ethernet network,
$\bar{t}_{in,DUT}$ the average time in to the DUT,
$\bar{t}_{app}$ the application average time running on the DUT,
$\bar{t}_{out,DUT}$ the average time out from the DUT,
$\bar{t}_{out,Target}$ the average time in to the target

Fig. 12 presents the round trip GOOSE latency for the BBB and the FPGA. Average round trip latency calculation based on (1) was 4.548406 ms for BBB and 2.384781 ms for FPGA. Based on the results, it is clear that the FPGA is a more promising instrument with less round trip latency (2.3 ms) that could be used for the smart grid or microgrid central controller. It was expected that the round trip latency would be less for the FPGA since it has Dual-Core ARM Cortex™-

A9 (925 MHz) processor as well as 10/100/1000 Mbps Ethernet with the high-speed bus to exchange data between the hard processor system (HPS) and FPGA whereas the BBB has AM335x 1GHz ARM® Cortex-A8, and 10/100 Mbps Ethernet. Fig. 13 presents the GOOSE messages processing time in both devices.

VI. Conclusion

In this paper, the performance of the reactive power control scheme developed on a light weighted intelligent electronic device has been investigated. The control solution and its relevant communication system have been designed based on IEC 61850 and implemented on two hardware platforms, FPGA and BBB. The performance of the IEDs has been evaluated through Controller-hardware-in-the-loop versus software-in-the-loop test in terms of communication latency, processing time, and finally, the performance of control action. The FPGA has performed better compared to BeagleBonBlack and is more suitable for a micro-grid central controller. It is worthwhile to mention that such an open-source flexible light-weighted IED based on IEC 61850 can provide a base to advance research in the direction of (Micro)-grid automation and control.

Acknowledgment

This simulation study has been performed using the ERIGrid Research Infrastructure and is part of a project that has received funding from the European Union’s Horizon 2020 Research and Innovation Programme under the Grant Agreement No. 654113. The support of the European Research Infrastructure ERIGrid and its partner OFFIS e.V. is very much appreciated.

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Hindawi
Journal of Electrical and Computer Engineering
Volume 2020, Article ID 8265373, 17 pages
https://doi.org/10.1155/2020/8265373

Research Article

Accelerated Real-Time Simulations for Testing a Reactive Power Flow Controller in Long-Term Case Studies

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Received 14 February 2020; Accepted 13 May 2020; Published 5 June 2020

Academic Editor: Yang Li

This paper presents the development of an accelerated real-time cosimulation and testing platform, especially for long-term simulations of power systems. The platform is planned to be utilized in the development and testing of active network management functions for microgrids and smart grids. Long-term simulations are needed in order to study, for example, the potential weekly, monthly, or yearly usage of distribution-network-connected distributed energy resources for different technical flexibility services. In order to test new algorithms in long-term study cases, real-time simulations or hardware-in-the-loop tests should be accelerated. This paper analyzes the possibilities and challenges of accelerated long-term simulations in studying the potential use of a large-scale wind turbine for reactive power flow control between distribution system operator (DSO) and transmission system operator (TSO) networks. To this end, the reactive power flow control is studied for different voltage levels (HV and MV) in the Sundom Smart Grid in Vaasa, Finland. The control of reactive power flow between HV and MV networks is realized with a reactive power window control algorithm for a 3.6 MW MV-network-connected wind turbine with a full-scale power converter. The behaviour of the reactive power controller during long-term simulations is studied by offline and real-time simulations. Moreover, the real-time simulations are performed with both software-in-the-loop and controller-hardware-in-the-loop.

1. Introduction

Utilization of the distribution-network-connected distributed energy resources (DER), that is, flexibilities, is becoming increasingly important for improving local and system-wide grid resiliency and for providing the technical flexibility services needed by DSOs and TSOs. Flexibilities consist of active (P) and reactive (Q) power control of flexible resources, such as controllable distributed generation (DG) units, energy storages (ESs), controllable loads, and electric vehicles (EVs), which are connected in DSO grids. The flexibility services from DER for DSOs and TSOs can, for example, be realized as part of active network management (ANM) functions for grid-connected microgrids.

Currently, the standards for microgrids, especially IEEE and IEC, for control and management are under development, and only a few standards for microgrids have been published so far [1–10]. However, for the development of microgrid control and management functions, different simulation studies and tests have been performed [11, 12]. Different kinds of vendor-defined microgrid controllers have already been developed and tested [13], but there is a lack of standardized tests for microgrid control [14]. One of the challenges with vendor-defined solutions is that they might not meet interoperability and grid-code requirements. Figure 1 presents the traditional impact of standardization on product development, illustrating the product's lifetime cycle and standardization phases [15]. Because of the phase of the standardization, it can be concluded that microgrid controllers are in the stage of "need for product standards to resolve issues." Despite this standardization situation, the different solutions for microgrid management are becoming increasingly global.

However, the software upgradability of new products becomes more important as requirements (e.g., grid codes and standards) change. Standardization takes more time as products and solutions become more complex, while at the same time, technology development goes faster, and the need for new solutions becomes faster. Start-ups in particular will probably not wait for the final standards. Therefore, many standards could be obsolete when they are released and require an immediate upgrade process.

The standardization of microgrid control systems is intended to define the requirements for microgrids "regardless of topology, configuration or jurisdiction and to present the control approaches required from the distribution system operator and the microgrid operator" [1]. The IEEE Standard 2030.7 defines the functions that a microgrid control system must perform, and the IEEE Standard 2030.8 presents the testing procedures for adopting the functional specification of microgrid control systems. According to [1], a microgrid control system is defined as "a system that includes the control functions that define the microgrid as a system that can manage itself, operate autonomously, and connect to and disconnect from the main distribution grid for the exchange of power and the supply of ancillary services; it includes the functions of the Microgrid Energy Management System (MEMS); it is the microgrid controller if implemented in the form of a centralized system" [1, 2].

One requirement for microgrid controller functions is to provide flexibility services like ancillary services (AS) [1], which can be realized with a technical or market-based approach. Technical AS are related to, for example, the control of reactive power (Q) flow between the DSO's and the TSO's networks. The testing approach of microgrid controllers should include definitions for the test scenarios, the performance metrics, and the testing environment, which can range from a fully simulated environment to real equipment installed in the field [2, 16]. Figure 2 presents the coverage and fidelity of the different testing methods [17, 18]. Pure simulation is utilized in the research stage and in a very early stage of product development. In controller-hardware-in-the-loop (CHIL) simulations, the controller is a real device, but everything else is simulated. In power-hardware-in-the-loop (PHIL) simulations, there are real power devices (e.g., photovoltaic units, loads, and storage) in addition to the controller.

Consequently, it is essential to build comprehensive test platforms for microgrid controllers that can perform the CHIL and PHIL simulations and the tests for different types of required functionalities [1, 2] to verify the proper operation of the functions of the developed microgrid controller. Besides, the test platform should be flexible so that it can serve different kinds of microgrids [4] with the purpose of

(i) Improving electricity supply reliability and network resilience by intentional islanding

(ii) Providing power to remote areas with lower cost

(iii) Reducing the energy cost for microgrid users in grid-connected mode

(iv) Providing preparedness for disasters

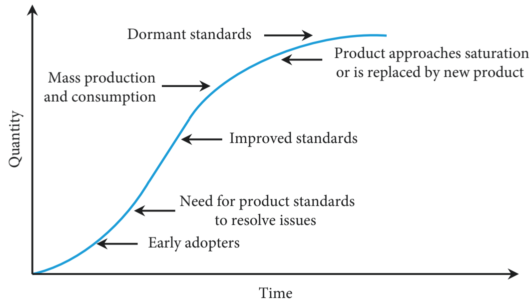


Figure 1: Product sales and standards cycle [15].

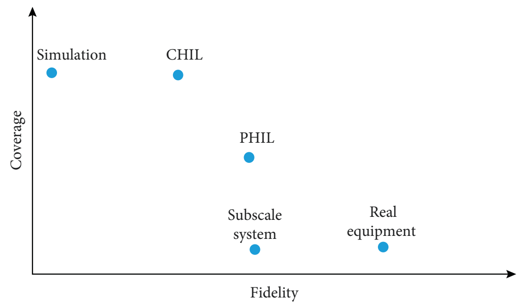


Figure 2: The coverage and fidelity of the different testing methods. Adapted from [17].

In HIL simulations, the Hardware under Test (HuT) is connected to the simulated system running in the real-time simulator or target. The real connection has delays and affects the stability of the system that has to be respected. In CHIL simulations, the delay consists of the target input/output processing and communication time delay/latency as well as processing time of the controller [19]. The effect of the delay should be taken into account when tuning controller control parameters. Further, in PHIL simulations, the error is caused by delays and distortion introduced by the power interface. Moreover, the power amplifier between the power hardware and the target (the real-time simulator) may cause the system to be unstable. Therefore, it is essential to develop an interfacing algorithm between the target (simulated system) and the HuT. In addition to the previous ones, the utilized sample time of the real-time simulation has a major impact on the stability behaviour. [18, 20].

Based on the literature review on selected CHIL testbeds [21–24] and PHIL testbeds [25] suitable for microgrids, transition and dispatch function in power balance management and ancillary services are of great interest. The focus of [21–24] is on implementing control algorithms on hardware and stability issues. Long-term case studies in simulations are lacking. The authors in [22] present the results of a software controller for dynamic power-sharing with three PV units in islanded microgrid operation in which the PV generation profiles are represented in one-day historical data. The time scale was compressed into 14 min in real-time simulations, but analysis of the method and the effect of delays are not presented. New kinds of algorithms, computational techniques, or models could be developed for accelerating long-term simulations.

The focus in this paper is on developing an accelerated real-time cosimulation and a testing platform and setup, especially for long-term simulations. Furthermore, the aim is to test controller behaviour in the accelerated real-time simulations, in which the feasibility of the platform is evaluated. This kind of platform is novel; we did not come across any similar solution in the literature. The platform is planned to be utilized for the development and testing of microgrid controller ANM functions for microgrids in the grid-connected mode, particularly for long-term case studies. The long-term simulations are needed in order to study, for example, the potential weekly, monthly, or yearly usage and operation of distribution-network-connected DER for different technical flexibility services. The simulation setup developed consists of the real measurement data from the Sundom Smart Grid (SSG), a simulated power grid, communications, control functions, and a controller.

In the next section, *Sundom Smart Grid (SSG)*, the SSG, and the different requirements for the reactive power flow are presented. After that, the section "*The Real-Time Cosimulation Platform*" presents the developed real-time cosimulation platform. The different simulations, executed tests, and experiments with the developed platform are presented in the section "*Executed Tests and Experiments*." The final section is "*Conclusions and Discussion.*"

2. Sundom Smart Grid (SSG)

Figure 3 presents the SSG, which is a pilot of a local MV-network-based smart grid created in cooperation with ABB, Vaasan Sähköverkko (DSO), Elisa (communications), and the University of Vaasa [27]. The SSG enables the development of AS solutions for future grids beyond the traditional boundaries from the HV level to the LV level. In the SSG, there are four MV feeders, and one feeder (J08) is only for the wind turbine (WT). Real-time IEC 61850 generic object-oriented substation event (GOOSE) measurements and sampled value (SV) measurements are gathered online from all the four feeders at the HV/MV substation, as well as from three MV/LV substations with 20 measurement points. For future research purposes, the measurement data are collected in servers.

The different requirements for the reactive power flow between the MV and HV networks in the SSG studied, with several requirements and targets, are presented in [28]. In Europe, the European Network of Transmission System Operators for Electricity (ENTSO-E) sets grid-code requirements, for example, for connection of demand facilities and generators [29, 30]. Moreover, the national TSO has set requirements for the DSO's reactive power flow by a "reactive power window" [31] at the point of interconnection (POI), that is, between the TSO and DSO networks. The reactive power window (RPW) specifies the amount of reactive power that can be exported to the HV network and imported from the HV network without separate compensation. This RPW requirement and related compensation tariff aim to optimize the reactive power flow from the transmission network's point of view. In addition, reliable and future-proof islanding detection, as well as the possibility of making a stable transition to islanded operation, can be considered simultaneously with the reactive power flow control between HV and MV networks [26, 32–34].

Based on the results presented in [35], there would be an 80 k€ yearly cost for the DSO, caused by the capacitive reactive power flow generated by the cables in the SSG. In [36], the use cases and future scenarios for reactive power management are developed further to study and develop the RPW controller. The scenarios studied are Scenario 2018, Scenario 2028, and Scenario 2035.

3. The Real-Time Cosimulation Platform

The utilized real-time simulation platform is based on an OPAL-RT system consisting of power system simulations with ePHASORSIM (transient stability, phasor mode), as well as control and communications with eMEGASIM (electromagnetic transients, discrete type). Communication between the controller and the interfaces of the simulated power system is implemented with IEC 61850 GOOSE messages on Ethernet. Figure 4 presents an outline of the platform.

In previous researches [19, 36] for software-in-the-loop (SIL) simulations, a GOOSE publisher block is implemented in the real-time simulation model to publish (send) the measured active power (P_{meas}) and the measured reactive power (Q_{meas}) from the target (OP5600 simulator). Furthermore, a GOOSE subscriber block is implemented to subscribe (receive) the P_{meas} and Q_{meas} values from the Ethernet network. For the CHIL tests, a GOOSE subscriber and publisher are implemented in the hardware under testing, in addition to the RPW control algorithm. The implementation process is presented in [19], in which the simulation time step (T_s) is 0.01 s for the real-time SIL and CHIL simulations. The results gathered by the real-time target are the hourly average active and reactive powers (P_{HVavg} and Q_{HVavg}), the instantaneous active and reactive powers (P_{HV} and Q_{HV}), the active and reactive powers from WT (P_{WT} and Q_{WT}), and the bus voltages. The CHIL tests are performed for the BeagleBone Black (BBB) as well as for the field-programmable gate array (FPGA) controllers. The IEC 61850 GOOSE message packets traveling over the network are captured by Wireshark software (.pcap files) from the traffic between the controller and the target. The results in [19] show that FPGA controllers are more efficient for future microgrid controller studies.

4. Executed Tests and Experiments

In this research, the parameters for reliably performing the accelerated real-time simulations are defined and analyzed by testing the improved RPW control algorithm [36]. The offline SIL, real-time SIL, and CHIL tests are performed with the parameters defined in the platform developed in [19] in order to determine how the real-time simulations could be accelerated, what kind of phenomena can occur, and when

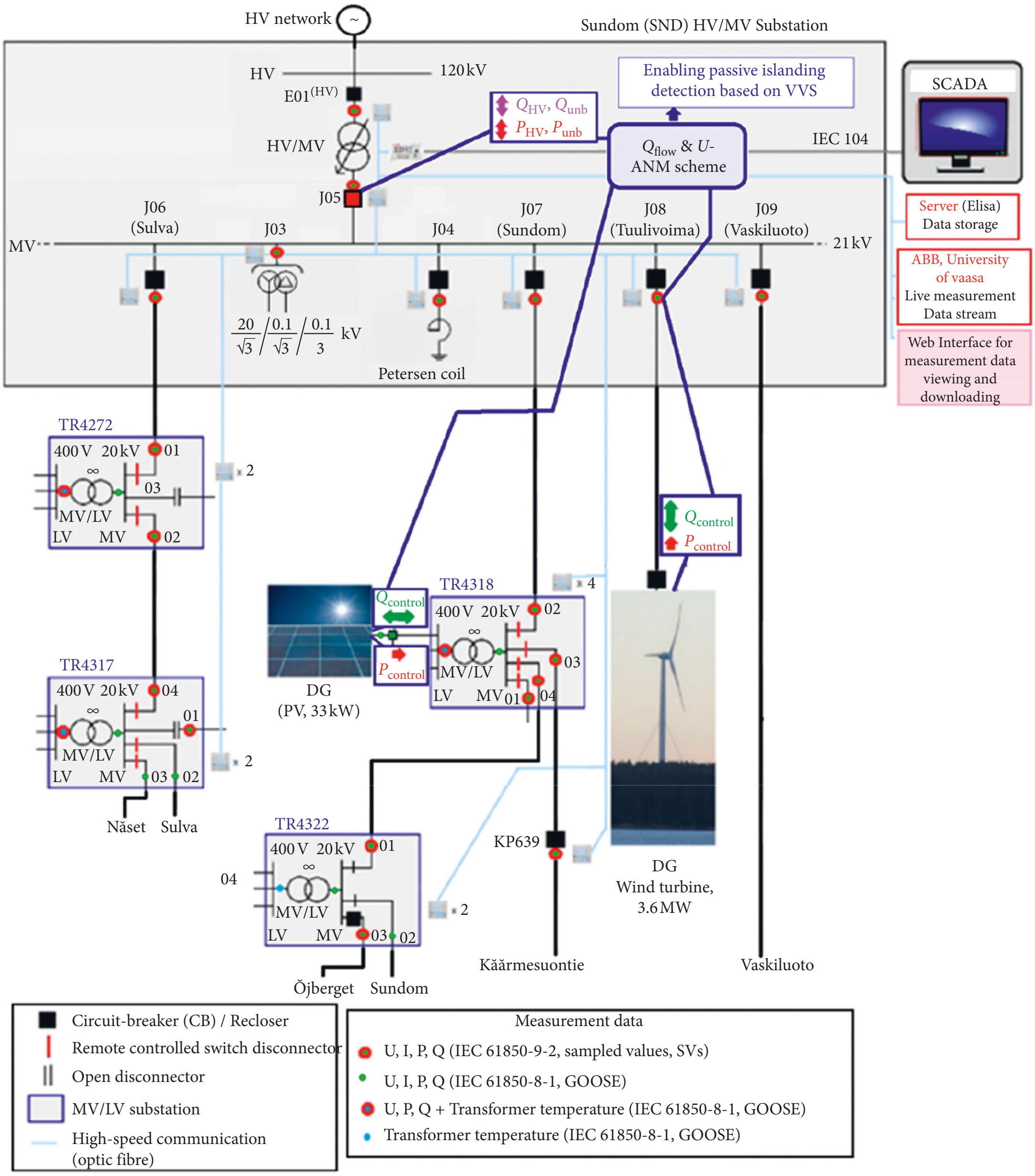


FIGURE 3: Sundom Smart Grid [26].

the results are reliable. The results from the real-time SIL and CHIL tests should correspond to the offline SIL results when there are no communication and hardware processor delays.

In this study, the simulations are performed with the controller limits set according to Figure 5. The limits for the controlled values are set ±50 kVAr tighter, except QD1 = Qi + 200 kVAr for the controller of the WT converter. In other words, the controller operation (a trigger for calculating a setpoint value for the WT converter) limits are the TSO limits (the red limits), but the setup limits for the WT converter are set tighter (the blue limits).

The offline SIL simulations, as well as the real-time SIL and CHIL tests, are presented below. In order to run long-term power flow simulations, for a one-year period, in this case, the simulations are accelerated by implementing the input-data-reading step from the

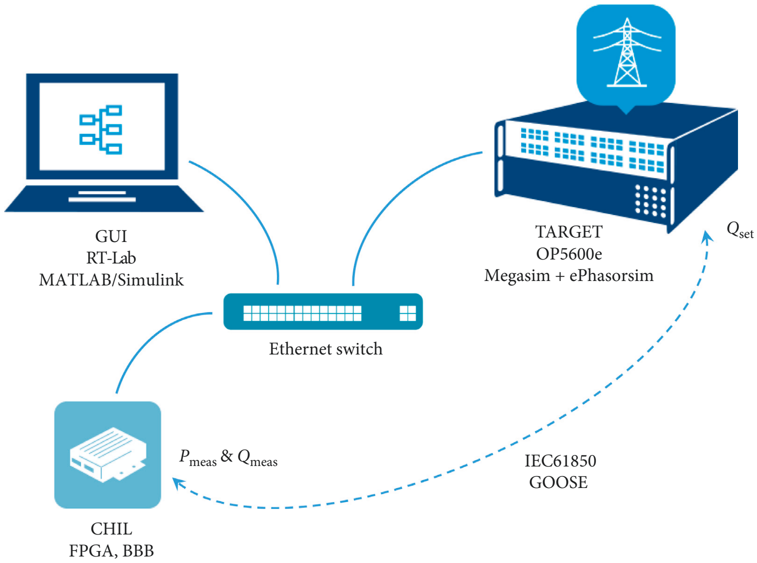


FIGURE 4: The real-time cosimulation platform [36].

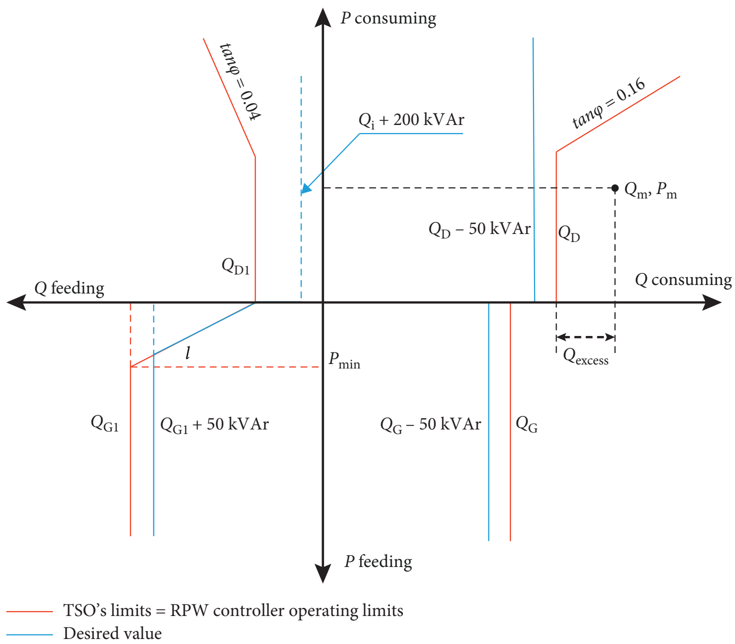


FIGURE 5: The setup for the controller limits.

OpFromFile block. This block reads from a Matlab file (.mat) and outputs the samples from the file. Further, the time factor, coefficient T_d, for reading a data row from the input data (in this case, the hourly average values over one year from the SSG) or the look-up table is set so as to correspond to the reading step of the one-hour input data. The aim of this study is to test different values for T_d to find a value that does not distort the results, that is, answering the question of how much the real-time simulations can be accelerated. For the one-year simulation, the hourly average values of the one-year measurements as input data generate 8760 rows of data, and the coefficient T_d is set accordingly to find the initial range for which the results are reliable.

Generally, the use of accelerated simulation would mean the modification of the models so that their behaviour in the accelerated time scale is equivalent to the behaviour in real-time scale. This means that the modified model is dimensionally similar. In this study, this kind of approach would have meant overly complicated modifications to the models, so another approach was used. Instead, the original time-scale-based models were used with a suitable selection of the simulation time steps so that the desired outcome was reached.

The cosimulation platform and the concept are presented in more detail in Figure 6. Different simulation time steps are also shown in Figure 6, where $T_s = 0.01$ s represents the simulation time step both for the simulated power system in ePHASORSIM and for the measurements, PI/I control, and so forth in eMEGASIM. Further, T_d represents the time step for the reading cycle of the input data (PQ_{load} and $PQ_{generation}$). T_c represents the time step for reactive power setpoint (Q_{set}) value calculation in the RPW controller.

The involved time steps and the limiting factors of the system are the following:

(1) Simulation time step T_s is the same for the SIL ($T_{s,m}$) and CHIL ($T_{s,p}$) setups: $T_{s,m} = T_{s,p} = T_s = 0.01\ s$.

(2) Data reading cycle T_d is the same for the SIL ($T_{d,m}$) and CHIL ($T_{d,p}$) setups.

The input data reading cycle has to be defined so that it enables maximum acceleration of the simulated system, while the results are not disrupted. The results can be proved with the equivalent results from offline SIL and real-time SIL as well as from the CHIL tests. In addition, the input data reading cycle based on the (measurement) data type has to be selected for real-time tests, so that reasonable computation times are achieved.

(3) RPW controller operating time step T_c in the SIL ($T_{c,m}$) and CHIL ($T_{c,p}$) setups.

$T_{c,m}$ for SIL controller can be selected as $T_{c,m} = n * T_s$, where n is an integer. Controller operating time step $T_{c,p}$ for CHIL controller depends on the processor of the hardware; FPGA has Dual-Core ARM Cortex™ A9 (925 MHz) processor, whereas the BBB has AM335 × 1 GHz ARM® Cortex-A8.

Both of these hardware controllers were fast enough, not limiting the accelerated CHIL tests in this case. Within one simulation time step, T_s, they were able to receive P_HV and Q_HV values, process the new setpoint value Q_{set}, and send it back to real-time simulator.

(4) I or PI controller operating time step: the I or PI controller operation depends on the defined sampling time for it. In this study, the sampling time is the same as the simulation time step T_s.

(5) Acceleration.

In this case, an input data (D_e) row represents the one-hour average value of active power, and the output values thus represent hourly averages. The data type could also be, for example, 10 min average (D_{10min}) or 5 min average (D_{10min}) keeping in mind that acceleration:

$$A = \frac{D_e}{T_d}. \quad (1)$$

The electricity network model is running in real time with $T_s = 0.01$ s, which is selected so that the transient phenomena have time to decay, and the system has reached steady state before new input data is read with time steps T_d of 0.1 s or more.

Table 1 presents the coefficients and the effects of their values. For example, in Option 1, selecting $T_d = 0.1$ means that a one-year accelerated real-time simulation will take 876 s (around 15 min) with one-hour average input data. Further, the simulation time step $T_s = 0.01$ s is equivalent to 360 s in real-world time, which means that the power flow of the system is known in intervals of 360 s. Option 29 ($T_d = 20$) presents the setup in which the power flow would be calculated every 1.8 s (representation of the real-world time). In this case, the accelerated real-time simulation would take 49 hours. The time step for the RPW controller action, T_c, could be selected in SIL, which is also presented. The selection of T_c mimics how often the RPW controller can calculate a new setpoint if desired, and T_s determines when the potential new setpoint value comes into effect for the WT converter. In the following sections, the evaluation of the suitable initial coefficients for accelerated real-time simulations is presented with the results from the offline simulations.

4.1. Offline SIL Tests. Several offline SIL tests are performed to define the initial coefficient T_d for the accelerated real-time simulations. The comparisons of the results between Option 1 and Option 6 ($T_d = 0.1$ and $T_d = 1$), as well as between Option 6 and Option 24 ($T_d = 1$ and $T_d = 10$), are presented in Figure 7. It can be seen that there is a difference between both comparisons due to the different T_d values, which means that the smaller values (0.1 and 1) are not suitable. For the next trial, the comparisons of the results between Option 14 and Option 24 ($T_d = 5$ and $T_d = 10$), as well as between Option 9 and Option 14 ($T_d = 4$ and $T_d = 5$), are made, and it can be observed that no difference exists between the results. The latter result indicates that a suitable initial T_d coefficient is ≥ 4.

By examining the results more closely, one can see that a difference in results emerges around 4000 h and later. Figure 8 shows that time point in more detail with different T_d values. When T_d is 0.1 or 1 and even when T_d is 5 or 10, Q_{WT} was "oscillating" in the time period between 4031 h and 4032 h. The oscillation form, that is, the amplitude of the oscillation, is increasing, which illustrates that the system is in an unstable region during that hour. Further, when T_d is smaller, the value of Q_{WT} after this oscillating hour is different. When $T_d = 0.1$, $Q_{WT} = -0.2213$ MVAr, and when $T_d = 1$, $Q_{WT} = -0.2305$ MVAr. These observations explain the difference in downstream results (after 4032 h). When T_d is 5

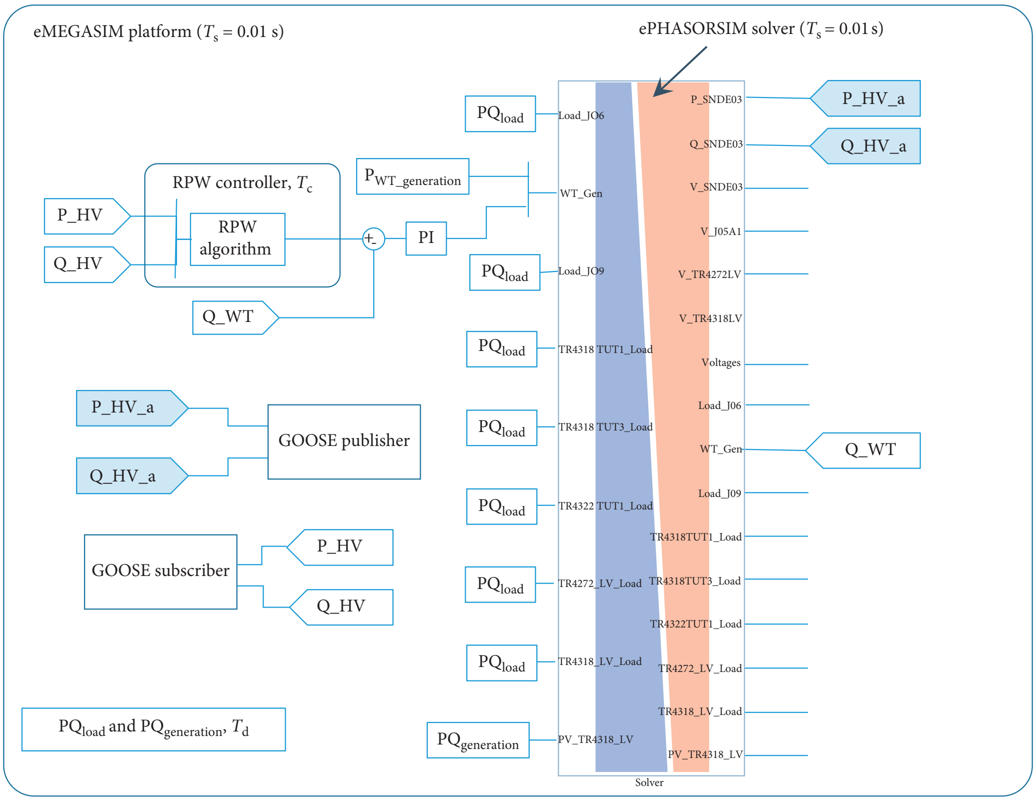


Figure 6: The emulated system and the RPW controller.

or 10, the oscillation also occurs, but now the resulting Q_{WT} is the same (−0.3103 MVAr).

This oscillation phenomenon is presented more closely in Figure 9. At $t = 403100$, the point (Q_{HV}, P_{HV}) is inside the window (0.7982 MVAr, 4.9824 MW), consuming active and reactive power, while the reactive power of the WT converter is capacitive, $Q_{WTset} = Q_{WTmeas} = -0.1869$ MVAr. In the next time step, $t = 403101$, the "measured" point (Q_{HV}, P_{HV}) is outside the window ($Q_{HV} = 0.9620$ $\text{MVAr}_{\text{ind.}}$, $P_{HV} = 5.399$ MW) (the limit is $Q_D = 0.83$ MVAr) when $Q_{WTmeas} = -0.1869$ MVAr. Then, a new setpoint of the WT converter is calculated, Q_{WTset} ($t = 403101$) = −0.1820 MVAr, which is realized by the control at the next time step, $t = 403102$. However, at that moment, Q_{WTset} is not high enough, and (Q_{HV}, P_{HV}) is outside the window (0.9994 MVAr, 5.4718 MW) again, while Q_{WTmeas} ($t = 403102$) = Q_{WTset} ($t = 403101$) = −0.1820 MVAr. This phenomenon occurs over a period of time, depending on the selected T_d.

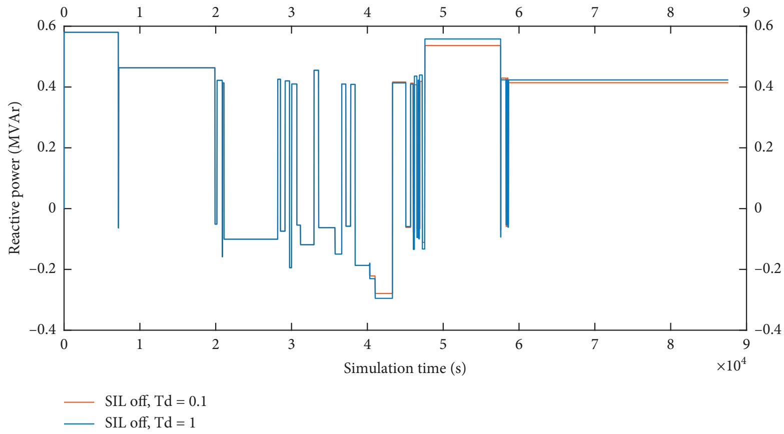
After all, a new setpoint aims to influence the reactive power Q_{HV} by correcting the output of the WT converter so that the next (Q_{HV}, P_{HV}) point will be inside the window. However, according to Figure 10, the RPW control is lagging a simulation step; that is, the new setpoint is calculated based on the last measurement of (Q_{HV} (t_{i-1}), P_{HV} (t_{i-1})). At this specific time, there is a possibility of having oscillations in the controlled system due to the delay of the control. This delay is dependent on two aspects: the selection of T_d as well as the delay of the I or PI controller. The I or PI controller was used to prevent algebraic loops in the modelled system.

Above we stated that the total oscillation time is dependent on T_d. The effect of T_d selection on the oscillation time is studied further in order to find a relationship. Figure 11 presents the results of the oscillation time in simulations with different values of T_d. Increasing the value of T_d seems to decrease the total oscillation time $\tau_{T_{d,i}}$. In addition, two other results are presented, one with an I controller and one with a PI controller. In both cases, $T_I = 99.5$ and $T_c = 0.01$ are used for the I controller. For comparison, a PI controller with $K_P = 1.2$ and $T_I = 99.5$, as well as $T_c = 0.02$, is investigated. The results are presented in Table 2. Based on both these results, with a suitable initial value (in this case, $T_d \geq 4$), it can be derived that the total oscillation time decreases linearly in the ratio

TABLE 1: Coefficients for accelerated real-time simulations.

Option	T_d (s)	Input data row equivalency in real-world time D_e (s)	Input data row equivalency in real-world time D_e (min)	Acceleration a (i.e., * times faster)	Number of data rows n	One-year accelerated real-time simulation time A_s (s)		Controller time step T_c (s)	T_c/Q_{WTset} equivalency: time rep. in real-world time (s)	Simulation time step T_s (s)	T_s equivalency: time rep. in real-world time (s)
1	0,1	3600	60	36000	8760	876	» 15 min	0,01	360	0,01	360
2	0,1	600	10	6000	52560	5256	» 9 h	0,01	60	0,01	60
3	0,1	300	5	3000	105120	10512	» 35 h	0,01	30	0,01	30
4	0,1	3600	60	36000	8760	876	» 15 min	0,1	3600	0,01	360
5	0,1	3600	60	36000	8760	876	» 15 min	1	36000	0,01	360
6	1	3600	60	3600	8760	8760	» 2,5 h	0,01	36	0,01	36
7	1	600	10	600	52560	52560	» 88 h	0,01	6	0,01	6
8	1	300	5	300	105120	105120	» 350 h	0,01	3	0,01	3
9	4	3600	60	900	8760	35040	» 10 h	0,01	9	0,01	9
10	4	600	10	150	52560	210240	» 350 h	0,01	1,5	0,01	1,5
11	4	300	5	75	105120	420480	» 1400 h	0,01	0,75	0,01	0,75
12	4	3600	60	900	8760	35040	» 10 h	0,1	90	0,01	9
13	4	3600	60	900	8760	35040	» 10 h	1	900	0,01	9
14	5	3600	60	720	8760	43800	» 12 h	0,01	7,2	0,01	7,2
15	5	600	10	120	52560	262800	» 438 h	0,01	1,2	0,01	1,2
16	5	300	5	60	105120	525600	» 1752 h	0,01	0,6	0,01	0,6
17	5	3600	60	720	8760	43800	» 12 h	0,1	72	0,01	7,2
18	5	3600	60	720	8760	43800	» 12 h	1	720	0,01	7,2
19	**7**	**3600**	**60**	**514**	**8760**	**61320**	**» 17 h**	**0,01**	**5,1**	**0,01**	**5,1**
20	7	600	10	86	52560	367920	» 613 h	0,01	0,9	0,01	0,9
21	7	300	5	43	105120	735840	» 2453 h	0,01	0,4	0,01	0,4
22	7	3600	60	514	8760	61320	» 17 h	0,1	51,4	0,01	5,1
23	7	3600	60	514	8760	61320	» 17 h	1	514,3	0,01	5,1
24	10	3600	60	360	8760	87600	» 24,5 h	0,01	3,6	0,01	3,6
25	10	600	10	60	52560	525600	» 876 h	0,01	0,6	0,01	0,6
26	10	300	5	30	105120	1051200	» 3504 h	0,01	0,3	0,01	0,3
27	10	3600	60	360	8760	87600	» 24,5 h	0,1	36	0,01	3,6
28	10	3600	60	360	8760	87600	» 24,5 h	1	360	0,01	3,6
29	20	3600	60	180	8760	175200	» 49 h	0,01	1,8	0,01	1,8
30	40	3600	60	90	8760	350400	» 97 h	0,01	0,9	0,01	0,9
31	80	3600	60	45	8760	700800	» 195 h	0,01	0,45	0,01	0,45

The total number of data rows is 8760, with a data-row equivalency in real-world time of 3600 s. ₁ equivalency: time representation in real-world time.



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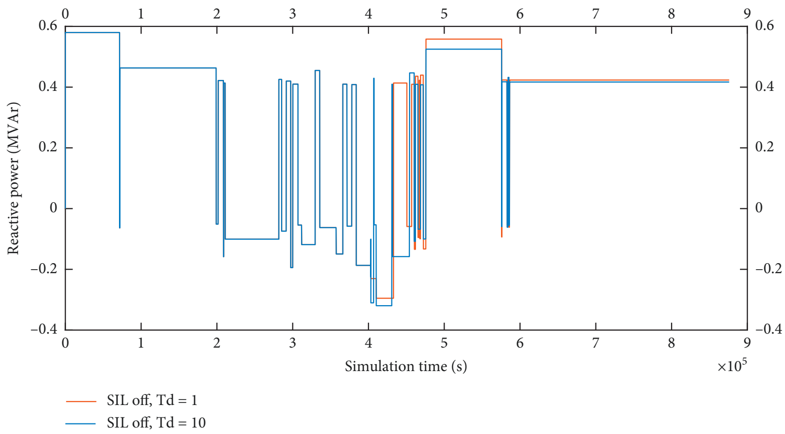

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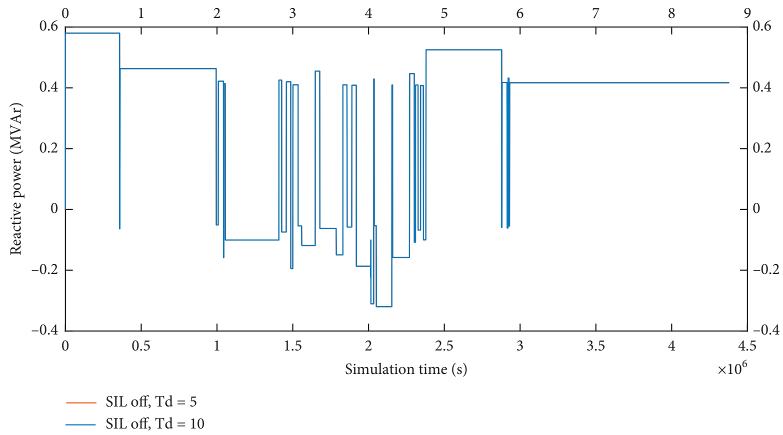
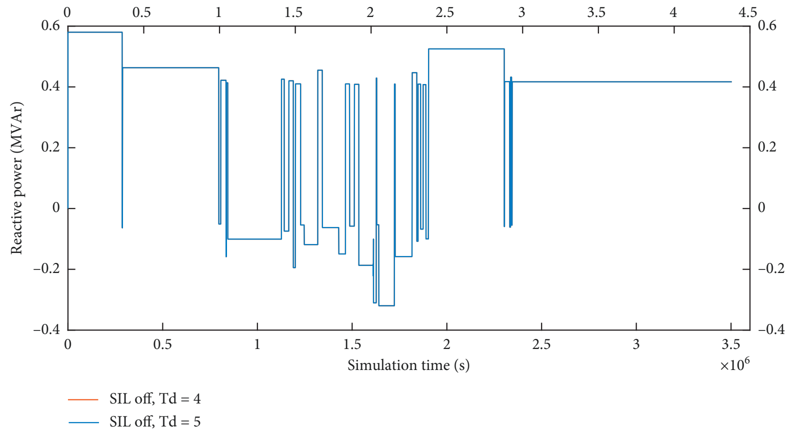


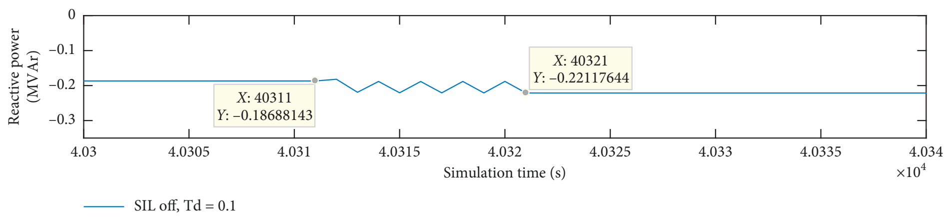
(c)

FIGURE 7: Continued.

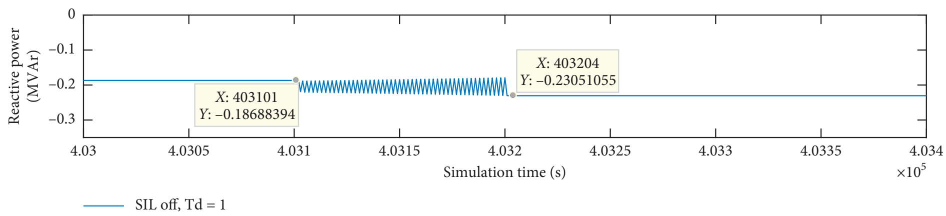


(d)

FIGURE 7: Results of the offline SIL simulations. Comparison of the reactive power of the WT converter when $T_d = 0.1$ or 1, $T_d = 1$ or 10, $T_d = 5$ or 10, and $T_d = 4$ or 5.



(a)



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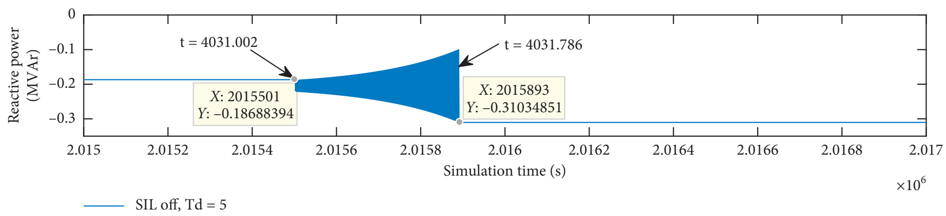

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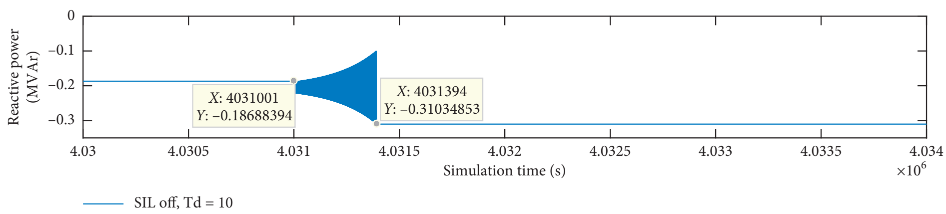


(d)

FIGURE 8: Results of the offline SIL simulations. Reactive power of the WT converter when Td was 1, 0.1, 5, or 10. The possible "oscillation" moment.

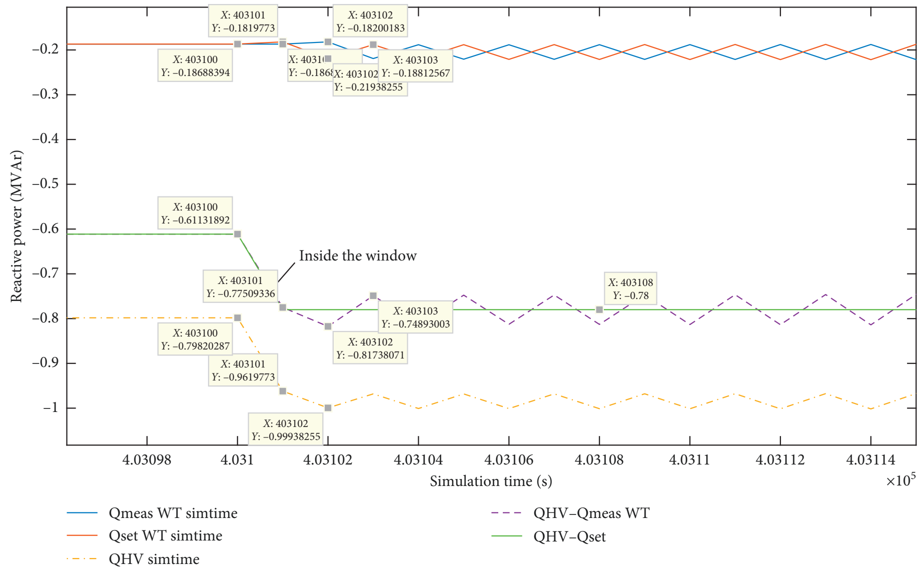


Figure 9: Oscillation investigation when $T_d = 1$.

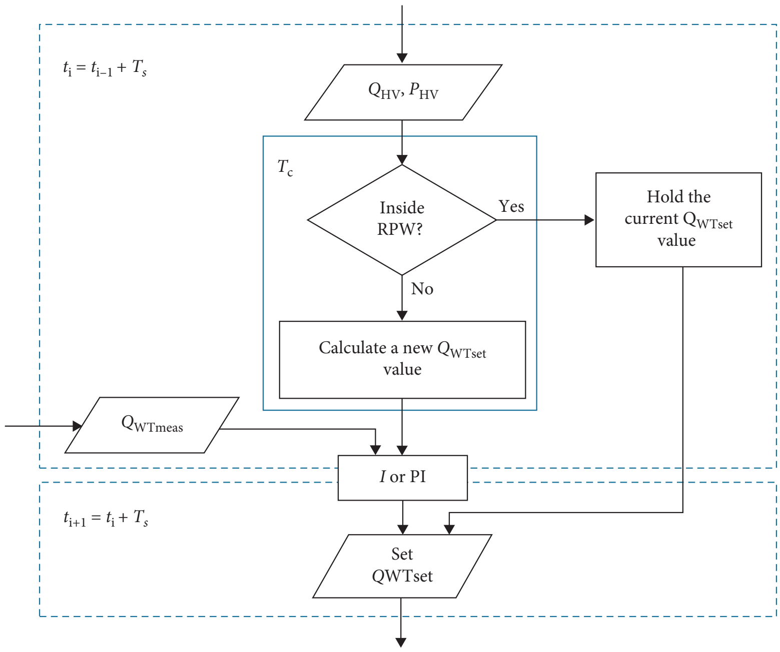


Figure 10: Flow chart of the RPW controller.

$$\tau_{T_{d,i}} = \frac{1}{T_{d,i}} \tau. \tag{2}$$

Based on equation (2), the oscillation time in real-world time would be 1.3 s in the I-controller case and 3 ms in the PI-controller case.

The above oscillation phenomenon occurs in accelerated simulations. However, it was found that the duration of the oscillation decreases when T_d increases or becomes closer to real time. The evaluation of how the P and I parameters depend on the accelerated real-time simulation could be a future research topic.

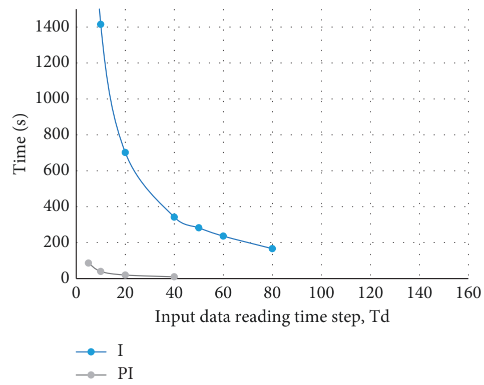
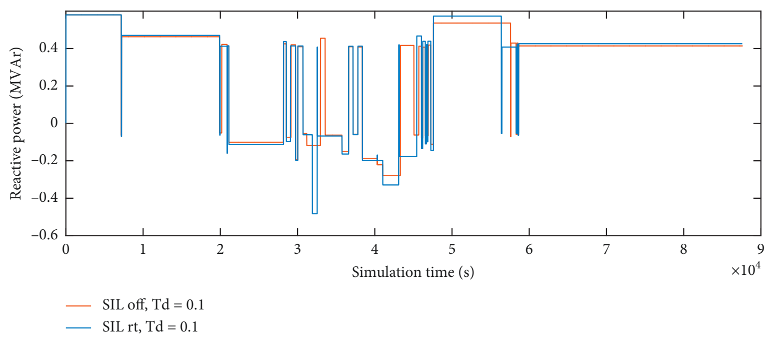


FIGURE 11: Duration of oscillation.

TABLE 2: Oscillation duration.

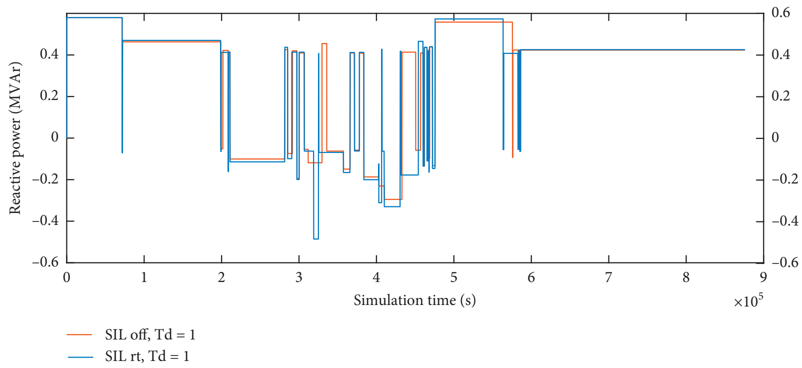
T_d	Oscillation duration [s]: case $T_c = 0.01$, $I = 99.5$	Oscillation duration [s]: case $T_c = 0.02$, $P = 1.2$, $I = 99.5$
0,1	3600	
1	3708	
5	2822,4	86,4
10	1414,8	39,6
20	702	19,8
40	342	*9,9**
50	282,888	
60	236,4	
80	166,5	4,95*
160	*83,25**	*2,475**
320	*41,625**	*1,2375**
640	*20,8125**	*0,61875**
1280	*10,40625**	*0,309375**
2560	*5,203125**	*0,1546875**
5120	*2,6015625**	*0,07734375**
8760	*1,30078125**	*0,038671875**

*Calculated values.



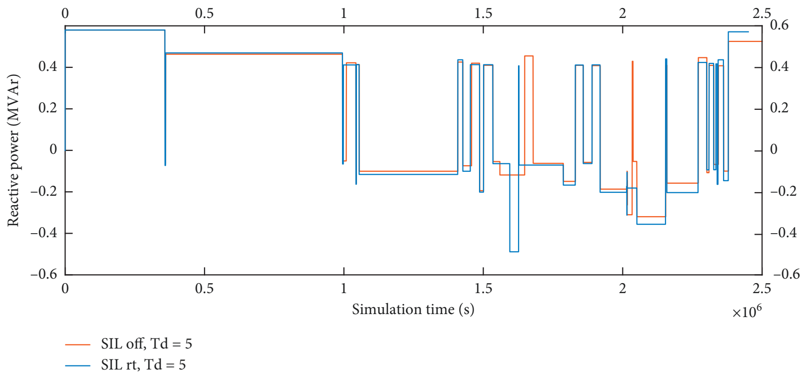
(a)

FIGURE 12: Continued.



(b)

FIGURE 12: Results from the offline SIL and real-time SIL simulations. Reactive power flow of the WT converter when $T_d = 0.1$ and 1. The RPW controller was set up to the TSO limits of ±50 kVAr, except $QD_1 = Q_i + 200$ kVAr.



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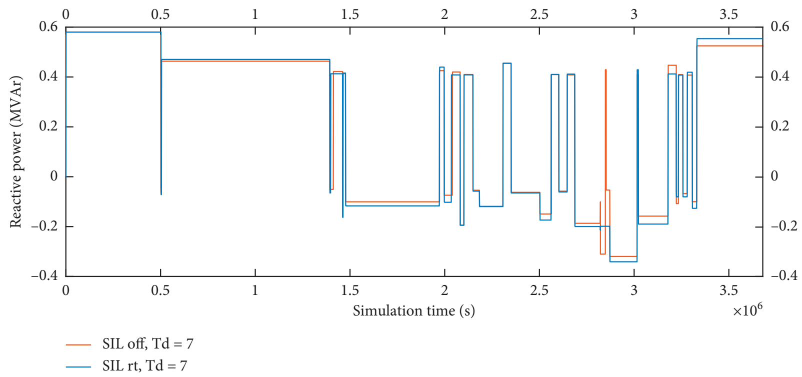

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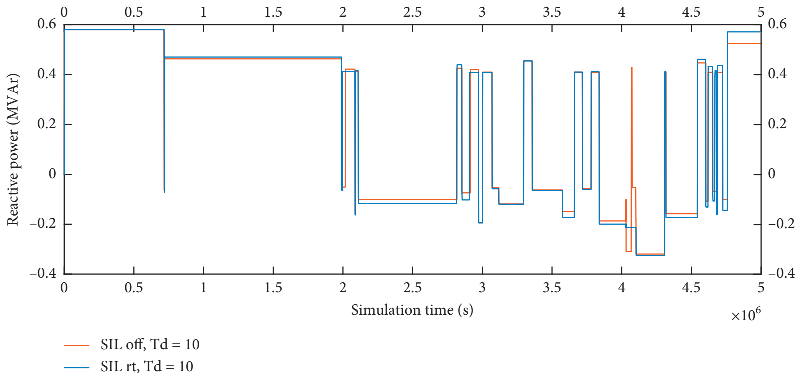
FIGURE 13: Continued.



(c)

Figure 13: Results of the offline SIL and real-time SIL simulations. Reactive power flow of the WT converter when $T_d = 5$, $T_d = 7$, and $T_d = 10$. The RPW controller was set up to the TSO limits of ±50 kVAr, except $QD_1 = Q_i + 200$ kVAr.

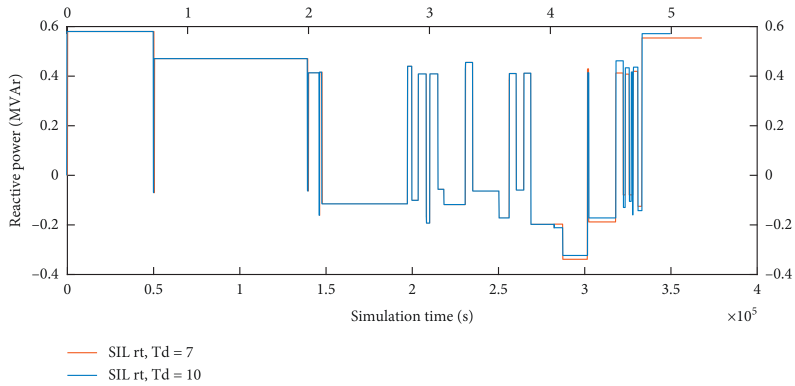


Figure 14: Results of the real-time SIL simulations. Reactive power flow of the WT converter when $T_d = 7$ and $T_d = 10$. The RPW controller was set up to the TSO limits of ±50 kVAr, except $QD_1 = Q_i + 200$ kVAr.

4.2. Real-Time SIL Tests. The first real-time SIL tests are performed with $T_d = 0.1$ and $T_d = 1$. The results are presented in Figure 12 by comparing them to the corresponding results of the offline SIL simulations. It can be observed that there are again small differences between both cases. This is due to the delay in communications.

Next, it is studied whether increasing T_d decreases the difference between offline SIL and real-time SIL results, that is, whether it can eliminate the effect of the communication delay. Based on the offline results, $T_d > 4$ could be a suitable value. The reactive power flows at the WT converter are presented in Figure 13 when $T_d = 5$, $T_d = 7$, and $T_d = 10$. It can be seen that the results of the offline SIL and real-time SIL simulations are different when $T_d = 0.1$, 1, 4, and 5, whereas the results look similar when $T_d = 7$ or 10. Based on the above, a suitable factor for real-time simulations could be $T_d \geq 7$. Figure 14 presents a comparison of the real-time simulation results when $T_d = 7$ and $T_d = 10$. It can be observed that now the results converge.

Further, the oscillating hour 4031 was investigated from a communication's point of view. Figure 15 presents the situation in which $T_d = 1$, $T_d = 5$, $T_d = 7$, and $T_d = 10$. Oscillations occur when $T_d = 1$ and $T_d = 5$ but not when T_d was 7 or 10.

4.3. CHIL Tests. The long-term CHIL tests were conducted with $T_d = 7$. Now, the coefficient T_c is dependent on the processor capacity of the hardware used. The hardware used for the CHIL tests is an FPGA that has a Dual-Core ARM Cortex™-A9 (925 MHz) processor, as well as 10/100/1000 Mbps Ethernet with a high-speed bus, to exchange data between the hard processor system (HPS) and the FPGA.

This scenario aims to compare the CHIL test results with the real-time SIL test results. The RPW controller is set up to the TSO limits of ±50 kVAr, except $QD_1 = Q_i + 200$ kVAr. Figure 16 presents the results from the tests with the FPGA against the real-time SIL test results when $T_d = 7$. It can be observed that the results are equal now.

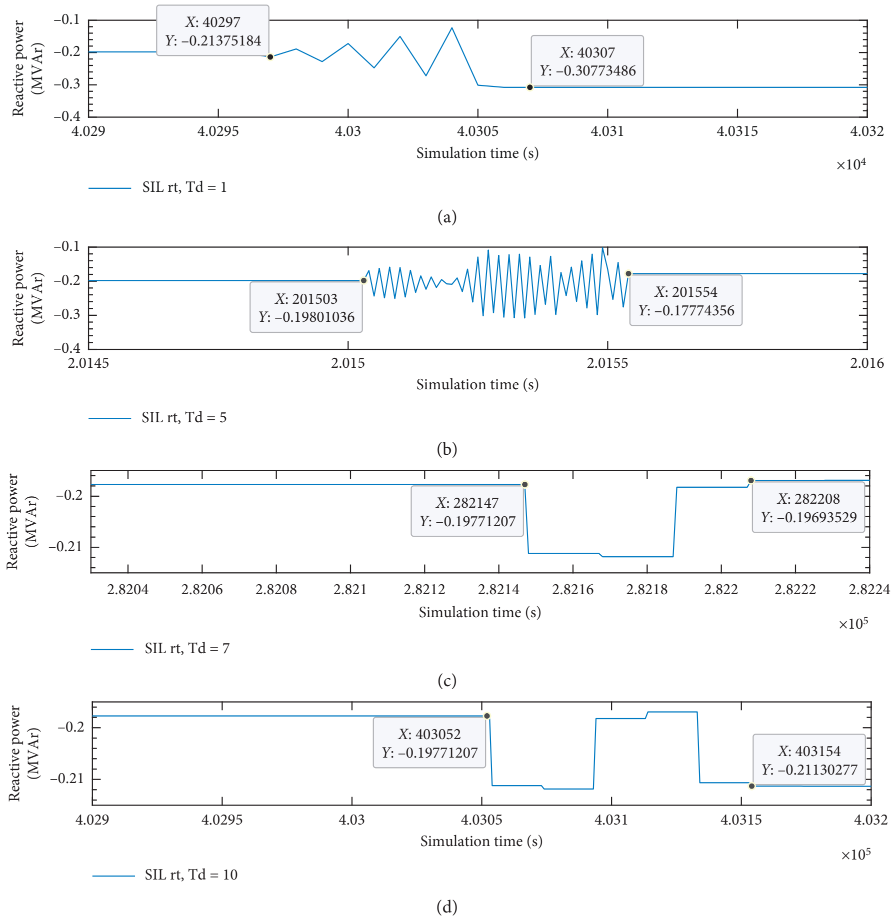


FIGURE 15: Results from the real-time SIL real-time test. Reactive power flow at the WT converter between 4029 h and 4031 h when $T_d = 1, 5, 7$, and 10.

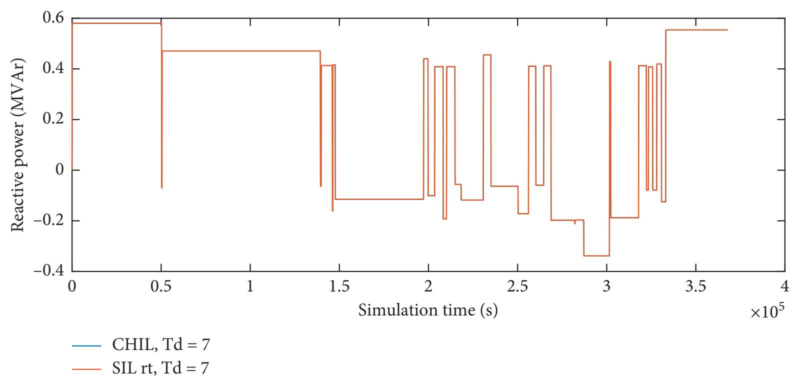


FIGURE 16: Real-time SIL simulation and CHIL results. Reactive power flow of the WT converter when $T_d = 7$. The RPW controller was set up to the TSO limits of ±50 kVAr, except $QD_1 = Q_i + 200$ kVAr.

5. Conclusions and Discussion

The accelerated real-time cosimulation platform proves to be useful and efficient in one-year power flow simulations. This research demonstrates how to accelerate the long-term simulations by different setups of the input data. Moreover, this paper clarifies how the input data processed in the long-term simulations or tests affect the results.

The offline SIL and real-time SIL simulations show that it is possible to find a data-reading cycle, coefficient T_d, to accelerate the long-term real-time simulations. When T_d is equal or greater than a particular value, the simulation results do not differ even when T_d is increased. Consequently, this value would be a suitable initial value for investigating the coefficient of the accelerated real-time simulations. In addition, it is found that, by increasing the value of T_d, the possible oscillation period becomes shorter. Further, based on this result, a suitable *I* or PI controller can be derived for accelerated real-time tests that enable adaptive closed-loop control, preventing oscillations in the closed-loop controlled system. Finally, even in CHIL tests with an FPGA and the selected coefficient T_d, the results of the real-time SIL and CHIL tests do not differ. The performance of the FPGA shows that it is suitable hardware for testing the algorithm in long-term simulations.

Our suggestion for long-term simulation runs is to carry out offline SIL simulations by using real-time simulation models with different time factors and verify that the results are equal. The time factor for the real-time SIL simulations can then be selected, and the results would be expected to be close to the offline results, with only an effect of the communication time delay. This method could be utilized to define the test procedure, for example, for CHIL applications in the development of microgrid controllers, especially for ancillary services.

The more detailed stability analysis of the proposed control method and detailed technical analysis of the proposed approach will be done in future studies. This paper's aim is to present the potential and the related issues of the developed method for accelerated real-time simulations.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request and with permission of Vaasan Sähköverkko.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The research was performed using the ERIGrid Research Infrastructure and received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement no. 654113. The support of the European Research Infrastructure ERIGrid and its partner OFFIS e.V. is very much appreciated.

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Functional Analysis of the Microgrid Concept Applied to Case Studies of the Sundom Smart Grid

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Received: 8 July 2020; Accepted: 12 August 2020; Published: 15 August 2020

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Abstract: The operation of microgrids is a complex task because it involves several stakeholders and controlling a large number of different active and intelligent resources or devices. Management functions, such as frequency control or islanding, are defined in the microgrid concept, but depending on the application, some functions may not be needed. In order to analyze the required functions for network operation and visualize the interactions between the actors operating a particular microgrid, a comprehensive use case analysis is needed. This paper presents the use case modelling method applied for microgrid management from an abstract or concept level to a more practical level. By utilizing case studies, the potential entities can be detected where the development or improvement of practical solutions is necessary. The use case analysis has been conducted from top-down until test use cases by real-time simulation models. Test use cases are applied to a real distribution network model, Sundom Smart Grid, with measurement data and newly developed controllers.. The functional analysis provides valuable results when studying several microgrid functions operating in parallel and affecting each other. For example, as shown in this paper, ancillary services provided by an active customer may mean that both the active power and reactive power from customer premises are controlled at the same time by different stakeholders.

Keywords: smart grids; microgrids; control; use case

1. Introduction

Microgrids can be classified according to the function demand, capacity, voltage type, voltage level, and mode of operation. The operation mode can be either steady-state in grid-connected or islanded mode or transition to grid-connected or to islanded mode. Moreover, a microgrid can be permanently islanded, which is an isolated or a remote microgrid. Microgrids are complex systems, which can be formed at different voltage levels in the electricity distribution network, and they are able to provide several technical functions in addition to supporting the requirements of reliability, efficiency, and reduced emissions. These functions are intended to the resilient operation, seamless transitions, provision of ancillary services, and communication between the actors as well as services for the resiliency needs of the participating communities.

The development of the management system for microgrids is a challenging task. The challenges arise from the distributed and intermittent, flexible energy resources, many of which are on customer premises playing a crucial role in the management of the microgrid. The management of microgrids can consist of several systems to be managed. Indeed, a microgrid management system (MMS) can be described as a management system of systems. The functions of the microgrids (e.g., energy management, Volt/Var control, or intentional islanding) are distributed to devices. An operation can be described as the method of a concept or a joint action of several systems or devices functioning together to accomplish the desired objective. Each individual system or unit has a specific function, and without their task execution, the operation would not succeed or be complete. Operation is the method by which a device or system performs its function while a function is what something does or is used for. In the same way, we can understand that the microgrid functions represent the tasks that a microgrid has to perform to fulfill the functional requirements imposed on it, and which methods are available to perform the required function(s).

For the microgrid control functions, several definitions have been suggested. The microgrid functions can be defined based on the control hierarchy, which are primary, secondary, and tertiary control levels, as authors in [1–3] present. Authors in [4,5] present the functions according to the microgrid architecture by layers 0, 1, 2, 3, and 4. IEEE standards 2030.7 and 2020.8 define the core microgrid controller functions as a dispatch function and a transition function, excluding the functions related to the protection of microgrids [6,7]. IEC TS 62898-2 defines the main control systems of the microgrids as the primary control, and further, a central controller takes care of the secondary control [8]. The microgrid control functions are also released by vendor-based solutions [9]. Now, however, standards are starting to appear and develop. There are concerns that regard how to utilize or map the early stage standardization, different requirements, and use cases in real microgrids, real microgrid functions, or test cases, which can vary [10].

Therefore, this research aims to define, study and analyze the functions of microgrids by taking into account the functionalities of microgrids, the aim of operation as well as the different power grid applications to the extent appropriate to the context. Furthermore, the studied microgrid functions are implemented in the operation of an MMS by developing relevant levels of use cases, that is, behavioral descriptions. Based on a selected (test) use case, a simulation model is developed for further case studies and controller development and vice versa, an existing simulation model and a simulation case study are described by developing a corresponding (test) use case. These selected cases differ with their operating or functioning time-frame—one is related to protection in electromagnetic transients (EMT) simulations, and the other two are related to demand response and reactive power control in RMS transient stability simulations. These three types of test cases were selected to highlight that use case modelling, simulation, and testing over different time domains, as co-simulation is essential in the research and development of microgrid control systems.

By starting this research with the definitions related to microgrid functions, functionality, operations, or applications, it is noteworthy that several terms are describing the control or management system: a microgrid management system, a microgrid controller, a microgrid central controller, and a microgrid energy management system. Therefore, Section 2 clarifies the terms mentioned above and different types of microgrid applications. Section 3 presents the microgrid functions as well as the general control and operational use cases of microgrids. Section 4 presents the functional analysis of microgrids and the use case modeling and, further, Section 5 presents the demand response and protection primary use cases with the help of the Sundom Smart Grid case. Section 6 presents the selected test use cases—ancillary services (AS) as well as protection—according to the defined microgrid functionalities. Section 7 provides conclusions.

2. Definitions and Applications

Several similar definitions exist for microgrids, but in the following, definitions for microgrids and microgrid management systems are presented based on the IEEE and IEC standardization. Furthermore, different types of microgrids are presented because the microgrids can work in different ways, depending on the microgrid concept application in addition to the targets of operational optimization. Finally, the definitions for the control hierarchy and control architecture of a microgrid management system are presented.

2.1. Microgrids

In IEEE standard 2030.7 a microgrid is defined as follows: 'A group of interconnected loads and distributed energy resources with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island modes' [6].

In IEC-TS 62898-1, a microgrid is defined as follows: 'Group of interconnected loads and distributed energy resources with defined electrical boundaries that acts as a single controllable entity and is able to operate in both grid-connected and island mode.' The definition covers both utility microgrids and customer microgrids [11].

The microgrid concept should provide a broad range of economic, technical, and environmental benefits to different stakeholders according to the use of configuration and operation schemes [3]. From the power system operator's viewpoint, the microgrids can be considered as an aggregation concept of the coordinated control (both supply and demand-side) based on the connected, flexible distributed energy resources (DERs). From the end user's point of view, microgrids should decrease the costs of energy, increase power quality and reliability, and offer energy services, for example.

Microgrids are often identified according to different kinds of communities, such as energy communities that could facilitate the power grid energy management. Participation in a community must be open to all potential local members, and it must be voluntary to join as well as leave the community [12]. For example, in energy communities, the owners of distributed energy resources (DER) participate in the energy generation that is sold to the local energy utilities, and the profits are divided among the participants. The generated electricity could also be consumed by participating prosumers, providing a valuable economic benefit of local energy generation. The Renewable Energy Directive (EU) 2018/2001 insists that local communities are organized in the vicinity of renewable energy projects they own and develop, while the Electricity Market Directive (EU) 2019/944 does not engage citizen energy communities in the same geographical location between generation and consumption [12]. The energy communities can be those such as homogenous energy communities, mixed energy communities, or self-sufficient communities. Energy communities can be composed of a part of a microgrid, a microgrid, or a subset set or a superset of microgrids that have the objective of the energy function for operation. In other words, microgrids are not equivalent to energy communities, but they can form the technical basis of microgrids.

A microgrid can be constructed based on a variety of benefit expectations, which might be the improved reliability, economy, or preparedness for disasters. Additionally, the geographical location sets conditions for the microgrid feasibility. Microgrids can be classified by their different aims to operate [11] as follows:

- Improving reliability: a distribution microgrid (a part of a utility grid, a campus, or another area of operation) or a facility microgrid (in a customer, a military base, or a hospital installation, etc.);
- Low-cost powering remote areas: an isolated microgrid (in rural areas, or islands);
- Reducing energy cost: the microgrid users offer ancillary services;
- Providing disaster-preparedness: asset optimization due to critical conditions (a disaster-prone area).

2.2. Microgrid Management System

The purpose of implementing an advanced control and optimization system in microgrids is to fulfill the functional requirements or benefit expectations set for the microgrid. The microgrid control or management system has several similar terms defining the system, but in this research, we rely on how standardization is describing an MMS.

IEEE standard 2030.7 defines a microgrid control system as follows: A system that includes the control functions that define the microgrid as a system that can manage itself, operate autonomously, and connect to and disconnect from the main distribution grid for the exchange of power and the supply of ancillary services; it includes the functions of the microgrid energy management system (MEMS); it is the microgrid controller if implemented in the form of a centralized system [6].

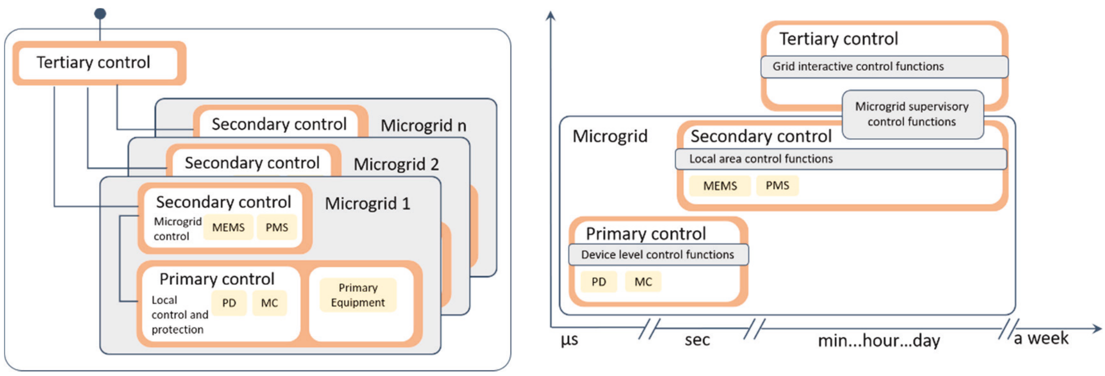
IEC-TS 62898-1 defines a microgrid energy management system as follows: 'System operating and controlling energy resources and loads of the microgrid' [11].

The purpose of the microgrid control system is to provide the microgrid with the means to control itself, operate independently or connected to the grid, and connect or disconnect the primary distribution grid for electricity exchange and ancillary services. It should have both real-time control and energy management functions for operating in the grid-connected and the islanded mode, managing the transition functions and providing ancillary services, supporting the grid, and participating in the operation of the energy market or the operation of the utility. A microgrid control system consists of software and hardware and can be physically centralized or distributed. The term microgrid control system (or MMS as used in this paper) describes the situation where the control functions can be distributed in the microgrid assets or being centralized in one controller [6].

2.3. Control Scheme Hierarchy and Control Architecture of a Microgrid Management System

The control system scheme is illustrated by particular interconnections of elements. An element is a set of any objects that make up a set. For example, in object-oriented modeling, the object can be a combination of variables, functions, and data structures referring to a particular instance of a class. The function of a control system defines the possible transformations made by the control system, which can change the information (change the state of parameters) or can change the scheme (structure) and the behavior [13]. The composite of a control system depends on the elementary control systems, and it can be realized in different hierarchies [13].

A hierarchical control scheme is proposed consisting of three control levels, which are primary, secondary, and tertiary control levels [1]. The hierarchy of these three control levels is presented in Figure 1a.



(**a**) (**b**)

Figure 1. Three control levels of a microgrid management system. (**a**) Hierarchical control levels: primary control, secondary control, and tertiary control. Adapted from [1]. (**b**) Microgrid control system time-frame and action time domain. Adapted from [6].

Primary control is the local of DER, featuring the fastest response, and it is based on local measurements. The primary control includes current and voltage control loops, active and reactive power droop control loops, as well as virtual impedance loops [14,15]. For example, for power (P/Q) sharing in microgrids, multiple power electronic converters can operate in parallel, and droop control can be employed in this control level. Another example is in the islanded microgrid, where the essential function of the energy storage system (ESS) is to adjust power by charging or discharging the storage in order to achieve the power balance in the grid. Additionally, primary control is involved in balancing the energy between the ESs. Depending on the state of charge (SoC) of the ESs, their support for active power can be adjusted in coordination with the controllable DER units. Islanding detection is also included in this control level.

Secondary control includes the microgrid energy management system (MEMS) that is responsible for energy management either in the grid-connected or islanded mode of the microgrid. Energy management system (EMS) functions include economic dispatching and unit commitment [16]. Unit commitment can provide setpoints for a day(s) based on prediction, and economic dispatch provides setpoints based on measurements [16]. Hence, there can be several requirements and different time-frames for dispatching of DERs, especially when controlling a multi-microgrid or a cluster of microgrids [16].

Secondary control is utilized for the control of power quality, voltage unbalance, harmonic compensation, as well as synchronization and power exchange with the primary grid and the other microgrids [16]. In the following, some examples of these duties are pointed out [1].

Power quality control includes voltage and frequency deviation restoration, which aims to ensure that the deviations are regulated toward zero after changes of demand or generation inside the microgrid. The differences are processed by the new reference parameters for the power electronics connected DER units to restore the output voltage frequency and amplitude. Several methods and resources have been proposed, for example, in [17–20].

In an islanded microgrid, voltage unbalance compensation is used in sensitive load bus (SLB) by equalizing the compensation efforts among the DG units. Additionally, the limitations for the harmonics can be satisfied with secondary control algorithms. The optimal setting points or compensating references for primary controllers are calculated in this control level [21,22].

Power exchange can be controlled, for example, for economical operation of the grid. The optimization procedure is for minimizing a cost function, which outputs references either for the active power and voltage or the reactive power and frequency [23].

Tertiary control gives setpoints for long-term control regarding the requirements from the hosting power system [1]. Furthermore, tertiary control coordinates the operation of multiple microgrids, which interacts with each other in the system (for example, functioning as a nested microgrid), and communicates the requirements from the host grid, such as voltage support and frequency regulation [1]. Tertiary control deals with ancillary services, for example, frequency support, load following support, and hourly ramping [24]. Additionally, tertiary control can be utilized for power quality improvement, such as a procedure for differentiating the power quality level, multiple-power-quality-level (MPQL), for different areas, which is presented in [25]. Furthermore, tertiary control can be applied for the blackout situation of the primary grid by the management of a group of interconnected microgrids or a microgrid cluster for acting as a virtual power plant (VPP) in order to supply the critical loads [26].

In addition to the previously discussed control, zero-level control is defined as the internal control (the level 0) that is responsible for managing the voltage or current output of the power electronic interface (of DG units) [27]. These interfaces can be divided into current-source inverters (CSIs) and voltage-source inverters (VSIs) [28]. The CSIs are utilized for injecting current to the grid, whereas the VSIs are used for maintaining the stable voltage in the network [29].

Figure 1b presents the time frame and action time domain of an MMS. The device-level control or the primary control of a microgrid act in the range from microseconds to seconds. The local area control functions and microgrid supervisory control functions are the secondary control acting in the range from seconds to days. The tertiary control is the grid-interactive control functions or microgrid supervisory control functions acting in the range from minutes to days or a week [6].

The architecture of the microgrid control system can be centralized or decentralized. In centralized control architecture, the decision of the control actions is made in a single place, due to the advantage that the complete knowledge of the system is there. In contrast, in decentralized control architecture, several subsystems are controlled by themselves, but they share information. Furthermore, the architecture of the one single system may be the internal architecture of a control product, as well as it can be a bill of material, including both software and hardware. The question is how the "bill of material" of the microgrid management system as a "system of systems" is structured to solve the functions required by users. It is essential to describe the control system adequately so that everyone understands and agrees that it does what is expected. An architectural layout can be created to house all control systems, and a functional specification can be written for the control system, although their interpretation is usually tricky. However, none of these things provide the necessary assurance for a particular performance. The control system architecture is meant to translate the functional requirement into hardware.

Concerning this, the microgrid control system architecture can be illustrated by four layers: layer 1–layer 4, but it is attached to layer 0. Layer 0 presents the primary microgrid components. In the following, the different layers are presented from the device or subsystem perspective. Layer 0 (primary devices) includes devices and actions such as transformers, lines, circuit breakers, switches, generation, load, or storage. Control, monitoring, or sensing devices at layer 1 have hardwired connections to the primary equipment for monitoring or controlling of them. Layer 1 (device-level control) can be load controllers, protection relays, distributed generation controllers, and meters for layer 0 devices. Layer 2 (network levels control) contains communications equipment, sensors, security gateways, and data processing and aggregating devices. Layer 3 (supervisory level control) includes a supervisory controller or energy manager, which can host, for example, forecasting, data management, or optimization. The equipment in layer 1 receives commands from layer 3 algorithms. The commands can be related to, for example, power factor control, demand response, dispatch of renewables, load shedding, Volt/VAr management, generation source optimization, or secondary frequency control. Layer 4 (grid integration and analytics layer) is responsible for the diagnostic and engineering elements, such as automatic event report retrieval, detailed sequential event recorder reports, and management of settings for all microgrid central control system equipment. Human–machine interfaces in this layer provide the real-time status of the controller to network operations and maintenance staff. Layer 4 includes economic optimization, automated financial transactions, and forecasting functions [4,5,30].

3. Microgrid Functions and Control and Operational Use Cases

Regardless of the microgrid application, there are general functions defined for microgrids that are presented in this section. Additionally, it can be realized that depending on the application, some functionalities might not be needed. Despite this, it is necessary to define the representative functions that an MMS has to perform as well as the representative use cases, where the aim is to fulfill the operational requirements of smart grids (system, metering, as well as grid operations). In this research, the defined microgrid functions are considered and presented as functional requirements for the MMS.

3.1. IEEE and IEC TS Standardization

IEEE standardization [6,7] defines the core functions of microgrids that are dispatch and transition. The dispatch function is a command for the microgrid components or their separate controllers that might be open/close, start/stop, set the generation levels, or reduce the load. The control system has to dispatch the microgrid assets in terms of power. In the grid-connected mode, the dispatch function should fulfill interconnection agreement in energy and interconnection requirements in power quality, but also it should satisfy the microgrid operator's internal requirements. The dispatch function should apply in grid-connected, islanded, and in transition mode. Transition function is defined for several transition actions. The transition function might be planned or unplanned. Additionally, reconnection to the grid and black start are transition functions. [6]

The testing of the microgrid control system should include proper and representative (i) test scenarios, (ii) performance metrics, and (iii) testing environment ranging from an entirely simulated environment to field-installed equipment. For example, the testing scenarios of the dispatch function should be defined in the grid-connected operation as well as in the islanded operation. In grid-connected and islanded operations, the impact of load and generation variation, as well as active and reactive power, (P, Q), flows within the microgrid should be verified. Additionally, at the point of interconnection (POI), the power flows (P, Q) should be verified in the grid-connected mode and the voltage and frequency (V, f) in the islanded operation mode. A real-time hardware-in-the-loop (HIL) simulation environment is suitable for testing the components of the microgrid control system [7].

The management of microgrid functions can be established through four layers (or communication function blocks) presented in Figure 1b, which are (1) a device layer (e.g., control of voltage/frequency, reactive power, electric vehicle (EV), energy storage (ES), load, generation, islanding detection, or fault management, protection); (2) a local area control layer (e.g., load management, building energy management, automatic generation control, fast load shedding, a plant controller, sequence logic, status control, resynchronization, or disturbance recording); (3) a supervisory control layer (e.g., forecasting, optimization, state estimation, topology chance management, data management, visualization, dispatch, generation smoothing, spinning reserve, emergency handling, protection coordination, or black start); and (4) a high-level grid interface layer (e.g., an area electric power system control, spot market, a distribution management system, SCADA, or connection to an adjacent microgrid). The functions in these four blocks can reside in different hardware and software components that make up the microgrid control system [6].

According to [11], the functions of the microgrid control system should include power balance management, demand-side management, economic dispatch, and information exchange between the grid-connected microgrid and the main grid. Both IEEE and IEC standardization recognize the EMS as a part of a microgrid management system.

3.2. Use Cases

Ten primary use cases were modeled for a microgrid control system or an MMS in Oak Ridge National Laboratory [31] based on microgrid controls and operational functions described in [32]. These use cases aim to capture the key requirements of a microgrid controller. The basic functions or use cases modeled were:

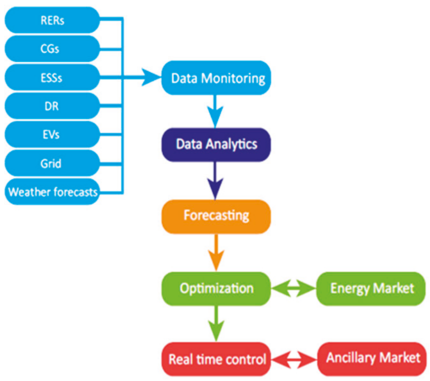
1. Frequency control;
2. Voltage/reactive power control;
3. Intentional islanding;
4. Unintentional islanding;
5. Transition to grid-connected operation;
6. Energy management;
7. Protection;
8. Ancillary services;
9. Black start;
10. User interface and data management.

Other similar definitions can be found in [33], for example:

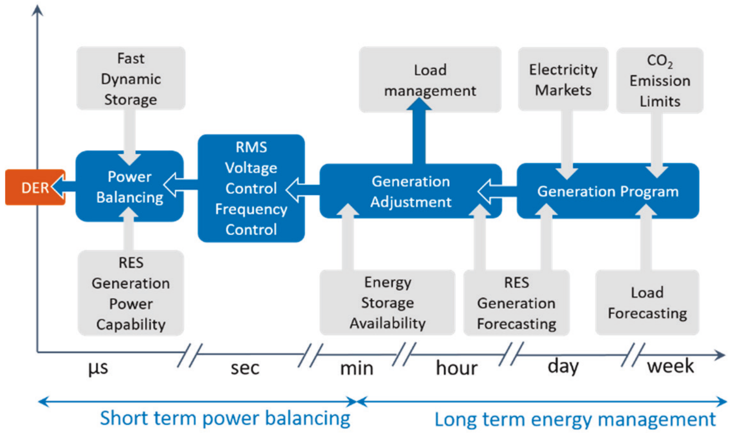
1. Coordinated dispatch of DER;
2. Seamless transition;
3. Power exchange with the main grid;
4. Provision of AS;
5. Enabling market participation of DER.

3.3. Microgrid Energy Management System

The microgrid EMS (MEMS) aims to provide optimized operation of a microgrid while satisfying its technical constraints. The EMS functions are presented in Figure 2a, which are the real-time control of microgrid assets for providing ancillary services as well as an optimization of the assets for the energy market. These functions run based on data monitoring, data analytics, and forecasting (generation, load, storage, meteorological data, and market prices) functions [34].



(**a**)



(**b**)

Figure 2. Microgrid energy management system: (**a**) microgrid EMS functions [34]; (**b**) timing classification of the EMS control functions. Adapted from [35].

Furthermore, the MEMS can be considered for long-term energy management as well as a short-term power balancing system, as presented in Figure 2b. Long-term energy management includes load forecasting, generation prediction, energy storage reserve, energy estimation, peak shaving, operational planning, reduction in CO_2 emissions, provision of adequate capacity of power reserve in conformity with the electricity market, and demand forecasting. Short-term power balancing includes real-time power dispatching between DER internal sources as well as RMS voltage regulation and primary frequency control [35].

3.4. Protection System

Traditionally in the radial distribution systems, overcurrent protection schemes have been used, but also distance and differential protection schemes are employed. In microgrids, the MMS is responsible for the protection system management so that the protection system is adaptable depending on the operation mode of the microgrid (grid-connected or island), and if necessary, on the changes in generation and demand. Due to the existence of the distributed generation, the fault currents can vary substantially, and the fault current flow can be bidirectional. Therefore, the traditional non-directional overcurrent relay protection schemes are not able to operate properly in most situations. For the protection of microgrids, voltage or total harmonic distortion (THD) based protection could be suitable. The authors in [36] claim that the protection system of low voltage microgrids should be based on the voltage measurement because the inverter connected distributed generation (DG) units can provide low short circuit currents and thus delay the operation of the protective device. In this research, the protection system is not studied further. Communication-based protection systems/concepts have been proposed in [37–39]. Additionally, suitable communication standards for protection systems are available, such as IEC 61850. In this research, protection techniques are not studied further.

4. Functional Analysis and Use Case Modelling

Micrograms are often discussed from their feasibility point of view even though microgrids are not a new invention, they have been operated in non-interconnected islands or remote locations. There have been standby or backup generators, providing a secure electricity supply to hospitals, industrial plants, or communities. The unique element is that the concept is applied to a single customer end, and various actors participate in microgrid management while expecting benefits. With a functional analysis of microgrids, the aim here is to represent the abstraction related to microgrids and sharpen the focus of the functions.

4.1. Functional Analysis

The framework for the functional analysis of microgrids is made "top-down", as illustrated from left to right in Figure 3. The highest level describes the application where the microgrid concept is applied and further the aim of the microgrid operation, as presented in Section 2.1. Next, the microgrid functionalities from the management point of view are given, highlighting that functionality (or feature) is the sum of functions or any aspect of what a microgrid can do for a user, e.g., distribution system operator (DSO). In other words, functionalities of the microgrids are used for identifying its features but also for enabling a user to gain specific capabilities. Finally, the general microgrid functions are defined as presented in Section 3.3 and especially two core functions: dispatch and transition, which are presented in Section 3.1. The last column in the left shows examples of the goals of the microgrid functions. In the following, some examples are used partly from [9,40] to present how a microgrid functionality can be formed from several microgrid functions or how different functions are interlinked.

1. Power balancing and load balancing
   - Frequency control (in islanded mode): steady-state device-level control (P/f droop), coordinated control of DERs, transient device-level control, frequency smoothing, low-frequency ride-through (LFRT), emergency load shedding;
   - Volt/VAr control: steady-state device-level control (Q/V droop), coordinated control of DERs, management of voltage fluctuations due to intermittent power generation of DERs, low voltage ride-through (LVRT);
   - Energy management (in islanded mode).
2. Congestion management
   - Energy management: grid-connected energy balancing, operation optimization, forecast;
   - Volt/VAr control: secondary level voltage control (settings for voltage controllers);
   - Intentional islanding: network reconfiguration;
   - Transition to grid-connected operation: network reconfiguration;
   - User interface (UI) and data management (DM): energy exchange information and V/VAr support schedules between the main grid and the microgrid, real-time data (voltages, currents, active power, and reactive power) at POI.
3. Fault management, fault location, isolation and supply restoration (FLISR)
   - Unintentional islanding: anti-islanding protective schemes'
   - Protection: short-circuit protection, earth-fault protection, adaptive protection settings'
   - Black start: system restoration procedure.
4. Responding to external orders
   - Ancillary services: frequency control support (TSO), voltage control support (DSO), congestion management (utilizing generation curtailment, load curtailment or load shedding, ES);
   - Intentional islanding: request from the operating entity, a scheduled tariff transition or operation agreement;
   - UI and DM: energy exchange information and V/VAr support schedules between the main grid and the microgrid, real-time data (voltages, currents, active power, and reactive power) at POI.
5. Resiliency

- Intentional islanding: Islanding operation plans for particular outages;
- Frequency control: Uninterruptable power supply function for the critical load (intelligent load shedding).

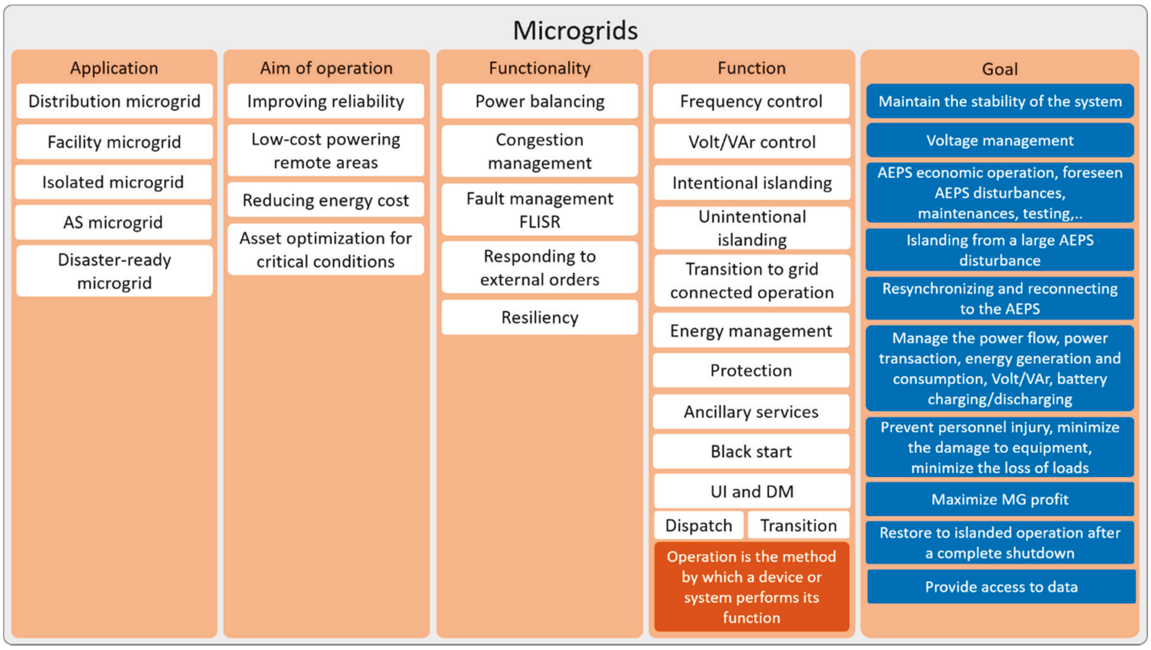


Figure 3. The functional analysis of microgrids.

For the functional analysis of microgrids describing the functions of an MMS, the secondary and tertiary control level functions are considered here. Figure 4 presents the microgrid control functions and functionalities based mainly on [3,6,8,31,41,42]. The description of the functionalities may vary because a microgrid design has no set of constraints on network topology or system configuration, demand, and generation resources. However, Figure 4 highlights the fact that an MMS consists of different systems, coordinates between them, and the operation mode can be set up based on the optimization interest. The functions are presented between the control hierarchy levels and the control system architecture layers. It can be noticed that the functions of an MMS do not extend to the internal control of the primary equipment.

The development of the MMS is complex, involving various systems to be merged for operation according to defined goals. Therefore, an MMS, which may consist of systems from different vendors, needs to address several objectives in a coordinated manner. Hence, the operational or behavioral descriptions of the system with the various levels of use cases are vital for implementing and testing the total system operation and the functionalities. Furthermore, for developing new intelligent concepts for microgrids as well as implementing the microgrid concept in a particular or special application, the use cases are essential.

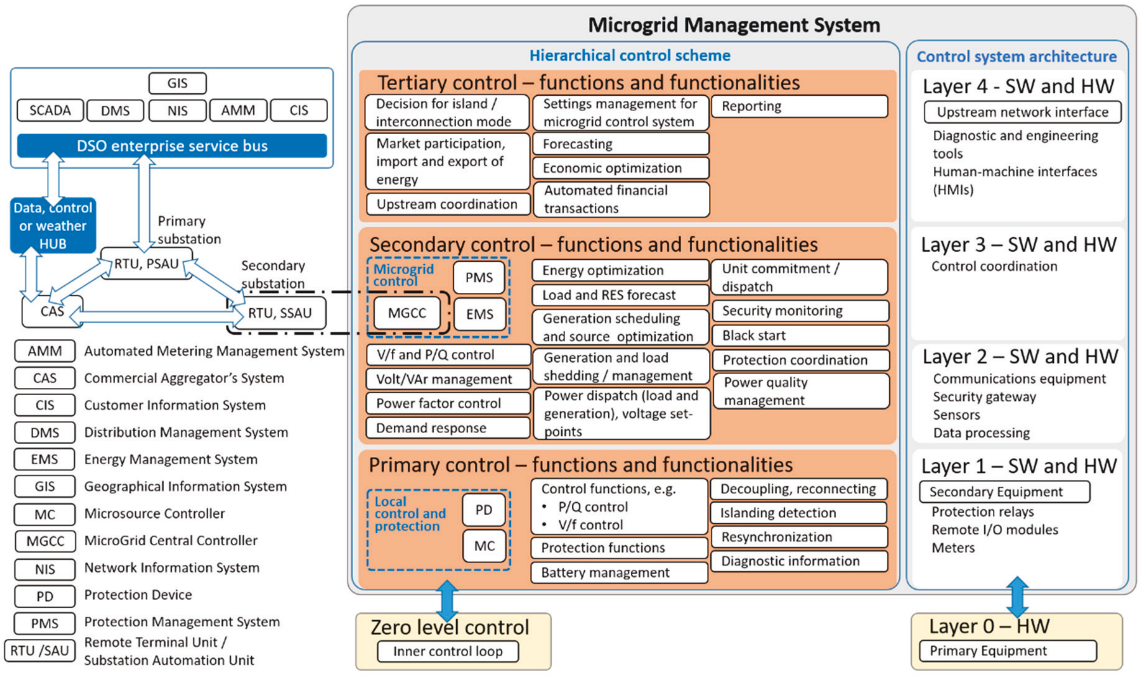


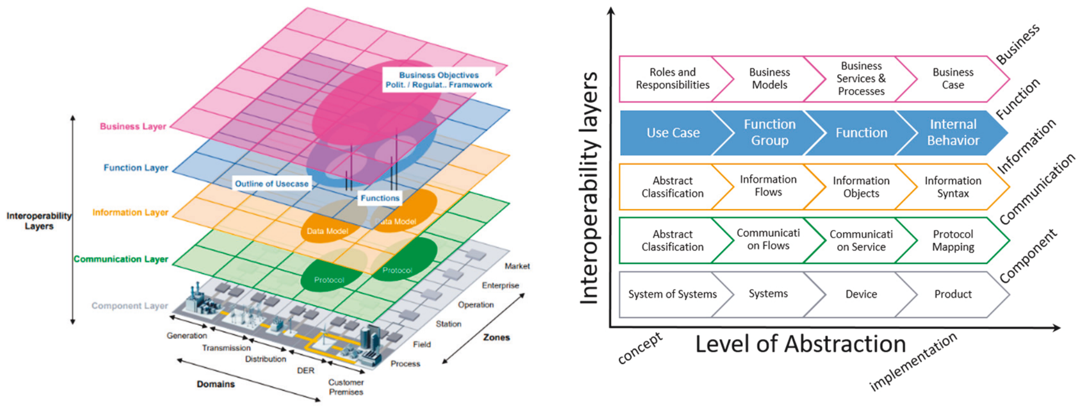
Figure 4. The functions of a microgrid management system.

4.2. Use Case Modelling and High-Level Use Cases

Use case (UC) methodology supports the engineering process for complex systems and standardization [43]. UCs describe the system and its functionalities to be developed. The system can be described by static or dynamic presentations, in which static presentations describe the actors' relations to the system (for example, by class diagrams). In contrast, dynamic presentations or behavioral diagrams illustrate the relationship or interaction between actors (for example, use case diagrams or activity diagrams). The UC descriptions can vary in the level of the abstraction and the scope of the design. The building of UCs can be made from top-down or bottom-up approaches [44].

Visualization of different smart grid UCs in the architectural viewpoint is possible with the framework and methodology of the Smart Grid Architecture Model (SGAM), which is neutral regarding the solution and technology. The three-dimensional SGAM framework is presented in Figure 5a. The domains describe the complete chain of electrical energy. The zones describe the hierarchical layers of power system management. The interoperability layers represent the interoperability of any two components of the smart grid, that is, the interoperability needs to be considered on five different interoperability layers [45].

The smart grid systems cover all five SGAM interoperability layers, in which the function layer hosts functional architectures. Consequently, different systems have specific content in the functional architecture viewpoint. UCs represent certain operational scenarios in which the smart grid functions are performed. From a functional point of view, a function represents a logical entity that performs a dedicated function; consequently, a function group is a logical aggregation of one or more functions. For example, the substation automation function group can be divided into protection, control, monitoring, and data acquisition, which can be further decomposed into other subdivisions. The aim is to define the basic functions that can be utilized as building blocks for complex systems, which make possible the study and comparison of different functional setups [45].



(**a**) (**b**)

Figure 5. Smart grid architecture model (SGAM) and the levels of abstraction: (**a**) SGAM framework [45]; (**b**) exemplary categorization of different abstraction levels per SGAM layer. Adapted from [46].

For each interoperability layer, abstraction levels can be defined, as illustrated in Figure 5b. This paper focuses on the function layer that describes UCs, functions, and services of the system, including their relationships from an architectural viewpoint. The abstraction levels defined in [46] are utilized to describe the meanings of different levels of functions, as presented in Figure 5b.

Several ways and a methodology were previously introduced, and they are applicable for determining the functions of microgrids. However, it is the manner of the UC "level", that is, the conceptual description, the use case concept or user stories, that provides an overview of the system or background for a cluster of use cases with appropriate accuracy. Therefore, the different levels of use cases are defined.

The use cases can be developed on several levels and for several purposes [47]. The general idea of a function together with generic actors is described by a high-level use case (HL-UC). The HL-UC can be implemented by various ways, so it cannot be mapped to a particular system or architecture. Furthermore, a use case implemented on a specific system, characterized by a defined boundary, is defined by a primary use case (PUC). A PUC can be mapped on a defined architecture. Mapping is used to break down the higher-level abstract use case into one or more implementation possibilities, namely specializations. The PUCs can be mapped to the SGAM. Next, secondary use cases (SUCs) are used for describing key functionalities used by multiple PUCs (for example, dispatch or transition) [48].

The principal or conceptual functions of an MMS can be described with HL-UCs, which represent the scenarios that the investigated system (microgrid) has to perform with the involving actors. Figure 6 presents the HL-UC diagram of an MMS, which is based on the functions present in Figure 3. Protection and energy management functions are highlighted, as they can illustrate EMS and PMS. Additionally, three PUCs are shown: demand response (DR), reactive power window (RPW) control as well as overcurrent (OC) protection.

Different levels of behavioral diagrams are developed in the next sections by the exemplary UC studies of the Sundom Smart Grid (SSG), in Vaasa, Finland. For the description of MMS for the SSG, the following levels of use cases are applied: (i) conceptual description, (ii) high-level use cases, (iii) primary, (iv) secondary, and (v) test use cases. Conceptual descriptions are described in Section 2 (definition and applications) and the HL-UCs are presented in Section 3.3. and in Figure 3. The SUCs, dispatch, and transition are described in Section 3.1.

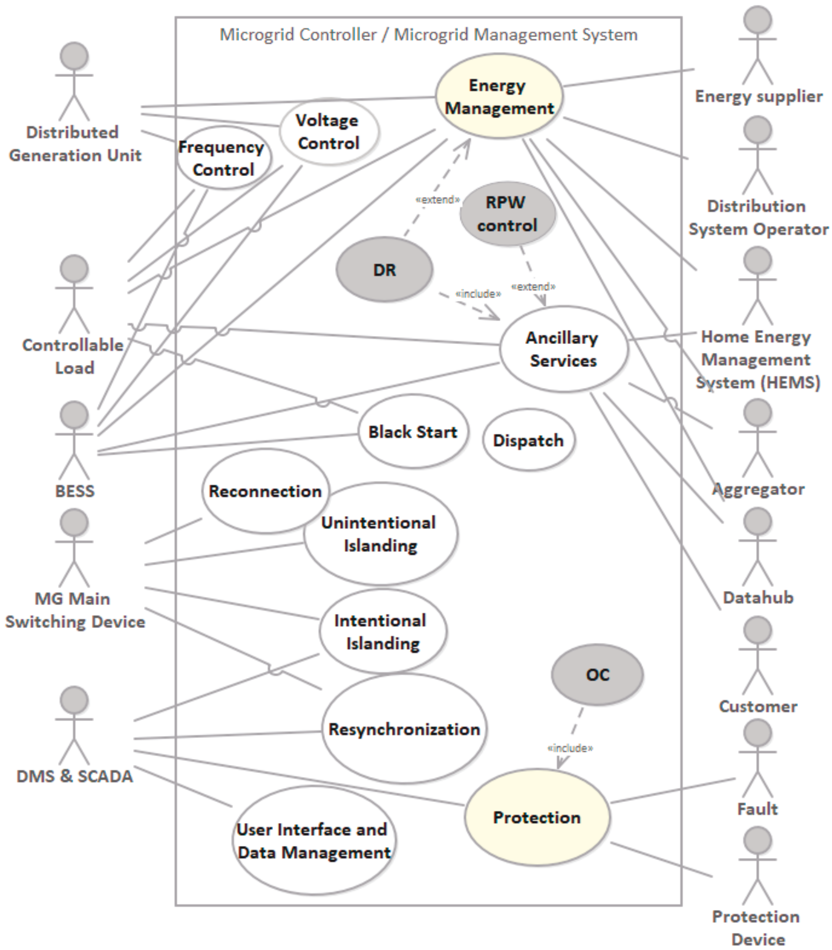


Figure 6. The high-level use cases of a microgrid management system.

In Section 5, two PUCs will be developed in order to apply the microgrid concept, and the microgrid control functions into a particular application. The PUCs are selected based on the functions operated by two defined subsystems: the MEMS and the protection management system (PMS). The PUCs are demand response (DR) for ancillary services (AS), and overcurrent protection, developed for the SSG.

Furthermore, in Section 6, three test use cases (TUCs) will be developed for the SSG that consists of the developed real-time simulation test scenarios with software in the loop (SIL) or HIL capabilities. The TUCs are based on the developed PUCs. The first two are the demand response for ancillary services TUC and the RPW control for technical ancillary services TUC, and the third is the fault F1 at the transformer terminal TUC. Figure 7 presents the different levels of the developed UCs.

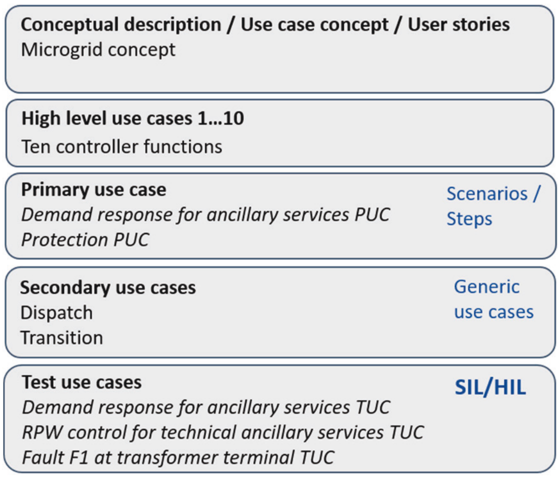


Figure 7. The applied use cases.

5. Demand Response and Protection Primary Use Cases for the Sundom Smart Grid

The SSG is a living lab established in a medium voltage (MV) network in Vaasa, Finland. There are four MV feeders and an additional feeder for the wind turbine (WT) only. Modern IEDs with fiber-optic connections are installed in the primary substation and four secondary substations. The IEC 61,850 sampled values (SV) and the generic object-oriented substation event message (GOOSE) measurements from the network at 20 points are collected in a cloud service. The SSG is connected with a direct communication link and the data collection facilities to the University of Vaasa's Future, Reliable, Electricity and Energy Systems Integration (FREESI) laboratory. Figure 8 presents the single line diagram of the simplified SSG. The microgrid is considered to cover the whole MV grid, and the connection point is at J05.

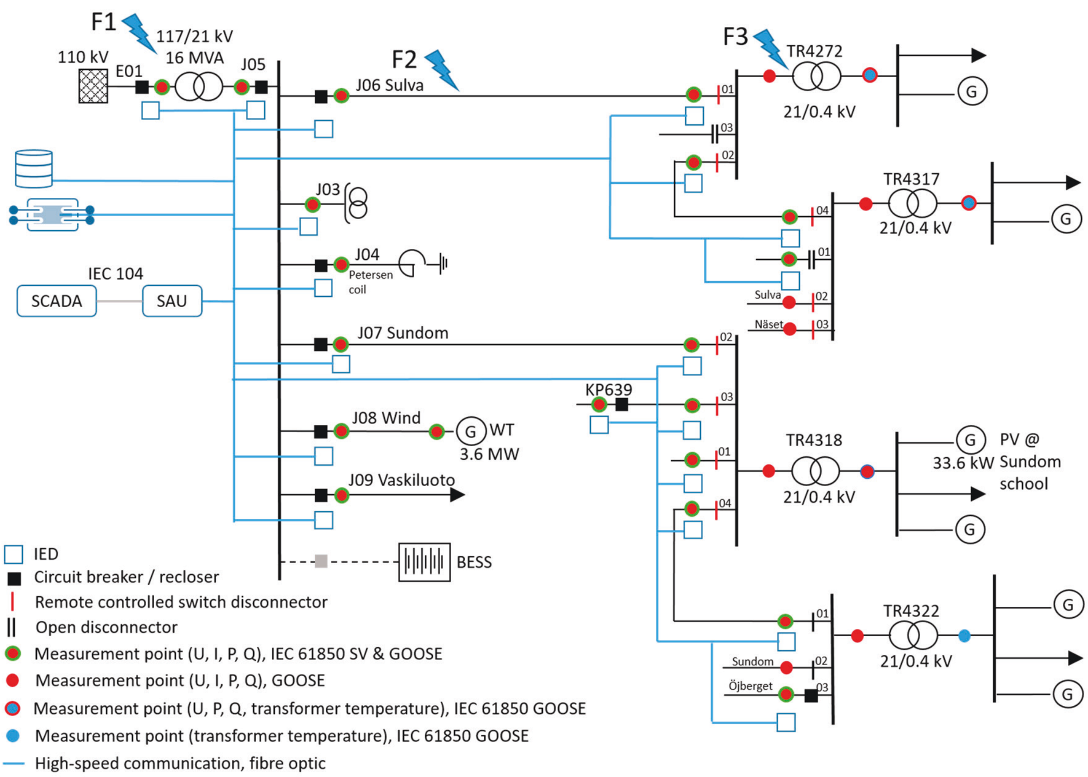
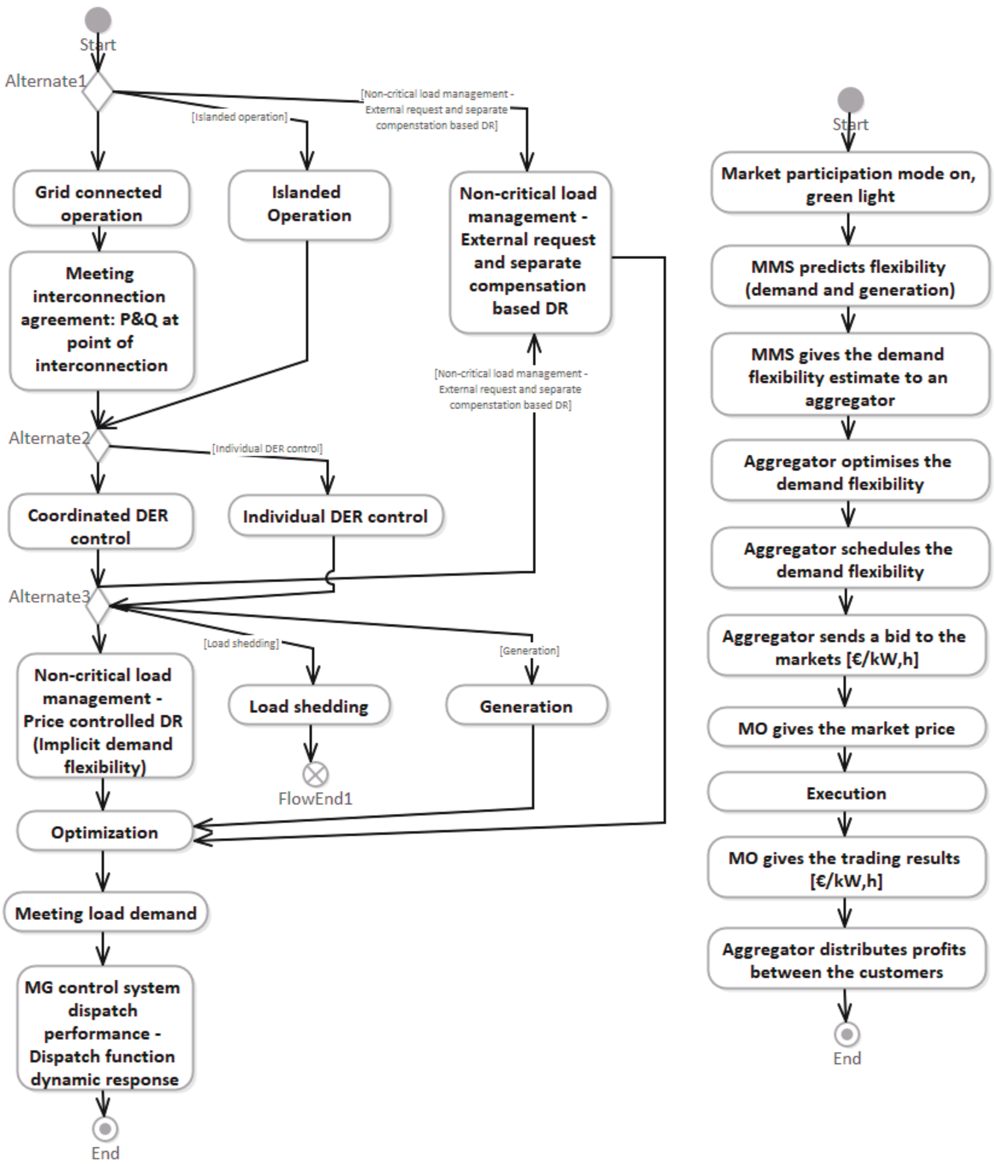


Figure 8. Single line diagram of the Sundom Smart Grid. Adapted from [49].

5.1. The Demand Response for Ancillary Services PUC

The demand response for ancillary services PUC is associated with energy management as well as ancillary service HL-UCs, as Figure 6 illustrates. Figure 9a presents the activity diagram of the energy management HL-UC, where the path "non-critical load management—external request and separate compensation-based DR" relates to the demand response for ancillary services PUC. The activity diagram is one of the UML behavioral diagrams that present a process or algorithm as a sequence of steps. With the activity diagram, the alternative scenarios can be given, and it is a more sophisticated version of the flowchart diagram. In Figure 9a, energy management is divided into three scenarios, which are aimed for grid-connected operation, islanded operation, and ancillary services. In grid-connected and islanded operation modes, the DER control can be either coordinated or individual.



(a) (b)

Figure 9. Microgrid energy management system: (**a**) activity diagram of the energy management high-level use case (HL-UC); (**b**) activity diagram of the demand response for ancillary services protection use case (PUC).

Furthermore, the management of DER can be non-critical load management that is price-controlled DR (implicit demand flexibility or tariff controlled) and generation, which are optimized by EMS. Load shedding stabilizes the voltage or angle and supports to maintain the power balance within the microgrid. In more detail, Figure 9b presents the activity diagram of the demand response for ancillary services PUC, and Figure 10, in turn, gives the use case diagram of it.

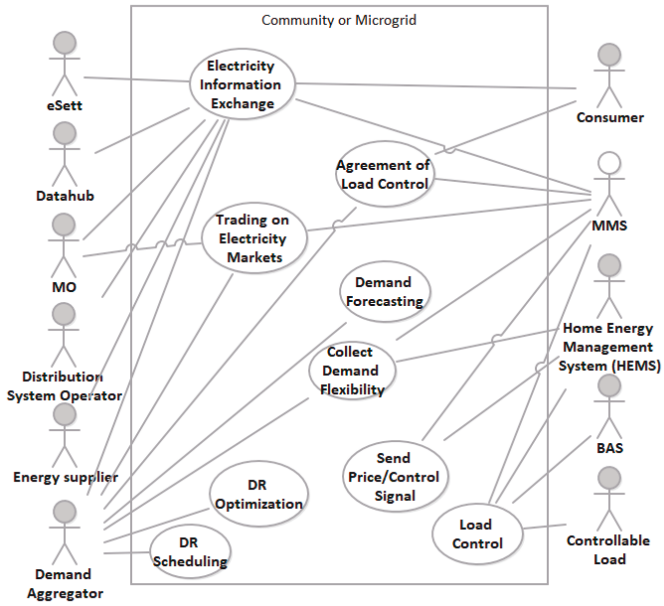


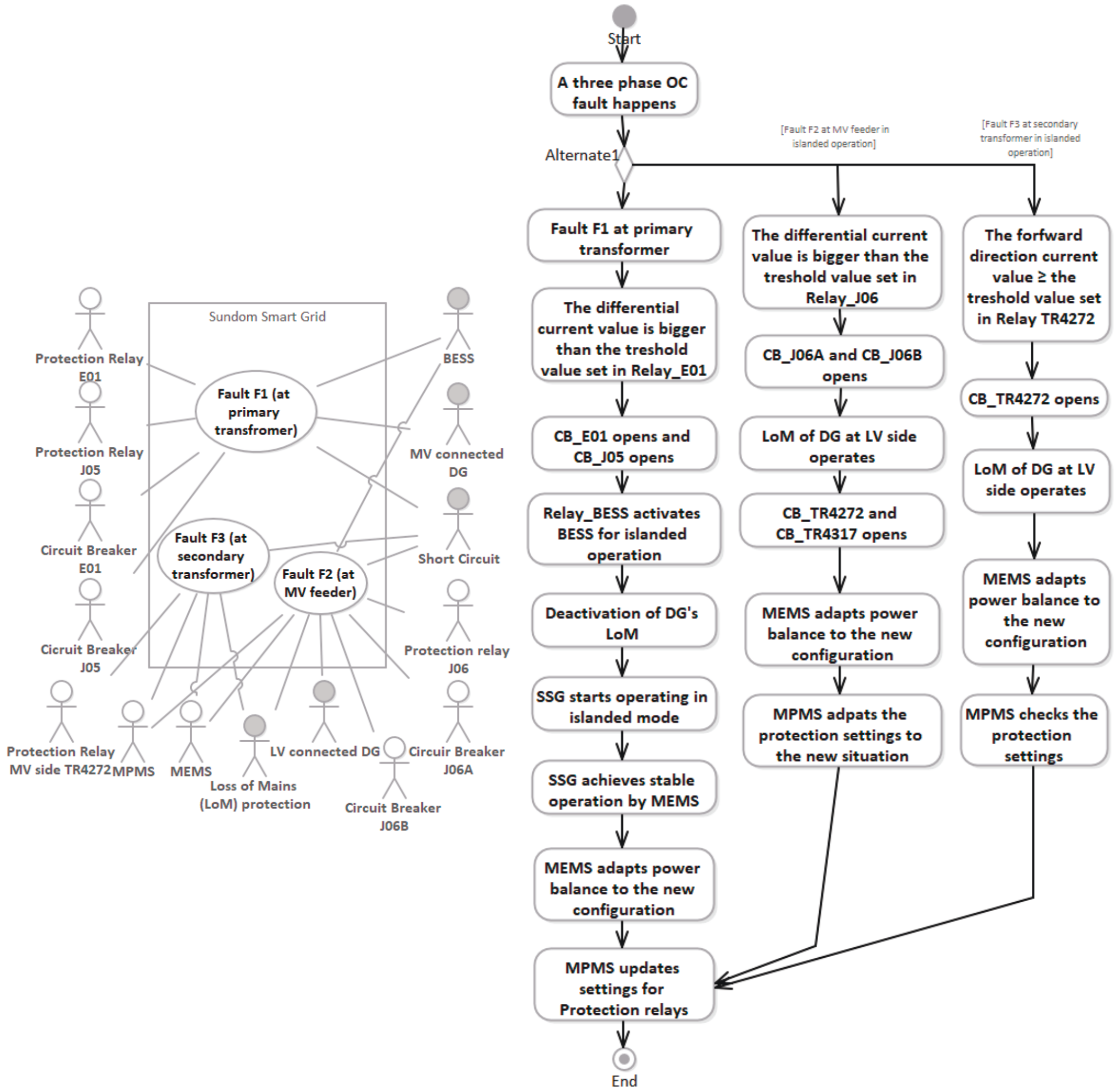
Figure 10. Use case diagram of the demand response for ancillary services PUCs.

Figure 10 presents the use case of demand response for ancillary services, where the related actors are associated to the following sub-use cases: electricity information exchange, trading on electricity markets, agreement of load control, demand forecasting, collection of demand flexibility, DR optimization, DR scheduling, sending of the price signal, and load control. Moreover, Figure 9b presents the activities within the use case, which are:

- Market participation mode on—green light;
- MMS predicts flexibility (demand and generation);
- MMS gives the demand flexibility estimate to an aggregator;
- Aggregator optimizes the demand flexibility;
- Aggregator schedules the demand flexibility;
- Aggregator sends a bid to the markets (EUR/kW,h);
- Market operator (MO) gives the market price;
- Execution;
- MO gives the trading results (EUR/kW,h);
- Aggregator distributes profits between the customers.

5.2. The Protection PUC

Figure 11a presents the use case diagram of protection PUCs in the SSG. The use cases are fault F1 at the primary transformer, fault F2 at MV feeder, and fault F3 at the secondary transformer. The locations of the faults are presented in Figure 8. Fault F1 describes the situation were a fault happens in the primary transformer protection zone. Fault F2 describes the situations where a fault occurs in the MV feeder protection zone, and fault F3 describes a situation where a fault happens in the secondary transformer zone, that is, in the LV distribution network.



(**a**) (**b**)

Figure 11. The protection PUC for the Sundom Smart Grid: (**a**) use case diagram; (**b**) activity diagram.

Figure 11b presents the activity diagram of the protection PUC in the overcurrent (OC) protection cases. The cases of the interest are faults F1, F2, and F3, where

- F1 presents OC fault at the primary transformer;
- F2 presents OC fault at MV feeder in the microgrid islanded operation mode;
- F3 presents OC fault at the secondary transformer in the microgrid islanded operation mode.

In the case of F1, differential protection operates, and after that, the battery energy storage system (BESS) is activated for islanded operation, and loss of mains (LoM) protection is deactivated in DGs. The MEMS takes care of stabilizing the islanded operation of the microgrid, adapts the power balance to the new grid configuration, and updates the settings for protection relays. In the case of F2, line differential protection operates, and after that, LoM operates at the LV side. Here, the line differential is used since it provides the required selectivity conveniently in this kind of system. Next, circuit breakers (CBs) open at related secondary transformers. Finally, the MEMS adapts the power balance in the new microgrid configuration, and the microgrid protection management system (MPMS) adapts the protection settings to the new situation. In the case of F3, the directional OC protection operates at the MV terminals of the transformer, and the CB (in the future) at the secondary substation opens.

After that, the LoM of DG operates at the LV side, the MEMS adapts power balance to the new grid configuration, and the MPMS checks the protection settings.

6. Demand Response, Reactive Power Control and Protection Test Use Cases for the Sundom Smart Grid

In the following, the TUCs are developed for creating test scenarios for real-time simulation, which aims to conduct SIL or HIL testing of microgrid control functions. The TUCs are generated in different ways, from top-down and bottom-up, as well as based on different functioning time-frames. For the first case, the demand response for ancillary services TUC, a higher-level use case (PUC), was developed and further extended to a TUC and finally a control algorithm in the simulation platform. For the second and the third cases, the reactive power control for technical ancillary services TUC and the overcurrent fault F1 at the transformer terminal TUC the, existing simulation platform, developed models, and case studies were utilized for developing the TUCs. The functioning time-frame differs in the following manner: in the first case, the control can be considered as a grid interactive control or a tertiary control function; in the second case, the control can be considered as a microgrid supervisory control or a secondary control function; the last case can be considered as a device level controller or a primary control function, as well as a secondary control.

6.1. The Demand Response for Ancillary Services TUC

The demand response for ancillary services TUC was developed for the SSG. In this scenario, the DSO operates as a microgrid operator or owner, and there is no contract for load control with customers. The energy company contracts with customers and acts as a retailer aggregator that contributes to the control of electric storage heating and water boilers, which are the most prominent general load types of residential customers.

The customers are divided into three groups: group 1 represent residential customers with electricity use of up to 10,000 kWh per year; group 2 consists of residential customers with annual consumption of over 10,000 kWh; and group 3-type customers represent other residential customers who are not included in group 1 or group 2. The customers with electrically heated houses are included in group 2. The DR program is applied for electric heating of customers in group 2 and the water boilers of customers in group 1 and 2. Additionally, control of the battery for the DR program could be applied to all customers with photovoltaic (PV) units including battery storage, but this is left for future studies. Furthermore, control of PV generation and active power could be utilized for power balance management/renewable energy resources (RES) control.

Figure 12 presents the evaluation of DR potential in the SSG, showing the peak power measurement in 2018 as well as the estimates for years 2020, 2025, and 2030. The values are categorized by demand and by generation, according to feeders J06 Sulva, J07 Sundom, and J09 Vaskiluoto. Additionally, the increasing amount of electric vehicles—harging of them, is considered here. The potential of the DR in water boilers and electric storage heating is presented as a negative load as well as in wind power and an increasing amount of PV generation. It can be noticed that there is potential for executing DR programs in the SSG.

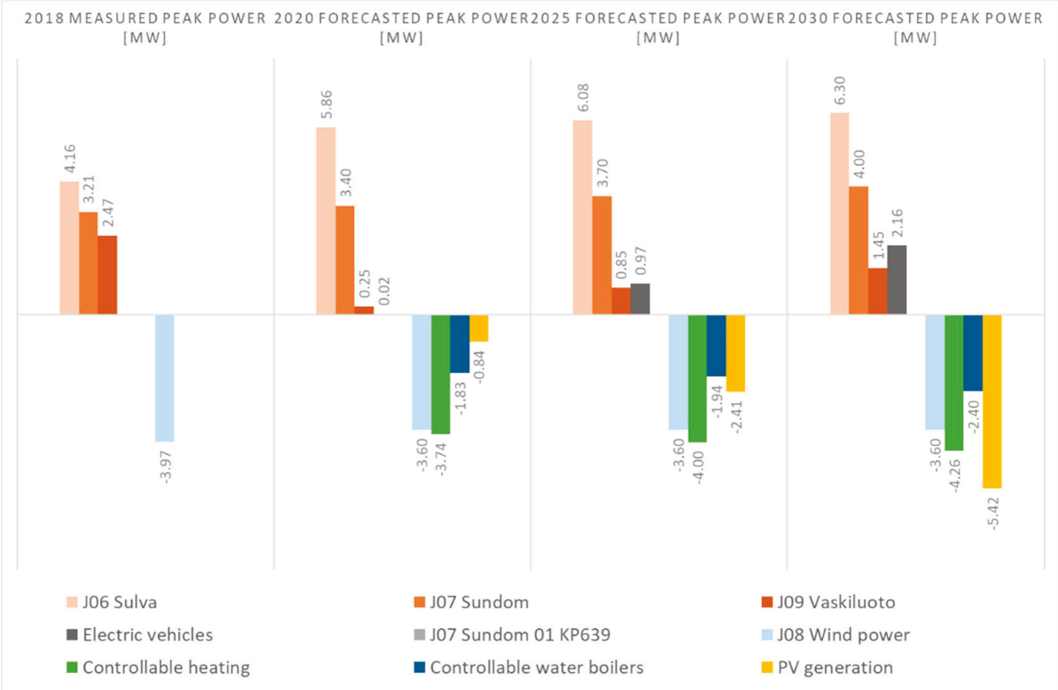


Figure 12. Peak power, the potential of demand response, and the estimation of distributed generation in the Sundom Smart Grid.

The DR program is executed according to the load control agreement between an aggregator and customers. The aggregator submits a bid to the MO based on criteria agreed with the customers. In this case, the criteria or measures include the level of the spot electricity price forecast and the temperature forecast. The spot price level has to be over 4 cents/kWh (the DR program will be permitted), and the temperature has to be below 5 °C (the limit where the heating is generally activated, that is, there exist controllable loads), in order to execute the DR program. Figure 13 presents the operation of the developed control or the "flowchart" for the simulation model development as aforementioned by the activity diagram of the developed TUC. The activity diagram presents the control signal generation based on the measurements that mimic temperature and price forecasts.

Next, the TUC was exploited in the development of a simulation model of the DR controller. A previously developed simulation platform was exploited, which is based on OPAL-RT's real-time co-simulation platform. The emulated system consists of the power grid simulations in ePHASORSIM and the control algorithm simulations in eMEGASIM in parallel with interactions. This is presented in more detail in [10]. The simulations in this study were carried out with real-time simulation models but in offline mode, which is sufficient to verify the methodology described in this paper. The benefit is that in the future, the developed models can be utilized in the real-time SIL simulations and HIL testing.

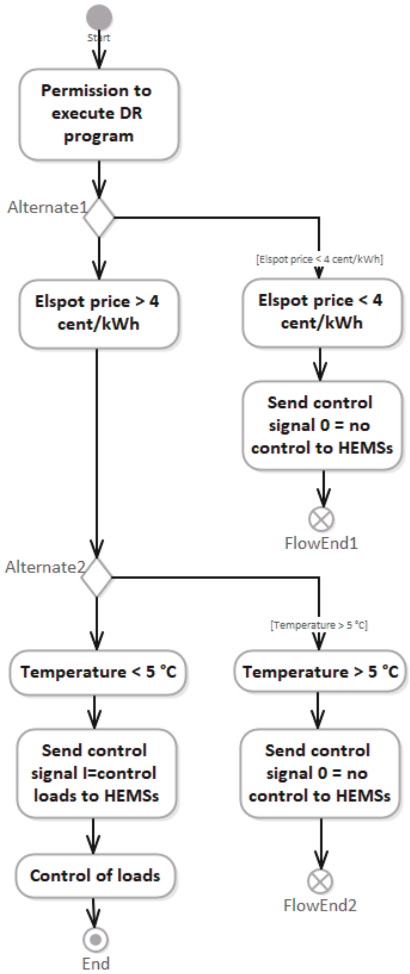


Figure 13. Demand response in the Sundom Smart Grid—activity diagram of the demand response for ancillary services TUC.

The simulation concept for the DR (as well as reactive power control to be presented later) TUC is presented in Figure 14, where the simulated power grid, control algorithms, and a subsystem are present. Active and reactive power inputs are implemented with the PQ_{load} subsystems, where P_{load} expresses the measured power. The data of measured power consist of the hourly average values of the active power of the year 2018. Next, participation factors nG1 … nG3, express the share of all customers for generating the loading of a feeder by the customer type groups (group1–group3, as described above). Active power P_{wb} represents the price-controlled active power from the water boilers. Furthermore, active power from electric storage heating is represented by P_{h}, which is price-controlled and depends on temperature conditions. The reactive power of the loads Q_{load} was generated with a constant power factor of 0.995_{ind}. Overall, participation in the DR program was set to nDR = 0.3, representing the fact that 30% of potential customers have contracts with the retailer/aggregator.

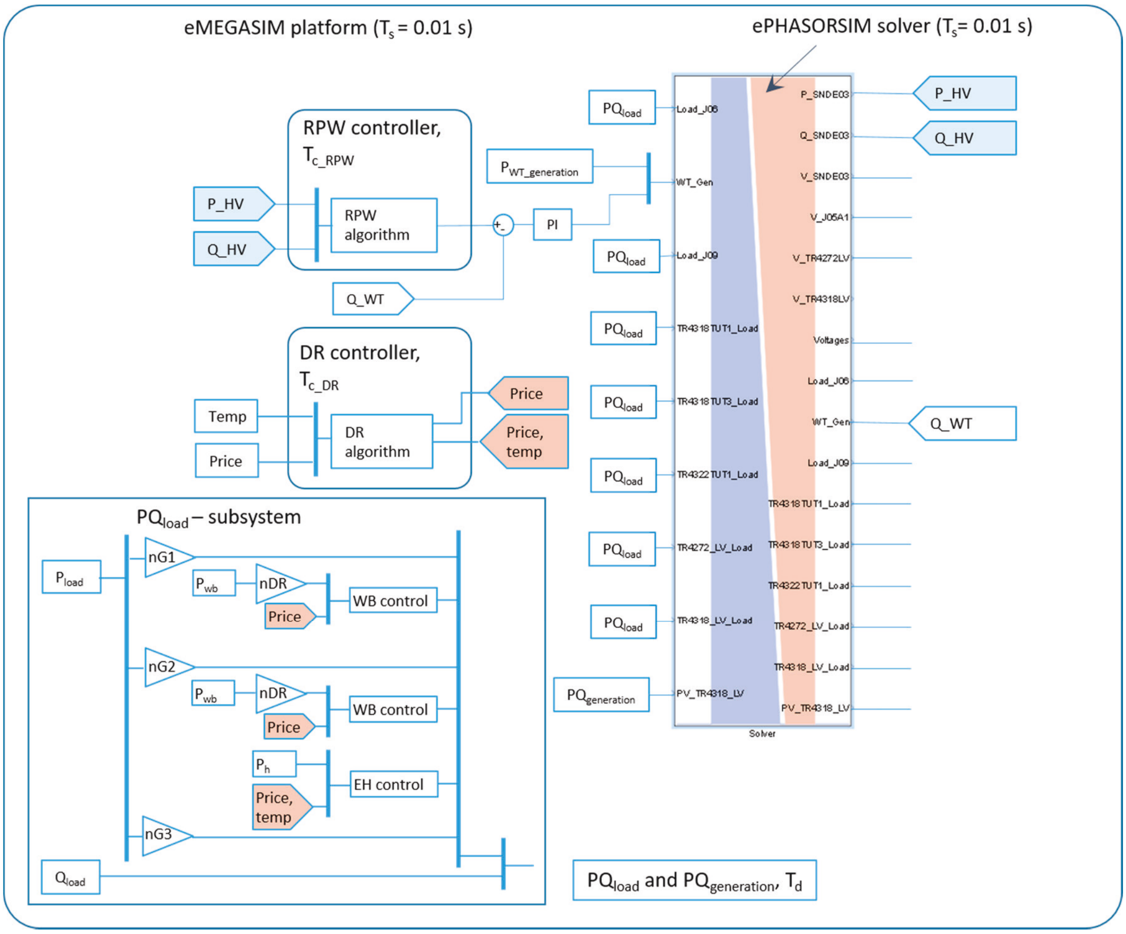


Figure 14. The simulation architecture for the emulated power system and the controllers.

The simulation was executed for the full year of 2018. The simulation model utilizes the measurement and historical data, which are hourly values of average active power by feeders, time series of temperature, and Elspot electricity prices. Load data are gathered from the measurement database containing real data from the SSG.

Four test cases were developed for power flow calculations in different situations.

(1) No wind generation and no DR control;
(2) No wind generation and DR control applied;
(3) Wind generation from a 3.6 MW turbine considered and no DR control;
(4) Wind generation from a 3.6 MW turbine considered and DR control applied.

Figure 15 shows the active power flow at the HV/MV connection point in the different cases. It can be seen that wind generation produces fluctuation of the active power flow at the HV connection point. Furthermore, by executing price-based DR control, the fluctuation of active power increases.

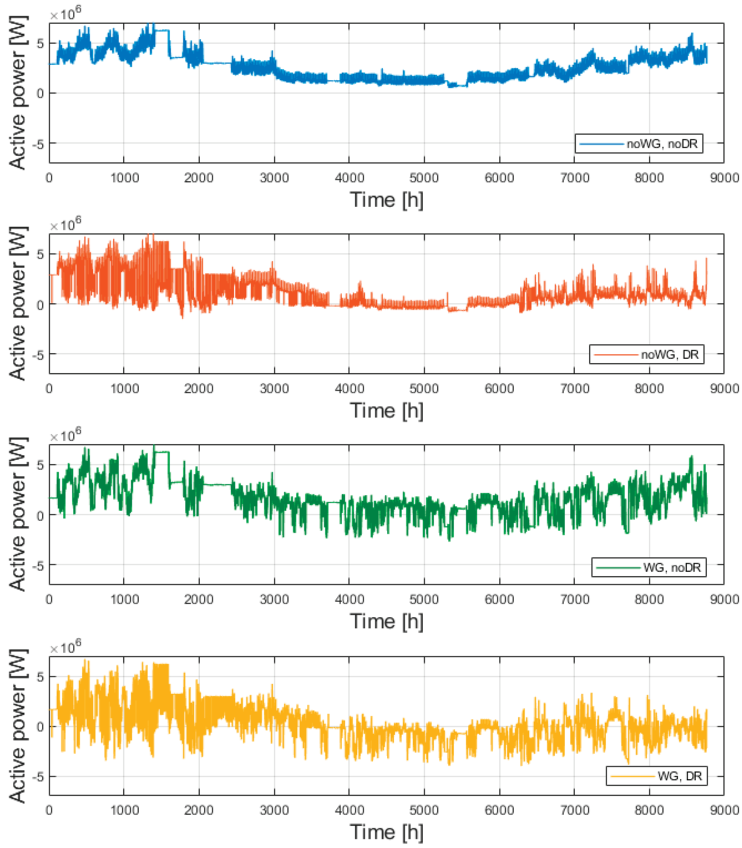


Figure 15. Demand response in the Sundom Smart Grid—active power flow in the HV/MV connection point in different case studies.

6.2. The Reactive Power Control or the Technical Ancillary Services TUC

The reactive power window (RPW) control for technical ancillary services TUC was developed for the SSG, which presents the management of reactive power at the interconnection point of the microgrid. In this case, the point is the HV/MV connection of the SSG, and the RPW control represents a secondary control function of an MMS. The task of the RPW control is to manage the reactive power flow to stand within the RPW limits defined by the transmission system operator (TSO) [50]. The control is executed through a full-scale wind turbine (WT) converter that is connected to the substation with its feeder J08.

The RPW control algorithm, as well as the simulation platform, are developed in previous studies, and they are presented in [10]. Figure 16 shows the developed activity diagram of the RPW control algorithm for the technical ancillary services TUC. Furthermore, the simulation architecture where the controller is functioning is presented in Figure 14.

Six test cases were developed for power flow calculations in different situations:

(1) No wind generation, no DR control, and no RPW control;
(2) No wind generation, DR control applied, and no RPW control;
(3) Wind generation from a 3.6 MW turbine considered, DR control applied, and no RPW control;
(4) Wind generation considered, no RPW control, and DR control applied;
(5) Wind generation considered, RPW control applied, and no DR control;
(6) Wind generation considered, RPW control applied, and DR control applied.

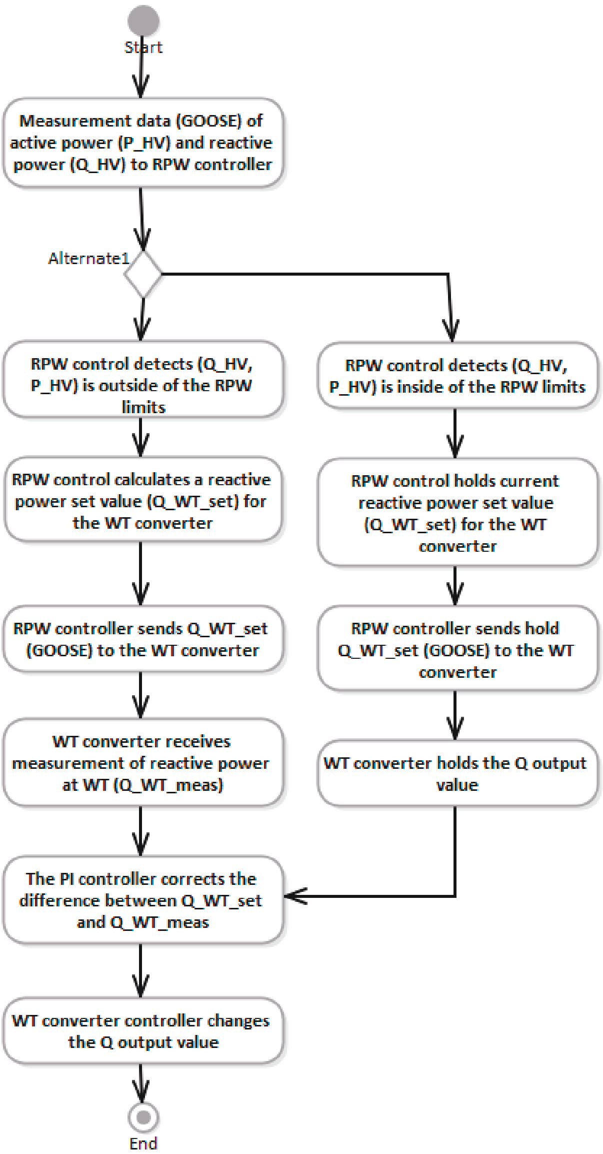


Figure 16. Reactive power control in the Sundom Smart Grid—activity diagram of RPW control for the technical ancillary services TUC.

Figure 17 shows the results of the reactive power flow at the HV/MV connection point in different case studies. The first figure at the top describes case 1 (case 1 also in DR). When comparing it to Figure 15, it can be noticed that the reactive power flow curve follows the curve of the active power flow. The second figure, case 2, describes the situation that is the same as case 2 in DR. It can be noticed that executing the DR program causes fluctuations in the reactive power flow similar to active power. The third figure, case 3, is the same as case 3 in DR. In this case, the curve of the reactive power flow does not follow the shape of active power. This can be explained by the fact that the WT is connected via a short connection directly to the MV bus at the primary substation and, therefore, the line does not generate reactive power to a great extent. In the fourth figure, case 4 (the same as case 4 in DR), the shape of the reactive power flow curve differs from the active power flow because of the changes in the active power generation of the WT as well as because of DR. The generation is near the substation, but the demand is happening in "customer premises" via long connections. The cabling affects the amount of reactive power generation (capacitive). In this study (the year 2018), the cabling degree (the share of the length of the underground cables in the network) is 31%. The next two figures present the results of case 5 and case 6. Reactive power control is executed in these cases, and it can be noticed that executing DR generates fluctuations in the reactive power flow.

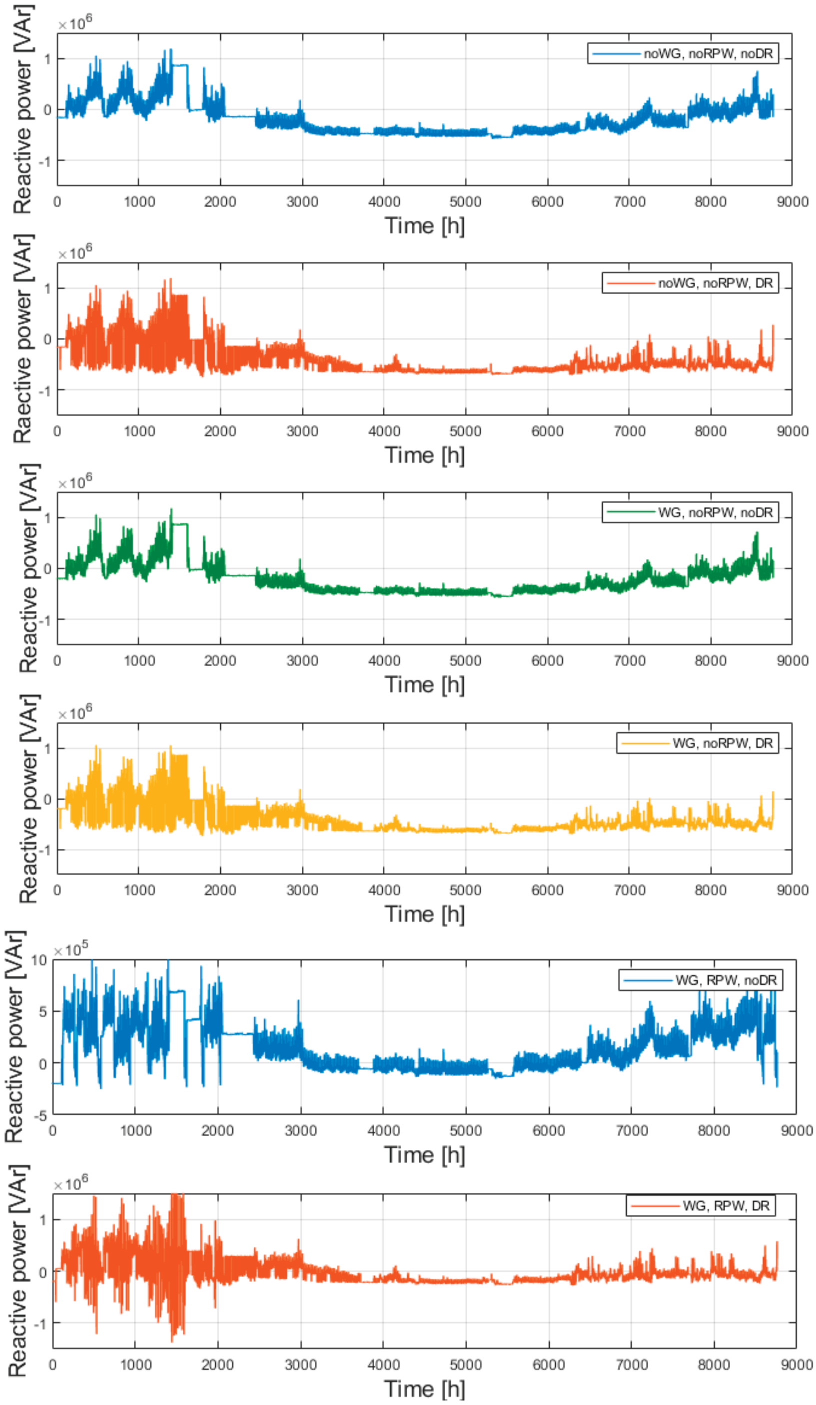


Figure 17. Reactive power control in the Sundom Smart Grid—reactive power flow at the HV/MV connection point in different case studies.

Based on these results, it can be stated that for the reactive power flow at the HV/MV in the SSG connection point: (i) the effect of wind generation is negligible, (ii) the effect of DR control is notable, (iii) the effect of RPW control is remarkable, and (iv) the effect of DR and RPW control in parallel is noteworthy. These phenomena can be explained based on the characteristics of the studied distribution network. The less cables loaded, the more reactive power produced by the cables. The wind turbine is connected to the MV bus by a short cable. All the loads are modelled as constant power types, but in reality, the loads in the SSG are also voltage-dependent (constant current or constant impedance) in addition to constant power types. Hence, the controlled loads are resistive and thus of constant power type, not consuming reactive power. The effect of DR on the reactive power flow is noted for the cables increasing the reactive power generation.

6.3. The Overcurrent Fault F1 at Transformer Terminal TUC

The OC fault F1 at the transformer terminal TUC is associated with the fault F1 at the primary transformer PUC as well as the protection HL-UC and the unintentional islanding HL-UC. The OC fault F1 at the transformer terminal TUC relates to the path fault F1 as illustrated in Figure 11b. In this case or path, the transformer protection is implemented by the circuit breakers (CBs) operated by the protection relays. According to Figure 8, for the protection of the primary transformer, there is a protection device (PD) that is located at the bay E01.

In this TUC, the transformer protection is implemented at the primary side protection relay IED-E01, which operates the CB at E01 and is connected to the secondary side relay IED-J05, as shown in Figure 18. The secondary side relay IED-J05 is a part of the MV busbar protection and also operates the POI of this microgrid (CB J05). The function of the PD1 is to isolate the primary substation from the utility grid during the line fault conditions. The PD2 (LBS + IED-J05) is located on the secondary side of the transformer. Figure 18 shows the single line diagram for the overcurrent fault F1 at the transformer primary side terminal. Figure 18 is drawn based on Figure 8 to include only the related devices involved in fault F1 to understand how they interact with each other in this fault case. As indicated in Figure 18, the differential protection function is used as the main 1 protection and definite time overcurrent protection function is used as the main 2 protection at IED-E01, IED-J05 and IED-J06, which receive local sampled value (SV) measurements (SV_{Local}) available at these locations. The remote SV measurements (SV_{Remote}) of other bays in the substation can be subscribed by these IEDs using the Ethernet-based high speed communication network, station bus 1. The local and remote SV measurements are used for the detection of the fault by the main 1 and main 2 protections, and GOOSE messages are published and subscribed to indicate and determine whether a fault exists on the remote end.

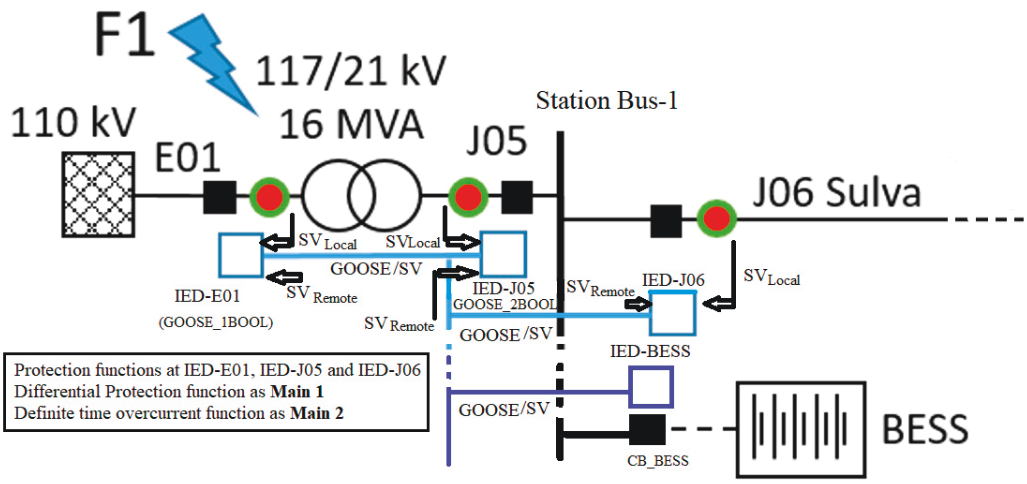


Figure 18. Single line diagram of the overcurrent fault F1 at the transformer terminal TUC (based on Figure 8).

The activity diagram of the OC fault F1 at the transformer terminal TUC is presented in Figure 19, which is developed based on the IEC 61,850 GOOSE communication-based definite time overcurrent relay case studies conducted in [51]. The main difference between the network presented in [51] and the SSG (Figures 8 and 18) is that in the SSG, there is also differential protection functioning as the main 1 protection and the definite time overcurrent protection function as the main 2 protection for the transformer, whereas in [51], there is only an overhead line protected by a definite time overcurrent protection function.

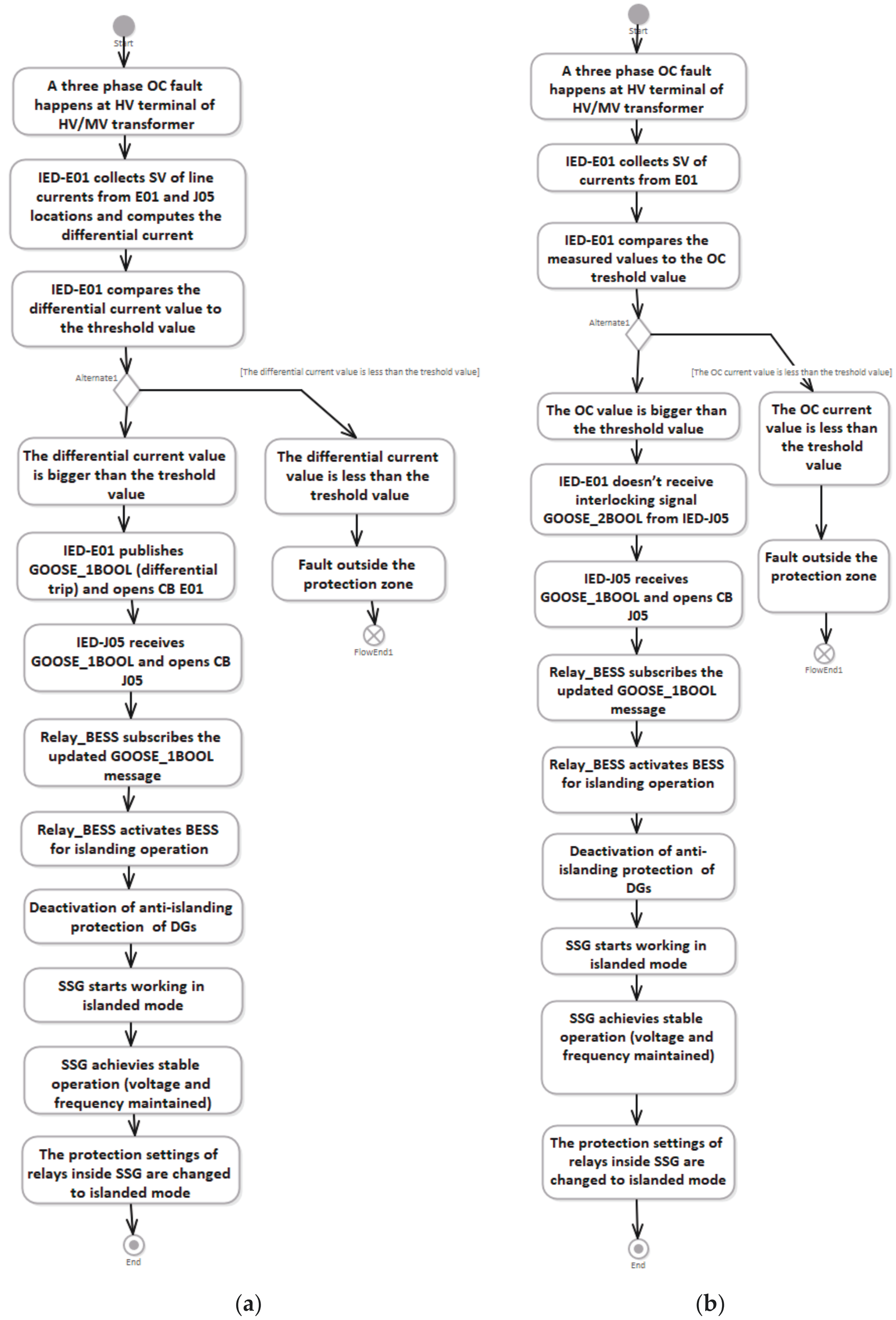


Figure 19. Activity diagram of the overcurrent fault F1 at the transformer terminal TUC: (**a**) main 1 protection; (**b**) main 2 protection.

In Figure 19, it is assumed that the IED-E01 detects the fault F1 either with its main 1 differential protection function (a) or main 2 definite time overcurrent (b). If the fault is detected by the differential protection function, IED-E01 publishes the fault detection GOOSE message "GOOSE_1BOOL" (transfer trip of the POI) and sends the tripping command to CB E01. After receiving the GOOSE_1BOOL message, IED-J05 sends the tripping command to CB J05. Alternatively, the fault F1 is detected by the main 2 definite time overcurrent function of IED-E01. Here the reverse interlocking scheme can be applied, so that if IED-J05 detects a fault at the MV busbar, it publishes the GOOSE message "GOOSE_2BOOL" (interlocking signal). In the fault F1, IED-E01 detects the overcurrent and receives no GOOSE_2BOOL message, which also results in the tripping of CB E01 and a transfer trip command "GOOSE_1BOOL" is sent to IED J05. Additionally, the IED-BESS receives the GOOSE_1BOOL from the IED-E01 and activates/connects the BESS rapidly so that it can act as the grid-forming source for the islanded part of the SSG without the disconnection of DGs. In this fault case, the fault is removed completely after the tripping of CB J05, and smooth transition to the islanded mode can be ensured without the disconnection of DGs. Moreover, the anti-islanding protections at the DGs need to be deactivated until a stable islanded mode operation is reached. After reaching a stable islanded mode operation with voltage and frequency maintained in the islanded section, the anti-islanding protections of DGs are reactivated, and the protection settings of IEDs are changed to the settings suitable for the fault detection in the islanded mode. In this use case, the BESS is assumed to be normally disconnected in the grid-connected mode, and it is activated only during the islanded mode of operation.

In this paper, only the potential methodology is discussed for the overcurrent fault F1 at the primary terminal of the transformer based on the previous work conducted in [51]. The use case will be further evaluated for its practical implementation into case studies, and the results will be presented in future research papers. A real-time simulation model of the SSG model will be created using Matlab/Simulink, implementing the IEC 61,850 standard based GOOSE and SV messages in order to evaluate the performance of the proposed protection scheme.

7. Conclusions

This paper introduced several microgrid management functions based on the current standardization and research. Based on these, the functionalities of microgrids were aligned not only to the control scheme hierarchy that includes three known control levels: primary, secondary, and tertiary, but also to zero control levels. In addition, a control architecture, including four control layers, was presented. Two specific separate systems were identified, namely, the energy management system and the protection system.

The microgrid management system is a system of systems, and therefore this paper focuses on defining the functions of the microgrids regardless of the practical solution. Moving from an abstract level or microgrid concept and going closer to practice, the utilization of use case modelling was presented. With reference to the depth and different levels of use cases, the relation of functionality between the concept and a single case study of the microgrid management system was highlighted.

In order to apply a microgrid concept as a management system in a real-world case, we propose that higher-level use cases and primary use cases should be clarified and only the particular requirements of the network in question should be deployed. In this paper, general microgrid functions were presented as HL-UCs. Further selected PUCs were developed for a real distribution network (the SSG), and finally dedicated TUCs, which rely on the real measurement data. Finally, various sets of simulation case studies were aligned with the developed TUCs. The simulation cases were developed for real-time SIL and controller hardware-in-the-loop (CHIL) simulations, and they function on different time frames. The AS use cases were tested in co-simulation setup with one-year measurement data, whereas the protection use case was tested in the EMT platform.

The description of the proper level of use cases becomes extremely important when applying several microgrid functionalities that can affect each other; for example, as shown in this paper, ancillary services where the active power, as well as reactive power, are controlled at the same time.

Because the end customer plays a crucial role in most of the microgrids, the management system is formed from different subsystems considering the aims of operation and goals. In order to recognize and realize the different levels of functions that can affect each other, a methodology for expressing the functions of the system like those in this paper is essential; for example, one that considers a residential customer, who owns the inverter-connected generation and controllable loads and wants to participate in both DR programs and reactive power management.

Multiobjective control of microgrids exerts pressure to develop test cases for utilizing a management system in a central, distributed, comprehensive and dedicated manner, as presented in this paper.

This paper presented TUCs for real-time SIL and CHIL simulation, which were selected based on different time frames. In the future, different configurations, with reference to the depth of use cases and time domain analysis, need to be developed in order to examine various microgrid functions running in parallel.

Author Contributions: Conceptualization, K.S.; methodology, K.S.; software, K.S.; validation, K.S.; formal analysis, K.S., and A.A.M.; investigation, K.S.; resources, K.S.; data curation, K.S.; writing—original draft preparation, K.S.; writing—review and editing, K.K., A.A.M., H.L., and L.K.; visualization, K.S.; supervision, K.K., and H.L.; project administration, L.K., and K.K.; funding acquisition, L.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was carried out in the VINPOWER project with financial support provided by the European Regional Development Fund (ERDF), Project No. A73094. In addition, this work was carried out in the SolarX research project with financial support provided by the Business Finland, 2019–2021 (grant No. 6844/31/2018).

Acknowledgments: The provision of measurement data by Vaasan Sähköverkko Ltd. is highly appreciated. The data that support the findings of this study are available from the corresponding author upon reasonable request and with permission of Vaasan Sähköverkko Ltd.

Conflicts of Interest: The authors declare no conflict of interest.

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Evolution of the Electricity Distribution Networks—Active Management Architecture Schemes and Microgrid Control Functionalities

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Abstract: The power system transition to smart grids brings challenges to electricity distribution network development since it involves several stakeholders and actors whose needs must be met to be successful for the electricity network upgrade. The technological challenges arise mainly from the various distributed energy resources (DERs) integration and use and network optimization and security. End-customers play a central role in future network operations. Understanding the network's evolution through possible network operational scenarios could create a dedicated and reliable roadmap for the various stakeholders' use. This paper presents a method to develop the evolving operational scenarios and related management schemes, including microgrid control functionalities, and analyzes the evolution of electricity distribution networks considering medium and low voltage grids. The analysis consists of the dynamic descriptions of network operations and the static illustrations of the relationships among classified actors. The method and analysis use an object-oriented and standardized software modeling language, the unified modeling language (UML). Operational descriptions for the four evolution phases of electricity distribution networks are defined and analyzed by Enterprise Architect, a UML tool. This analysis is followed by the active management architecture schemes with the microgrid control functionalities. The graphical models and analysis generated can be used for scenario building in roadmap development, real-time simulations, and management system development. The developed method, presented with high-level use cases (HL-UCs), can be further used to develop and analyze several parallel running control algorithms for DERs providing ancillary services (ASs) in the evolving electricity distribution networks.

Keywords: adaptive control; demand-side management; energy management; load flow control; load management; microgrids; power system control; power system management; power system simulation; reactive power control; smart grids; voltage control

Citation: Sirviö, K.H.; Laaksonen, H.; Kauhaniemi, K.; Hatziargyriou, N. Evolution of the Electricity Distribution Networks—Active Management Architecture Schemes and Microgrid Control Functionalities. *Appl. Sci.* **2021**, *11*, 2793. https://doi.org/10.3390/app11062793

Academic Editor: Pierluigi Siano

Received: 18 February 2021
Accepted: 18 March 2021
Published: 21 March 2021

1. Introduction

The European Union (EU) aims to be climate neutral by 2050, and this goal and the long-term strategy is the core part of the action plan called the Green Deal. The Green Deal aims to significantly reduce emissions, invest in cutting-edge research and innovation, and preserve Europe's natural environment. The climate and energy targets are set until 2030, including a reduction in greenhouse gas (GHG) emissions (at least 40% compared to 1990 level), an increase in the share of renewable energy (at least 32%), and improvement of energy efficiency (to be at least 32.5%). Currently, the European Commission (EC) proposes an updated Climate Target Plan 2030, where the GHG emissions reduction target is 55%. It was published together with the amended proposal for a European Climate Law, which would make the 55% target compulsory [1,2].

Future energy infrastructure must be developed to achieve the ambitious climate targets so that different energy vectors are interconnected to improve efficiency and security. The electricity network is the backbone of this flexible energy system. The future power system or smart grids aim to reduce GHG emissions by using all forms of renewable energy resources (RESs), both central and distributed. Smart grids should be operated intelligently, securing safe and reliable electricity distribution, energy savings, efficient use of energy, and based on advanced energy markets. Furthermore, the future electricity distribution networks or intelligent electricity distribution networks are supposed to connect different types of actors, including new actors and new roles of the existing actors, such as new management systems, aggregators, and prosumers. Different kinds of regulators, utility companies, vendors, and customers face questions such as what type of role(s) they have in the future networks and which kinds of systems must fulfill their needs.

Visions of power grids, evolutions, roadmaps, and development paths are presented in several high-level descriptions. For example, the European Technology and Innovation Platform on Smart Networks for the Energy Transition (ETIP-SNET) describes the European target energy system in Vision 2050 [3]. The roadmap toward 2050 defines 12 functionalities to be implemented in 2020–2030 across the energy system's value chain enabling the energy transition [4]. Two trends are set out: micro (focuses on local solutions) and mega (focuses on the system or even intra-system-wide solutions), enabling high penetration of RES, are presented in [5]. Microgrids can fulfill all 12 functionalities, as presented in [4] as an intelligent subsystem in the future flexible electricity distribution system. At present, significant efforts are devoted to low voltage (LV) grids, which in contrast to medium voltage (MV) grids are passive, and distribution management systems (DMS) are rarely implemented. The descriptions of a management system and a control strategy are essential to integrate the LV distribution networks in smart grids.

Moreover, for managing the LV distribution network in real-time, a DMS is required with transparent data architecture [6,7]. It is important that the transparent system has an object-oriented design, which provides a library with standard objects, and can be adapted to the local conditions. Transparent data architecture allows easy adaptation to specific customer installations.

This paper aims to demonstrate the development of the evolving operational scenarios and the related management schemes, including microgrid control functionalities. The objectives are to (i) define the evolution phases of electricity distribution networks, (ii) define the related key actors, (iii) develop operational scenarios, (iv) provide a structural description of the management system, and (v) conduct an analysis.

The basic elements of the purpose of scenario building for the future are (i) recognizing the facts of the present situation, (ii) a vision of a better future, (iii) state of mind, and (iv) action [8]. The prerequisite for the scenario building or anticipating and envisioning tomorrow is understanding the prevailing facts, which are then summarized by imagination [8]. In addition, the weak signals [9–11] are used individually since they are indicators of changing or emerging topics. The weak signals may be related, for example, to technologies, behaviors, markets, and regulations. It supplements the trend analysis. The megatrends, trends, and weak signals create the envisioned future scenarios expressed by the various use cases (UCs).

The organization of the paper follows the method's use process. First, the overview of the analysis method is presented in Section 2. Next, the key factors of the electricity distribution network development for scenario building are described in Section 3. Section 4 introduces the use of the method for a case study for a Finnish example. Section 5 contains operational descriptions of the evolving electricity distribution networks consisting of the energy management HL-UCs and the ancillary services (ASs) UCs in different evolution phases, the power balance management, and the overcurrent (OC) protection UCs in the microgrid phase. In Section 6, using the same case study as an example, the structural description of the future electricity distribution networks is created for the microgrid phase, including energy management, power balance management, and protection UCs. Section 6 also combines the outcome of the various UCs by developing structural illustrations to analyze the management system of the future electricity distribution networks. In Section 7, the results are discussed. It is shown that the method can help to develop, for example, a commonly understood roadmap. Finally, conclusions are drawn in Section 8.

2. Analysis Method Overview

This paper uses an object-oriented method for analyzing the operations and the structure of the evolving electricity distribution networks. Behavioral differences and differences in the static relationships in a studied system are illustrated by the object-oriented unified modeling language (UML) tool, Enterprise Architect. The UML is standardized by ISO/IEC 19501, and by using the UML tool, visual models of systems can be developed for system analysis. These are already used in software engineering for general-level UC descriptions. The UCs can be developed on several levels and for several purposes [12]. Based on the UCs and the diagrams derived from them, the system's operation can be illustrated and used for hardware and software development. This methodology is used in this paper for evolution path description and illustrating and analyzing the development of the distribution network management system.

The evolution phases of the future electricity distribution networks defined in [13] are used here. These are: (i) the traditional network, (ii) the self-sufficient in electric energy, (iii) the microgrid, and (iv) the intelligent network of microgrids, and they were made for LV distribution networks, but they are further developed in this paper to cover MV distribution networks. In the following, energy management, power balance management, and protection UCs are represented in evolution phases, as shown in Figure 1. The vertical axis represents evolution phases of the MV and LV distribution networks, in which the energy management development by the conceptual or high-level use cases (HL-UCs) as well as the case study level or primary use cases (PUC), the microgrid phase's power balance management and protection are studied. The horizontal analysis denotes the parallel and simultaneous HL-UCs, which are studied in this paper in the microgrid phase, affecting the system. An HL-UC can be implemented in various ways, so it cannot be mapped to a particular system or architecture, but a PUC applied to a particular system can be assigned to a defined architecture [14]. These HL-UCs aim to illustrate the system's dynamic behavior, which is studied further by defining the classified actors (objects), and their static relationships in the class diagrams. Hence, the class diagrams provide a static illustration of the system. The evolution phases apply to a suburban or rural area covering a whole electricity distribution network from a primary substation to the customer premises.

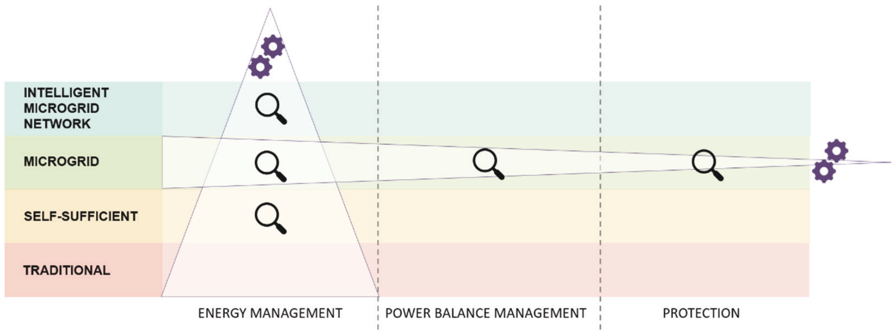
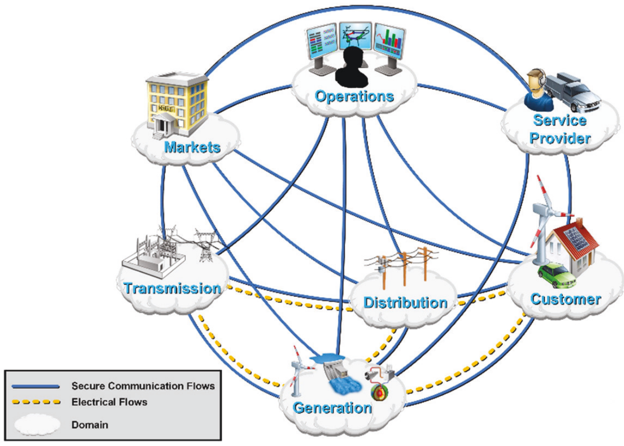
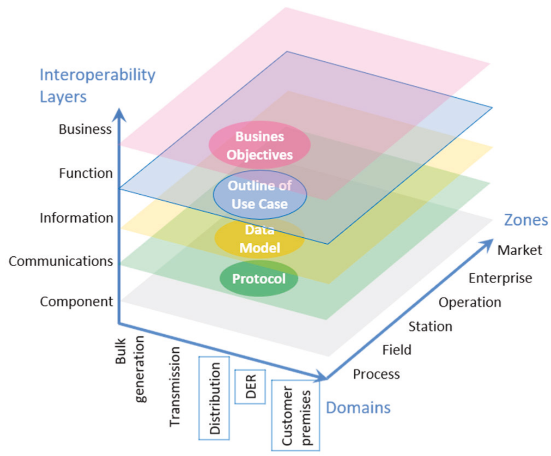


Figure 1. The studied use cases of the developing distribution networks.

The analysis can adopt the smart grid architecture model (SGAM) framework, which includes a methodology for developing UCs, reference architectures, communication technologies, and data-and-information models [15]. The SGAM model can be exploited, for example, for analysis and gap analysis of the developed UCs. Figure 2 illustrates the SGAM model [16], representing the functional information data flows between the main domains of the smart grids, which is adapted from [17] and later [18], to the European context. The concept integrates several systems and subsystem architectures. Figure 2a presents the smart grid conceptual domains used in this paper for locating the actors. Figure 2b presents the conducted research in the SGAM framework, the developed UC descriptions in the function layer over the distribution, DER (distributed energy resource), and customer premises domains.



(**a**)



(**b**)

Figure 2. (**a**) NIST smart grids conceptual model with conceptual domains [18]. (**b**) Smart grid architecture model, adapted from [16].

3. Electricity Distribution Network Development

Along with the social and economic aspects, technology plays a crucial role in developing electricity distribution networks. Technology solutions are the essential enablers giving benefits to the stakeholders, who are the actors operating the system or affected by its operation, having financial or social benefits. Actors can also be systems, devices, software, and events that can perform an operation that changes the state of the system. Implementing new or enhanced concepts in the evolving electricity distribution networks brings new technologies and operation methods but can also cause problems in the traditional electricity distribution operation. For example, the increasing amount of DERs in the power grids causes two-direction power flow between generation and consumption and intermittent power generation affecting the quality of electricity, safety, and protection issues. Consideration of these challenges is crucial in the electricity distribution network operation and planning.

3.1. Active Distribution Networks and Microgrid Concept

According to [19], active distribution networks are defined as: "Active distribution networks (ADNs) have systems in place to control a combination of DERs, defined as generators, loads and storage. With these systems in place, the ADN becomes an Active Distribution System (ADS). "Microgrids are defined in standards, in which IEEE 2030.7 determines: "A group of interconnected loads and distributed energy resources with clearly defined electrical boundaries that act as a single controllable entity concerning to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island modes" [20]. Microgrids are also defined in IEC-TS 62898-1 [21].

This paper assumes that microgrids will be widely used and developed in various installations, as envisioned in the recent power system development roadmap for the EU [4]. Roadmaps of the microgrids evolution are presented in [22–26] in which the microgrid is defined, the microgrid types are introduced, the critical microgrid technologies and functionalities are presented, and the expected benefits are discussed. The roadmaps for commercializing microgrids are presented in [27].

A review of the microgrid development [28] highlights the arguments and drivers, which include policies and research investments, system operators' activity, various stakeholders, and incentives. One of the key drivers for microgrids' implementation is the more efficient integration of DERs. Their control and protection need novel technical solutions and applications. Standardization is essential, thus providing compliance of the different (vendors) solutions in control and protection. Key issues are data models and protocols. Based on feasible, proposed, and evaluated business cases, the operational targets can be set.

3.2. Distribution Network Planning

ADN and microgrid planning principles and methods are reviewed in [29]. Accordingly, traditional distribution network planning (TDNP) focuses on the optimal sizing and location of distribution substations and feeders and other electrical components. The optimal sizing and location of the DERs can be seen as an extension of TDNP in its transformation to active distribution network planning (ADNP). The challenge with the TDNP is running several planning optimization problems, for example, multiple scenarios simultaneously. In the ADNP, multi-energy and active management strategies are integrated into the TDNP. The ADNP mainly involves the interactive information system, DER participation, and smart automation technology integration, highlighting the planning process. The main objectives are cost, technical features, and performance [29].

The ADN is extended from the TDN with the load forecasting [30], the network planning [31–35], and the power management and control [36,37]. The LV distribution networks are of great interest since they are significantly affected by the connection of DERs; hence, the development of the LV-specific tools is essential to manage and effectively control the LV distribution level. Integrating DERs into the electricity distribution networks raises issues such as uncertainties in various time-series of energy consumption or generation that have to be solved at the ADN planning stage. Spatial forecast, satellite maps, and the geographical information system (GIS) improve planning drastically [38]. Microgrids can be considered as a flexible resource in ADNP [39,40].

From the economic perspective, the methodologies for developing business cases for microgrids are presented, for example, in [41]. For the profitable microgrids creation, a method and a tool for microgrid planning are presented in [42] to decrease the microgrid development cost. In [40], the authors claim that the following high-level steps in the planning, deployment, implementation, and operation of microgrids are needed to succeed: (i) conceptual design, (ii) technical design, (iii) implementation, and (iv) operation and maintenance. In each step, a variety of tools are used. The authors convince that the optimum would be one ultimate microgrid software combining single tools in one platform.

3.3. Network Management, Controls, and Supervisory Systems

Increasing DERs in the power grids, the local energy generation, and the loads can be adjusted to support grid flexibility and congestion management. The two-way power flow and the power electronic interfaces of the DER units create challenges, particularly to the protection systems due to the reduced short circuit currents and the changed direction of fault currents. In addition, information and communication technologies (ICT) are required for managing the DERs and loads locally.

Advanced control technologies for active distribution network management (ADNM) need to be developed to implement various operation modes. The application in which a developed concept is aimed to use gives the ultimate terms and conditions of operation. For example, a microgrid concept application can be a distribution network-interconnected microgrid or an isolated microgrid [43]. Furthermore, the required functionalities can be, for example, power balancing, congestion management, fault management, resiliency, and response to external orders in utility microgrids [43] or a combination of all the above. The management schemes (and architectures) are developed for achieving (and implementing) these desired functionalities. The ADNM schemes can be coordinated voltage control (CVC) and adaptive power factor control (PFC). The protection and automation systems for the network operation management and the implementation of coordinated control and protection schemes make possible ADNM. The ICT and the remote monitoring systems are the enablers for ADN control.

Optimal distribution management planning tools for minimizing the operational costs are to be developed for demand-side management (DSM) [44,45] and Volt/VAr control [46], for example. For the LV distribution networks, the ADNM schemes can be active and reactive power flow optimization, unbalance and reactive power compensation at the point of interconnection (POI), the power balance management in the islanded operation, demand response (DR) at POI, as well as current clearing for the non-load switching operation [47].

The distributed generation (DG) and the consumer DR programs influence the DMS operation by increasing the need to act on real-time operational data, thus increasingly demanding the sensors and information on the power system operation. The DG also affects the traditional DMS applications, such as load modeling and estimation, load flow algorithms, short circuit analysis, relay protection coordination, and fault detection and location, isolation, and service restoration (FLISR) logic. Further, monitoring, control, and data acquisition extend down, even to individual customers, by an advanced metering infrastructure (AMI), DR systems, and home energy management systems (HEMS). The open architecture in the databases (CIM, SOAP, XML, SOA) and the applications permit the improvement in the monitoring and control application of the supervisory control and data acquisition (SCADA) and DMS; integrated Volt/VAr control, databases interfacing via a standard interface with a GIS, an outage management system (OMS), or a meter data management system (MDMS) [48].

3.4. Ancillary Services and Reserves

Ancillary services (ASs) support the reliable delivery of electricity and the operation of the transmission systems. The supply and demand must be balanced at every moment, ensuring that frequency, voltage, and power load remain within certain limits. When demand changes, the adjustments and corrections in the power grid are completed with ASs. These services include frequency stability support, power balance, voltage control, supply restoration, and system management, as presented in Table 1 [49].

Table 1. Ancillary services.

Ancillary Service Type	Means
Frequency stability support	Frequency control of power, regulation, and operating reserves
Power balance	Scheduling and dispatching of balancing energy
Voltage control	Tap-changer control Reactive power control
Supply restoration	Black start capability Island operation
System management	Power quality assurance operation Asset management

Frequency support services are applied for normal operations: power system balancing and the disturbance situations or unexpected events such as power plant outages or an unforeseen increase in consumption. For example, peak shaving by load shedding is a frequency support method, often provided by heavy industry loads that are deactivated for a short time to guarantee network stability. The spinning reserve compensates for the short-term power failures due to the kinetic energy of power plant generators. RESs do not yet provide spinning reserves, but large wind turbines (WT) might be used [50].

Voltage support services ensure the quality and safety of the supply. With power factor correction, the relation between active and reactive power is adjusted so that voltage is within the operational range and stabilized. The electricity transmission and distribution cause power losses that affect the voltage magnitudes in the grid. The use of the network's capacity (particularly in the cabled network) and capacitors affect energy losses, and consequently, voltage management [50].

After a power failure, supply restoration uses services that power plants can offer with automatic black start capabilities without external energy supply, such as hydroelectric or gas power plants. In addition, electricity storage can be used to ensure the black start capability [50].

ASs can be used for the power grid's operational and bottleneck management. The rise of RES increases demands for the grid operators to manage the network congestion, aiming to avoid the foreseeable potential grid bottlenecks. In congestion management, the power plant operators are instructed to shift the planned electricity generation, called re-dispatch. Another method is the feed-in management for regulating the supply in the case of a power surplus from RES. In addition, the available capacities and capacity mechanisms can be used as ASs. Such services can be for the grid reserves or the reserves to guarantee the reliability of power plants [50].

TSOs are responsible for managing the power balance in the transmission grid in each operating situation. The quality criteria for frequency and voltage must be met in normal operation and abnormal operations. For constant control of frequency in power systems, the frequency containment reserve (FCR) programs are used. Next, the frequency restoration reserve (FFR) programs are implemented for returning the frequency to its normal range and release the FCR back to use. Further, the replacement reserves (RR) can be released to activate the FFR to stand by in case of new disturbances (not used in the Nordic system) [51].

4. Evolution of the Electricity Distribution Networks—A Finnish Case

This paper focuses on the evolution of the electricity distribution networks in the Nordic countries; however, the analysis method and the results can be applied to the distribution networks elsewhere. In the Nordic countries, the electricity distribution system is mainly a three-phase AC system, but some old LV distribution network customers supplied via one-phase. In Finland, the MV distribution network's rated voltage is 21 kV, and the LV distribution is mainly 0.4 kV (in some exceptional cases, 1 kV is used). The earthing method can vary in the Nordic countries. However, in Finland, the MV distribution networks are typically earth-isolated or compensated systems, and the LV distribution networks are TN systems.

This research describes the UC development of the utility distribution MV and LV networks in a suburban area. The following energy system visions and roadmaps for Finland are used. The Finnish Energy and Climate Roadmap 2050 [52] emphasizes energy system transition to a nearly zero-emission system, energy self-sufficiency, and supply security for reducing emissions. Finland is highly dependent on energy, and the energy consumption per capita is high, and therefore it has traditionally invested in energy efficiency. Though Finland is among the top countries in energy efficiency, energy self-sufficiency is low. The Smart Grid Vision for 2025 [53,54] put the customer in the center for giving him better opportunities to participate in the electricity markets. It is also essential to improve the security of supply and create new business opportunities for the companies. A supplementary vision and roadmap for the Finnish power system, Vision for the Future Electricity Network and Electricity Market 2035 & a Road Map 2025 [55], is used in this research.

Next, an overview of the Finnish power system's electricity marketplaces is given. The evolution phases of the electricity distribution networks are defined, and a fictitious future network design for a study case Sundom smart grid in Vaasa, Finland, is presented.

4.1. Electricity Market Places for the Finnish Power System

Electricity is traded in the various marketplaces at different times before the actual supply of electricity. The electricity market for the power system consists of the day-ahead, the intraday, and the real-time or balancing marketplaces, which can be considered time windows for physical trading in electricity. For the Finnish power system, the basis of the power exchange, the primary marketplace is the Nord Pool's (Northern Europe power exchange) spot market, the Elspot market, where trades are made hourly a day before (day-ahead) the physical delivery of electricity, and the system price for Nordic is formulated for the next 24 h, giving a base for the other markets' time windows. Next, the intraday aftermarket or correction market of the Elspot trading is the Nord Pool's Elbas market, which aims to trade as close as possible to the actual electricity delivery. The trading closes an hour before the actual delivery of power. Further, for maintaining the power balance during the operating hours, automatic and manual reserves are traded in the Nordic TSOs' (Svenska kraftnät, Statnett, Fingrid, and Energinet) balancing markets [56].

For the balancing energy markets, both up-regulation (increase in generation, decrease in consumption) and down-regulation (decrease in generation, increase in consumption) bids are accepted, and the minimum bidding size of capacities is 10 MW for manually activated (within 15 min) and 5 MW if automatically activated [57]. In the balancing capacity market, the Finnish TSO, Fingrid, ensures that it has up-regulation offers of sufficient quantity for the next day's balancing energy markets. Balancing capacity markets are for additional acquisition of the disturbance reserves activated during the maintenance of reserve power plants. Purchasing is executed weekly, and the capacity is traded for one week at a time. The selected reserve seller is committed to giving up-regulation offers, a balancing capacity offer, in balancing energy markets [57].

Table 2 presents the reserve products and reserve marketplaces for the Finnish power system [51] defined in [58], which are the FCR [59,60], the FRR [61–64], and the FFR [65,66]. Demand elasticity, the demand-side resources (DSR), can be implemented in all markets [67]. Reserve maintenance obligations have been agreed in the joint Nordic system (Finland, Sweden, Norway, and Eastern Denmark) in a network operation agreement between the TSOs. In the Nordic system, the network normal operation mode frequency control is maintained continually with FCR-N agreed to be 600 MW. For disturbance situations such as disconnection of a large power plant, FCR-D is maintained over 1400 MW. Further, for low-inertia situations. The automatic frequency restoration reserve (aFRR) is agreed for 300–400 MW. In addition, the dimensioning faults are covered by maintaining the manual frequency restoration reserve (mFRR), which each TSO has to size according to a dimensioning fault and balancing deviation in its area.

Table 2. Reserve marketplaces in Finland [58,65,68,69].

	FFR	**FCR-D**	**FCR-N**	**aFRR**	**mFRR**
Volume	Finland 20%, Nordics tot. 0-300 MW (estimate)	Finland 290 MW, Nordics tot. 1450 MW	Finland 120 MW, Nordics tot. 600 MW	Finland 60–80 MW, Nordics tot. 300–400 MW	
Activation	In big frequency deviations In low-inertia situations	In big frequency deviations	Used all the time	Used in certain hours	Activated if necessary
Activation time	0.7–1.3 s	30 s	3 min	In 5 min	In 15 min
Minimum bidding size	1 MW	1 MW	0.1 MW	1 MW	10 MW or 5 MW (if electrical order)
Regulation	Up	Up	Up and down	Up and down	Up and down

4.2. Evolution Phases of the Electricity Distribution Networks

Four evolution phases for the LV distribution networks are proposed in [13]: traditional, self-sufficient in electric energy, microgrids, and intelligent network of microgrids. Further, customer evolution, according to these evolution phases, is defined in [70]. The descriptions of the evolution phases are developed further in this paper, including both the MV and LV distribution networks, and the naming is improved. In the following, a short overview of the evolution phases is given.

The Traditional phase describes the current electricity distribution network status in general, where most of the energy to the loads is fed from the upstream high voltage (HV) grid. In the LV distribution network, some micro-scale DG such as photovoltaic (PV) units can be present in Consumer-Customer premises, but to a small extent. There can be a battery energy storage system(s) (BESS) connected to the PV unit.

The Self-Sufficient phase is reached when the energy production from the DG mostly exceeds the demand for electric energy. Both the micro- (local) and small-scale (regional) DER units increases because consumer-customers aim for self-sufficiency in energy. The consumer-customer is evolved into a responsive customer or even a prosumer [70]. Energy villages or cooperative societies can be formed to produce energy regionally by a small-scale energy generation unit, such as a combined heat and power (CHP) unit. In addition, there can be an MV-connected DG unit, for example, a WT unit, and a BESS can be implemented in the primary substation (PS-BESS) and/or secondary substation (SS-BESS).

The Microgrid phase describes networks capable of operating independently in the island and the grid-connected modes. A microgrid can be formed within a primary or a secondary substation area or within an MV feeder area. In the microgrid phase, customers are more active because of the enhanced opportunities to manage the electric energy and the participation benefits in the ASs. The customer is called a Partner [70]. A microgrid management system (MMS) is needed to monitor and control the microgrid operations and communications to the upstream network controls.

In the Intelligent Microgrid Network, several advanced and different microgrids operate dynamically to meet the smart grids' operational targets. The electricity and the heating are managed as integrated energy systems by distributed multi-generation. Customers become Strategic Partners who operate in a dynamically operated network of microgrids having a more strategic actor role [70]. The operation mode can be selected based on the economic, technical, environmental, or combined modes of various stakeholders in real-time between all the parties. Hence several operation modes can be selected in the strategic partners' premises [70].

4.3. Sundom Smart Grid

The evolution of a typical suburban or rural area grid in Nordic countries is developed via the Sundom smart grid study case. Figure 3 presents an outline of the fictitious future design for the Sundom smart grid, located in a suburban/rural area. There are around 2500 residential and small commercial electricity users (metering points). The peak power is around 8 MW and increasing since the housing of the area is growing. There is a 3.6 MW WT connected with its own feeder to the MV bus. The current real system is represented on the left side, where the fictitious connections are denoted with dashed lines. There are two primary substations connected between the 110 kV high voltage (HV) bus and the 21 kV MV bus in the futuristic outline of the intelligent microgrid network phase. Both MV distribution networks comprise the feeders supplying electricity to the customers and the feeders to connect the WT and PS-BESS for power supply to the distribution grid and the AS. There are secondary substations along with the MV feeders, which connect 0.4 kV LV distribution networks to the power system. The LV distribution networks include households and small commercial customer types. At the customer premises, there exist DG units and BESS. For heating, the customers use the electric heating systems, which can be direct, partially storing, storing, or heat-pump systems. District heating is available in the suburban area.

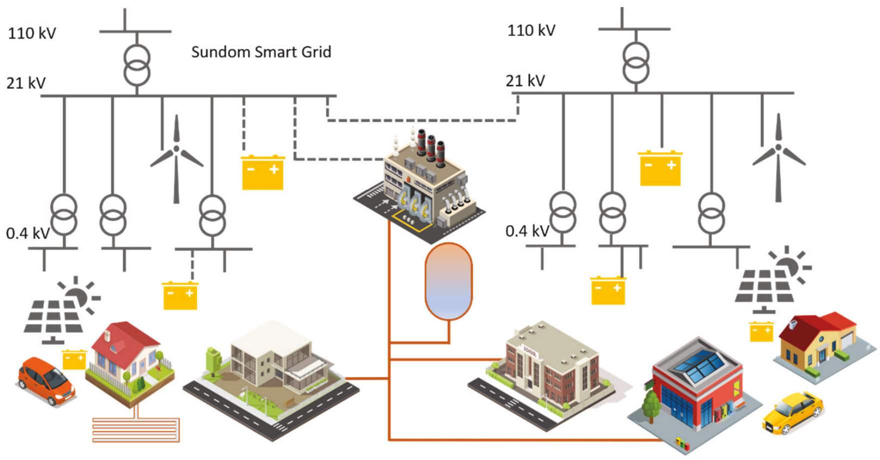


Figure 3. Outline of the developing electricity distribution networks, futuristic case of the Sundom smart grid.

This paper focuses on ADNM through DERs at the different evolution phases of the electricity distribution networks at the location of the Sundom smart grid. In the developed network scenarios, WT, PV, and CHP units are considered the DG units to be used in ADNM. Controllable loads can comprise loads in the customer premises and a part of the distribution network (e.g., a microgrid). The energy storage systems (ESSs) are considered to be BESS and the district heating storage system. Energy conversion is regarded between electricity and heating and later between electricity and liquid fuel (power-to-liquid-to-power). The primary focus on the AS case studies is the DSM via marketplaces, which can be offered at the first stage by aggregated customers and later by an energy community or the microgrid owners. ASs can be offered for TSO's power balancing or frequency stability support and later evolution phases for voltage control. The second focus is on the local ASs, which are envisioned for the DSO's network management purposes for voltage control. The DG owners, the aggregated customers, and later the microgrid owners can offer local ASs. A probable scenario could also be active power control of the customers' generation units for the DSO's ASs. However, these cases are not developed in this research and are left to future research.

The following describes the future electricity distribution network operations and management in a behavioral (Section 5) and structural (Section 6) manner. The descriptions use the previously presented review on electricity distribution network development, the definitions of the evolution phases, and the outline of Figure 3. The operational scenarios and the structural representations are developed considering the real distribution network to create a concrete roadmap of the network development and a description of the management architecture schemes. The current system is used to reference which of the future system's scenarios are built by increasing the DERs. The method can be used generally in the roadmap and management system architecture scheme creation, whereas the outcome is representations suitable for similar networks in type and environmental conditions.

5. Operational Descriptions of the Future Distribution Networks with the Sundom Smart Grid

The behavioral descriptions, the studied distribution network's operational scenarios in its different evolution phases, are presented by the different levels of UCs [43] in the following paragraphs. The HL-UCs define the main functions of the concepts in the electricity distribution network operation. In this context, the HL-UCs describe the energy management, power balance management, and protection functions. Further, PUCs are developed for describing a particular specialization of an HL-UC. For example, an introduced HL-UC of energy management is load control. A PUC conducted from that can be the economic DR for the load shifting (Self-Sufficient Phase) and the DR for the peak shaving by load shedding (Microgrid Phase).

5.1. Energy Management Use Cases

The energy management in the electricity distribution networks generally consists of production planning and control, energy procurement, electricity distribution management, energy demand management, building energy management, maintenance, and communications. DSM measures are used to reduce energy end-use or promote energy efficiency [71], for example, by adjusting consumption temporarily (peak shaving or load shedding). DSM also includes modification of consumer demand for power balancing purposes by transferring consumption from the high load and price hours to more inexpensive hours (load shifting). The DSM can be implemented via various marketplaces to the power system's energy and power balance management. The electricity utilities (in Finland, electric energy sellers, and aggregators) can offer DR capacity to the frequency-controlled reserve, balancing power, fast disturbance reserve, and strategic reserve markets in addition to the day-ahead and intraday energy markets. The implementation of DR is a crucial product considering the flexibility of the future MV and LV distribution networks. The value of DR depends on the accuracy of the estimation, the prediction, and the optimization of demand.

In this research, the HL-UCs of energy management are electricity supply, electricity consumption, load control, electricity generation, generation control, and Volt/VAr control. Energy management covers the power balance management in the active distribution networks [43]. However, the power balance management UCs are presented separately from the energy management UCs for the microgrid phase in Section 4.2.

5.1.1. Energy Management Use Cases of the Self-Sufficient Phase

At the self-sufficient phase, the LV distribution network customers can have a building automation system (BAS), including a HEMS. The BAS can control heating, ventilation, lighting and sockets, sauna stove, water boiler, and security. The home-away function is mostly applied for heating and ventilation, reduced while the residents are away. Customers have increasing micro-generation, which are PV units with or without BESS. The micro-generation unit's maximum output power is 50 kVA, according to the standard EN 50,438 [72]. In Finland, the network recommendations are set for connecting the micro-generation units maximum of 100 kVA [73]. Notable is that if connecting units based on the three-phase overcurrent protection for the unit, 3 × 16 A, the thermal limit is 11 kVA. The customers mainly aim at PV generation for their own use, but some might be interested in feeding in the utility grid. Three types or roles of customers appear in this evolution phase [70] as follows. Traditionally (in the traditional phase), the customers are just using electricity for their demand, and they are called consumers. In this evolution phase, most customers, called responsive consumers, become more active in the network operation participating in the DR programs with their controllable loads. Third, prosumers emerge increasingly, who own a generation unit and can produce, store, and sell electric energy in addition to the operations of the customer types above.

There can be SS-BESS, and there exists a PS-BESS. A WT unit is located near the substation and connected with its own feeder to the MV bus (see Figure 3). The customers or the energy community obtain a common small-scale generation unit, in this case, a CHP unit for the regional energy generation, aiming for self-sufficiency in energy. The CHP unit is connected to the district heating system. A small-scale generation unit's maximum output power is allowed to be 2 MVA [74,75].

A central energy management system (CEMS) over both voltage levels monitors the CHP unit's energy flows. The BESS units' and the customers' demand can be monitored, and the utility network for cost and compensation fee calculation purposes. Smart energy meters measure the energy consumption in the customers' premises and the secondary substation areas. A measuring unit for the generation from the CHP unit is required.

The HL-UCs for energy management over the LV and the MV distribution networks in the self-sufficient phase are described in Table 3.

Table 3. Energy management high-level use cases in the self-sufficient phase.

HL-UC Name	Events in the LV and MV Distribution Networks
Electricity supply	LV: Electricity is supplied to the customers' grids by the DSO and the energy retailer. The DSO provides voltage to the customers' main distribution board. It measures the consumed energy via smart energy meters for billing purposes (the energy retailer's energy charge and the DSO's transmission charge).
	MV: Electricity is supplied to the LV customers via the MV distribution network. The DSO measures the consumed energy in the LV distribution grid at the secondary substations.
Electricity consumption	LV: Customers consume electric energy in several ways. The most significant loads are electric heating, boiler, stove, sauna stove, lighting, ventilation, and heat pumps. The EVs, the PV-BESS, and the SS-BESS consume electricity while charging. The BESS inside the EV (EV-BESS) is considered a passive load in this phase.
	MV: PS-BESS consumes electricity while charging.
Load control	LV: The loads are divided into non-controllable and controllable, in which controllable are passive type loads, such as heating, boiler, heat pumps, and EVs. The controllable loads are used for the demand response (DR) programs by the aggregators, who can be "a market participant that combines multiple customer loads or generated electricity for sale, for purchase or auction in any organized energy market" [76]; in this study, they are called retailer-aggregators. CEMS can be used for a cluster of households by controlling the loads centrally as an option in DR, for example. In this case, the retailer-aggregator also sends the price signal to the CEMS. An SS-BESS can offer a controllable load with storage (charging) for the DSO's local ASs. For example, the summertime situation can be high PV generation and low consumption, which can cause the voltage rise, and by charging the SS-BESS, the voltage can be decreased in the network. Alternatively, an SS-BESS could be offered to be aggregated for the TSO's ASs via the marketplaces.
	MV: The PS-BESS can offer frequency stability support operations as an FCR via marketplaces (for example, store excess energy).

Table 3. *Cont.*

HL-UC Name	Events in the LV and MV Distribution Networks
Electricity generation	LV: The micro-generation is PV generation at the consumers' premises. The operation of the PV units can be separated, class 1 and class 2 equipment [77], from the LV distribution network, or the operation can be parallel with the LV distribution network, but the power flow to the distribution network is prevented by class 3a equipment [77]. In these cases, the purpose is to minimize the customers' electricity bills, as in the traditional phase. PV units also exist, which can supply energy to the distribution grid either without fees, class 3b equipment [77], or with fees, class 4 equipment [77]. The SS-BESS could also offer recharging operation in the local ASs for the DSO's congestion management. For example, in high demand time, the voltage can fall in the weak network parts. Alternatively, the SS-BESS could be obtained for gaining benefit by offering it as a resource for ASs via markets.
	MV: PS-BESS (as a generation unit) can provide back-up power for the energy community's consumers and the operations as a frequency control reserve. The CHP unit provides heat and electricity.
Generation control	LV:
	MV: The CEMS controls the electricity generation of the PS-BESS for self-sufficiency purposes. The CEMS monitors the generation from the WT and controls the CHP. The CHP unit is controlled so that heating energy is guaranteed (heat-led control/maximum heat output) for the connected residences. The electricity is treated via the PS-BESS and shared. The excess heat that is not used in the region/community is fed in the utility district heating system.
Volt/VAr control	LV: In the traditional and the self-sufficient phases, the LV distribution networks' voltage control is passive; off-load-tap-changers exercise it in the secondary substations.
	MV: Generally, for managing the voltage within the permitted limits, reactive power is controlled via on-load-tap-changers (OLTC) of the primary transformer. Additionally, in this phase, the reactive power flow from the full-scale converter of the large-scale WT (3.6 MW) owned by a DG partner is controlled for the DSO's ASs [78,79].

The load control HL-UC can be studied further by generating, as an example, the economic DR for the load shifting PUC. Generally, load shifting means a reduction in electricity consumption, while an increase in demand follows later when the electricity prices are lower. There are two basic options for the DR programs [80,81]: the price-based programs (PBP) and the incentive-based programs (IBP). The PBP programs are based on dynamic pricing, where the electricity prices vary according to the real-time cost of electricity. The PBP programs include the time-of-use (TOU), critical peak pricing (CPP), extreme day CPP (ED-CPP), extreme day pricing (EDP), and real-time pricing (RTP) programs. The IBP programs are divided into the classical load control programs and the market-based programs. In the classical IBP, the customers receive participation fees (an invoice credit or a discount rate) for their involvement in the programs. In the market-based programs, participants are rewarded with money, depending on the amount of load reduction. The classical IBP includes direct load control programs (DLC) and interruptible or curtailable load programs. The market-based IBP has programs of demand bidding (DB), emergency DR, capacity market (CM), and AS markets.

Some PBP programs are generally applied in suburban (and rural areas) in the current electricity distribution networks. The IBP programs, direct control, load curtailment programs, and DB are applied traditionally to industry loads in high-demand times. In this case study, no industry buildings are in the area, so these are neglected. Instead, the market-based IBP aggregated load control programs via DR marketplaces are the feasible options, which could be AS market programs. Hence, the economic DR for load shifting by load curtailment PUC was developed over the LV and MV distribution networks, and it includes the following UCs:

- DR via TOU (electricity storage heating and other passive loads): The houses with an electric storage heating system use TOU pricing with two time-blocks per day, which is currently (the traditional phase) used as the primary case in the electricity storage-heated houses. The consumption can be changed from the peak load times to off-peak times. The off-peak is at night with a lower rate, and the peak is at daytime at a higher rate.
- DR via RTP (passive loads): An option is RTP programs used in customers who want to be charged based on hourly fluctuation of electricity prices, reflecting the wholesale market's electricity cost. RTP customers are charged based on hourly fluctuating prices announced a day or an hour ahead (based on the base market, Elspot or Elbas, prices).
- DR via AS markets (electricity storage heating and other passive loads): A demand aggregator collects the demand flexibility, carries out the DR optimization and scheduling, trades on the energy markets, calculates the consumers' price-volume signals, and finally sends the price signal to the customers. Customers exploit the retailer-aggregator's price signals to decide energy consumption (by the agreed option). Hence, the HEMS displays the electricity price and the consumed energy volume and controls the loads according to the approved option. The demand aggregator is a retailer-aggregator, which is an existing market participant, the energy supplier [82–84]. The retailer-aggregator collects the demand flexibility from the passive type of loads and offers the aggregated loads for the day-ahead market Elspot (0.1 MW/12 h) [85] or intraday market Elbas (0.1 MW/1 h) [86]. An option is to participate in the TSO's organized power system reserves in balancing energy markets with either up-or down-regulating bids [86], in FCR-N [85] (0.1 MW, ≤3 min), but likely also in FCR-D (1 MW, ≤30 s).

5.1.2. Energy Management Use Cases of the Microgrid Phase

The microgrid is considered to be formed within the MV distribution network area. The energy management HL-UCs of the microgrid phase are similar to the self-sufficient phase. In the microgrid phase, customer types of the previous evolution phase exist (consumers, responsive consumers, prosumers) and a new customer role, the partners. Partners own the previous customer type characteristics, but they also have controllable dynamic loads, and they are active in AS programs through their resources. The dynamic loads are the EV-BESS of the vehicle-to-grid (V2G) and vehicle-to-home (V2H) type of the EVs. The V2H type can supply electricity to a small microgrid such as a house and act as a power source during a power outage (or mobile outdoors).

EV aggregators can provide services to the base and the peak power markets, the AS markets (reserve market), and offer additional storage and back-up power [87]. Hence, participation in the AS markets is a regular operation. The EV client types in the suburban area are assumed to be type 3 or 4, according to [87]. Type 3 EV owners provide the EV-BESS as a controllable load, in which charging location and time are known. Type 4 EV owners provide the EV-BESS as a controllable resource, V2G, assuming that the aggregator has contracted a specified amount of battery state-of-charge (SOC). The EV owner defines the charging volume, the available period of charging, the minimum battery SOC level for the next hours (or days). The EV aggregator gathers real-time information about the status, frequency, total capacity, and voltage of the controllable area.

The micro and the small-scale generation units are connected to the utility network by the devices and contracts, which allow the two-way power flow with payment of the energy surplus. The common CHP unit could be deployed to provide various ASs such as intraday balancing services, improve power quality, and provide black start services. The CHP unit could be used for DR purposes by controlling the power output (and the water temperature) by the energy management system (EMS) based on the DR optimization problem. In the future, the CHP unit could be coupled to a heat storage system, whereas it could provide flexibility in a generation such as is presented in [88].

Moreover, a higher-level control system is required, responsible for the regional DSM or DR, the energy and power balance management, and the protection management both in the grid-connected and the islanded operation modes. In this paper, the microgrid management system (MMS), including a microgrid energy management system (MEMS) and a microgrid protection management system (MPMS), is considered, of which functions are analyzed in [43].

The HL-UCs for energy management of the LV and the MV distribution networks in the microgrid phase are described in Table 4. Only the new events are presented compared to the previous, the self-sufficient phase.

Table 4. Energy management high-level use cases in the microgrid phase.

HL-UC Name	Events in the LV and MV Distribution Networks
Electricity supply	LV: In the islanded operation mode, the energy supply is provided by the microgrid owner or operator, who is the local DSO, which is a natural case with the utility-connected microgrids. The electricity is supplied to the loads from the customers' PV units and BESS within the islanded microgrid.
	MV: The microgrid operator is responsible for providing electric energy that is safe and high quality in the islanded and grid-connected mode.
Electricity consumption	
Load control	LV: The dynamic load types are used for the DR programs. Independent aggregators, "an aggregator that is not affiliated to a supplier or any other market participant" [76] or "a market participant engaged in aggregation who is not affiliated to the customer's supplier" [89], emerge. A third-party, independent aggregator, an EV aggregator, can collect the flexibility from charging or discharging EVs. In the islanded mode, loads are controlled by the MEMS for maintaining power balance in the microgrid.
	MV: MEMS is responsible for charging the PS-BESS in the grid-connected and the islanded modes. In the islanded operation mode, the PS-BESS is the primary resource to be controlled for maintaining power balance in the microgrid.
Electricity generation	LV: The SS-BESS can be used for power balance management in the islanded mode.
	MV: In the islanded mode, the generation from PS-BESS is controlled by MEMS for maintaining power balance in the microgrid.
Generation control	LV: The electricity generation from the class 4 PV units can be controlled to maintain the supply quality. The prosumers and the partners can agree with the DSO or the microgrid operator to control their PV unit's active power generation for congestion management purposes. The frequency-controlled micro-generation units can offer frequency support in the islanded mode.
	MV: In the grid-connected and islanded modes, the MEMS controls the share of generated heat and electricity from the CHP unit according to its optimization target. In addition, the PS-BESS recharging is controlled via MEMS. In the islanded operation mode, the MEMS is also responsible for the WT's generation control.
Volt/VAr control	LV: The reactive power can be controlled for the DSO's local AS purposes; the customer PV units and BESS and the SS-BESS can be used for maintaining the quality of the supply. There can be an OLTC at the secondary substations.
	MV: In the grid-connected mode, voltage and reactive power are controlled the same way as in the previous evolution phase, but also, the PS-BESS and the CHP unit can be used.

Based on the load control HL-UC, the DR for the peak shaving by load shedding PUC description can be developed for the energy management over both voltage levels. Peak shaving is a quick reduction of the power consumption for a short period, the activation of the generation, or the battery. In this HL-UC, the customers belong to the energy community, but in reality, not all customers might join the energy community. Responsive consumers, prosumers, and partners can reduce power consumption by load shedding to avoid spikes in consumption in the LV distribution networks and the microgrid area. In the MV grid, the CHP unit and the PS-BESS can be used for supplementing power to avoid peak loads. The LV- and MV-connected DG units are connected to the MEMS, which controls the DG units centrally within the microgrid area. In the island operation mode, the MEMS behave like a retailer-aggregator, sending the price signal to the CHP unit's EMS and the customers' HEMS to be exploited. The MMS (MEMS) can send direct load control signals to the customers to secure the network's reliable operation. The DR for peak shaving by load shedding PUC was developed over the LV and MV distribution networks, and it includes the following UCs:

- Economic DR via AS marketplaces: In the customer's premises, the HEMS displays the energy signals to the responsive consumers, prosumers, and partners to decide consumption and electricity generation and supply to the distribution grid (prosumers and partners). The HEMS (at the customer connection point) and the MEMS (at the POI of the microgrid) monitor the energy flows. The HEMS generates forecasts of the load based on the history data and the generation forecasts based on the weather forecasts. The MEMS optimizes the power to be consumed or generated within a microgrid area depending on the energy community's agreed AS programs, market prices, and the network's security.
- Generation activation: The electricity generation of the energy community's CHP unit and the PS-BESS can be controlled to produce more electricity to flatten or reduce the distribution grid's peak demand (can be for the TSO's or the DSO's load shedding).
- DR from the frequency responsive reserves and intermittent generation: The retailer-aggregator collects the demand and generation flexibility and agrees on using them within the microgrid with the energy community. The loads can be collected for the FCR-N reserves (0.1 MW, $P_{100\%}$ in 3 min [60]). In addition, an option is the FFR reserves (1 MW, 49.6 Hz in 1.0 s [66]) for the inverter-connected dynamic loads, that is, various BESS units, but also controllable loads having an enhanced controller as studied in [90], for example. In this study, they are called smart loads.

5.1.3. Energy Management Use Cases of the Intelligent Microgrid Network Phase

In this phase, the different energy sectors are coupled, and they operate flexibly interlinked via different energy conversion devices; hence, the conversions of power-to-X-to-power are reality. The power system, the smart grid, is the backbone of the whole energy system [3,4,91].

The integration of various microgrids and optimizing their operation as a regional basis enables the electricity distribution networks to operate as a building block of the smart grids. In the intelligent microgrid networks, electricity and heating are managed and integrated, and the operation strategy can be chosen from the different operation modes [26,92], such as economical, technical, and environmental.

The central microgrid management system (CMMS) behaves as an energy retailer over several regional MMSs and CEMSs [13] and cooperates with the different aggregators and suppliers of energy. The CHP unit is connected to heat storage (HS), which acts as the seasonal heat storage [93]. The customer roles are like in the previous phases, but, increasingly, Strategic Partners appear. The strategic partners operate actively in the dynamically operated energy networks, meaning that the operating strategy can also be chosen in the strategic partners' premises. The customers' load types can be passive and dynamic (the smart and the frequency-controlled loads), like in the microgrid phase. Several independent aggregators can collect the customers' flexibility, in addition to the retailer-aggregator. There can be dedicated aggregator roles for the ASs such as a PV, a BESS, an EV, or an energy community aggregator.

The HL-UCs are similar to the previous evolution phase, except that new actors are the strategic partners, the CMMS, and the various aggregators. In addition, new actors from the other energy systems are interlinked to the intelligent microgrid network for optimizing the operation of the whole energy system both in the normal operations and in the disturbance situations of the backbone or the power system. The studied HL-UCs for energy management of the LV and the MV distribution networks in the intelligent microgrid network phase are described in Table 5. Only the new events are presented compared to the previous, the microgrid phase.

Table 5. Energy management high-level use cases in the intelligent microgrid network phase.

HL-UC Name	Events in the LV and MV Distribution Networks
Electricity supply	
Electricity consumption	
Load control	LV: The controllable loads used for the DR programs are passive and dynamic load types, from which several independent aggregators can collect various controllable loads: electric heating systems, water boilers, ventilation, various customers' BESS, and the SS-BESS.
	MV: Load control within a microgrid is as in the previous evolution phase. In this phase, a single microgrid can be considered a controllable load to be controlled to reduce or eliminate its demand even by intentional islanding. Load control by a microgrid set can be optimized for the DSO's congestion management or the TSO's ASs.
Electricity generation	LV: Several independent aggregators can collect power from various generation units: customers' BESS (as a generation), PV units, and the SS-BESS.
	MV: Grid-connected microgrids can be operated to supply electricity to the utility grid.
Generation control	LV: MV: A grid-connected microgrid can be operated as a flexible generation unit.
Volt/Var control	

The HL-UCs for energy management of the MV distribution network in the intelligent microgrid network phase are presented in Figure 4, and they relate to the total energy system's HL-UCs, which could be:

- Electricity conversion to heat: Power to heat (PtH) conversion is made in the electricity surplus situation or the low electricity price time. The excess heat is stored.
- Electricity conversion to liquid: Power to liquid (PtL) conversion is made in the electricity surplus; the liquid is stored in liquid storage, and it can be used as fuel for a generator set (Genset).
- Liquid conversion to electricity: Liquid to power (LtP) conversion is made in the case of electricity demand. The liquid(s) can be used as fuel for Gensets.

Based on the load control HL-UC, the economic DR for load shifting by load curtailment PUC and the DR for peak shaving by load shedding PUC are applicable the same way as in the microgrid phase. Both of them are flexibilities that could be used in the base power markets, Nordpool's day-ahead and intraday markets, the TSO's balancing and reserve markets, and the DSO's local ASs. Overall, various PUCs of ASs could be developed in this evolution phase since a microgrid can be considered a dynamic load (and generation) reserve shaped in different voltage levels.

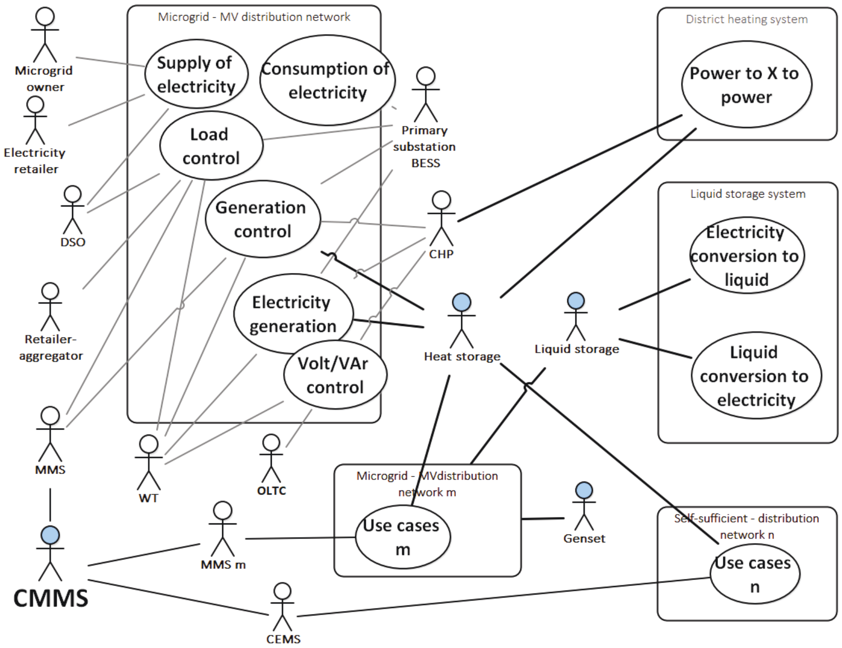


Figure 4. High-level use case diagram of energy management of the MV distribution network in the intelligent microgrid network phase.

Further, considering the operational scenarios of the various flexible resources from the different voltage levels, a responsive generation control PUC could be developed for the electricity generation HL-UC. Similarly, a responsive demand control PUC could be developed for the electricity consumption HL-UC. In these circumstances, these PUCs could be combined and named the flexibility control PUC. It would be worth exploring whether the flexibility control could be a new concept level building block presenting a new HL-UC for future power systems' energy management.

Like previous chapters, we can derive UCs for all evolution phases, but in the following, the focus is only on the microgrid phase, as presented in Figure 1.

5.2. Voltage and Frequency Control via Power Balance Management Use Cases of the Microgrid Phase

Power balance management aims to maintain the power system frequency that results from the balance between electricity production and consumption. The demand can be predicted, but deviations occur due to unexpected load variations, fluctuation of the renewable generation, or disturbances. Power balance management and a hierarchical control strategy are required for the microgrids [94] because of the autonomous operation requirements. In microgrids, the system's stability is achieved by optimizing active and reactive power flows through the DG units, the BESS units, and the controllable loads. The BESS system should support the microgrid reliability and efficiency. The loads have to be classified and prioritized for demand flexibility. In the grid-connected mode, the power output of DG and BESS units is to be optimized. The controllable loads are committed according to the requirements of the energy markets in which they participate. Considerable is the limit of the active and reactive power flow at the POI without losing the possibility of safe islanding operation.

The DSOs are in charge of the safe power supply in the electricity distribution networks, and they have the control and management systems for that. For the utility-connected microgrids, the dedicated functions and functionalities have to be integrated with the existing control and management systems, at least to some extent. For example, Chuang and McGranaghan [95] present the functions and the functional requirements for a controller that manages the local generation, the storages, and the controllable loads, and the smart switches control the normal, emergency, and island operation modes. They present two functions: the local grid reconfiguration and the optimization functions related to economic, environmental, and customers' comfort. These can be considered as energy management functions and power balance functions operated by the MEMS in the microgrids [43]. If there is an OLTC in the secondary substation, it can be used for active management [96–98]. The DSOs (or the microgrid operators) must have permission to configure the alarm settings, rank the load priorities with the customers, enter the profiles, and configure the regional generation [95].

The power balance management in microgrids is presented in [94,99], consisting of four control levels, according to the standard IEC 62264. Hierarchical control of microgrids is also presented in [100], according to the ANSI/ISA-95 standard. All four control levels manage the power balance, but the highest level, the tertiary control, is not used in the island operation mode. The basic operations in the hierarchical control of microgrids are described and presented by the UCs in the following.

The internal control or level 0 manages the operating point between the DG and the BESS units and their interfacing devices or the power electronic interface [94]. These interfaces can be classified into the current-source inverters (CSIs) and the voltage-source inverters (VSIs) [94]. The CSIs are used for injecting current to the grid, and the VSIs for maintaining stable voltage in the grid [99]. Further, the VSIs are connected to the BESS, typically using droop control. The CSIs are connected to the PV or WT generation units, which require the maximum power point tracking (MPPT) algorithms [99].

The primary control or level 1 is responsible for regulating the voltage (frequency and amplitude) delivered to the zero-control level [94,99]. There are different methods to regulate the voltage within the microgrid. In addition to the active load sharing (usually in the islanded mode), the most common control is the droop-based control (grid-connected mode typically) for regulating the active and reactive power consisting of the active power/frequency (P/f) and the reactive power/voltage (Q/V) droops. The primary control's tasks are to stabilize the voltage and frequency after islanding, guarantee interconnection capability for DERs, share the active and reactive power between DERs (even without communications), and reduce circulating currents [101]. The primary control manages the power balance between the central BESS and the inverter-connected DG and BESS units. In addition, frequency-controlled load types such as the dynamic loads, for instance, V2H or V2G, can be worthwhile to connect to the primary control system.

The secondary control or level 2 is responsible for correcting the grid frequency and amplitude deviations. A (central) controller is needed for regulating voltage and frequency deviations toward zero after any change in demand and generation within the microgrid [99]. The secondary control's tasks are to compensate for the voltage and frequency deviations after primary control actions, for the reason the BESS cannot provide long-term power control [101]. Without this control, both the frequency and amplitude of the voltage would depend on the loading [94]. The frequency and voltage at the DERs' terminal are compared with the reference values sent by the primary controllers, and the deviation or the error values are sent to the primary controllers for compensation [101].

The tertiary control or level 3 is responsible for optimizing the power flow in the microgrid and the power flow between the microgrid and the utility or main grid. The tertiary control also enables electricity suppliers' and aggregators' participation in the electricity markets. This control level is responsible for managing the active and reactive power flows through POI by regulating the voltage and frequency in the parallel operation mode [99]. The active and the reactive power are compared with the reference values at the POI. The active power flow at the POI can be controlled by adjusting the reference frequency in the grid-connected mode [94]. An islanding detection algorithm is needed to disable the tertiary control for detecting islanding [99].

The microgrid frequency and voltage are managed mainly by the power electronic interfaces and BESS (although direct load control affects power balance, it is not desirable in the first place). The power converters of DER units can be divided into grid following (controls current and phase angle), grid forming (controls voltage magnitude and frequency), and grid supporting based on their functioning types. Grid following inverters (CFLs) are connected with non-dispatchable DG units, and they operate as a CSI with a unitary power factor (cos φ = 1). This inverter requires a voltage reference, and it tracks the grid by injecting current in phase with the grid voltage. The maximum MPPT algorithm modifies the operating point (voltage or current) of a micro-source by the DC/DC converter that sends the DC power to the inverter. The CFLs operate similarly in the grid-connected and islanded microgrid. The grid-forming inverters (GFM) are connected with the BESS units. In the grid-connected mode of the microgrid, the GFMs tasks control the active and reactive power injected into the AC bus to maintain the SOC of the BESS and improve the power quality. They generate voltage on the bus in the islanded mode, thus acting as a VSI. The GFM usually uses the P/f and the Q/V droop control methods. The grid supporting inverters (GSIs) aim to maintain the power quality in the islanded microgrid by supplying active and reactive power with the droop controllers. The GSIs can be connected with the dispatchable DG units and the BESS units [102].

The BESS control is essential in the microgrid's power balance management and AS. The AS can be load-following, operational reserve, frequency regulation, peak shaving, black start (during island operation mode), and integrating renewables. The power balance within a microgrid can be maintained by charging or discharging the stored energy. The BESS controls the charging power by increasing it if the grid's frequency exceeds the maximum value and decreases it when the frequency reaches the minimum setpoint. The central BESS is fundamental for the voltage control in the island operation mode due to the dynamic variations such as the delayed response or some DG units' slow controllability. In this case, the BESS contains the primary and the secondary control levels only. The BESS monitors active power in the microgrid, where the system's frequency reflects the system's capacity. Each DG unit's power setpoint should be controlled through the secondary control level to maintain the BESS's zero power output [94].

In this study, the power balance management in the microgrid phase is reviewed both in the parallel and island operation modes. The OLTC, the PS-BESS, the SS-BESS, the DG units, and the controllable loads can contribute to the active voltage level management. The studied power balance management HL-UCs of the LV and the MV distribution networks in the microgrid phase are described in Table 6.

Table 6. Power balance management high-level use cases (HL-UCs) in the microgrid phase.

HL-UC Name	Events in the LV and MV Distribution Networks
Regulate the output voltage and control the current of the inverter-connected DER	LV: The primary control actions of each inverter module. The inverters are associated with the dynamic loads EV-BESS, PV-BESS, class 4 PV units, class 3 b PV units, and SS-BESS. The PV and BESS inverters can be either GFL or GSI units. The control and monitoring can be executed via BAS and HEMS.
	MV: The primary control actions of the PS-BESS, the CHP, and the WT interfacing units. The primary control has been in use since the self-sufficient phase in Volt/Var control, aided by the OLTC of the primary transformer, the WT converter, the CHP unit, and the PS-BESS. In this phase, the BESS, the CHP, and the WT unit can be used as the GFM units.
Regulate the active and reactive power	LV: The secondary control actions to keep the system stable. The deviations in voltage (amplitude and frequency) between the dispatchable DER units and the grid are regulated. The controllable loads, PV inverters, the OLTC of the MV/LV transformers, and the SS-BESS can balance the power. The SS-BESS behaves as a GSI unit.

Table 6. *Cont.*

HL-UC Name	Events in the LV and MV Distribution Networks
	MV: The secondary control regulates the voltage deviations of the WT, the CHP, and the PS-BESS. In addition, the OLTC can be connected to the power balancing in the grid-connected mode. For example, during the high generation and low consumption time, the voltage level can rise in the LV grids and highly cabled MV grid, in which case the PS-BESS (and SS-BESS) can be charged.
Control power flow at the POI	LV:
	MV: The MEMS is in charge of the tertiary control in the grid-connected mode aiming to provide the setpoints for active and reactive power flows at the POI according to the microgrid's operational target
Seamless switching between the operation modes	LV:
	MV: The MEMS is responsible for synchronizing the different control loops, thus enabling smooth transitions between the different operation modes. The secondary controller includes the synchronization control loop for the switching between the islanded and grid-connected modes.

Further, the seamless switching between the operation modes HL-UC in the power balance management can include the following PUCs: intentional transition to the islanded operation and unintentional transition to the islanded operation; while the control power flow at the POI HL-UC in power balance management can include the following PUCs: microgrid provides voltage control service and microgrid as a resource in the congestion management.

5.3. Protection Use Cases of the Microgrid Phase

In the microgrid phase, protection is considered for the MV and LV distribution networks, which both can form a microgrid. In this instance, the analogy of the microgrid area protection is intended for both voltage-level microgrids. In connection with the MMS, the MPMS is responsible for the microgrids' protection coordination. The protection system is adaptable depending on the microgrid's operation mode (grid-connected or island) and, if necessary, on the production and demand changes. The MPMS must react to various fault situations in both operation modes.

The LV microgrids' protection system could be based on the combination of current and voltage measurement because the inverter-connected DG units can cause the short circuit current to be low and delay the operation of a protection device (PD). The LV feeder protection can be implemented by circuit breakers (CBs) with electronic trip units. The electronic trip units can measure voltage, current, and frequency on which the different protection functions are based. The protection functions can be against overcurrent (OC), directional OC, earth fault, phase unbalance, under/over frequency, under/over voltage, and power reversal. Timestamps of the event data are used to log the events in the correct sequence [96].

In this study, the operational scenarios are developed regarding OC protection. Figure 5 presents an exemplary outline of a microgrid in the Sundom smart grid area. The microgrid is considered to be formed within the MV distribution grid (or the LV distribution grid). There are PDs located in the MV or LV distribution networks. The numbering of the PDs carries the analogy of a microgrid. PD0 and PD1 are marked as (0) and (1) in the primary substation (and the secondary substation), whose function is to isolate the microgrid from the utility grid during the fault conditions in the supplying feeder (F1). The (1) includes the microgrid main switch, or it is connected to control the microgrid main switch. PD2s marked as (2) are for the MV (or LV) feeder line protection against the fault F2, and they are capable of performing adaptive protection functions based on a command from the MPMS to change their protection settings. The PD3Cs marked as (3C) are for the LV feeder line protection against fault F3, and they are CB-based devices. The PD3Fs marked as (3F) are for customer installation protection, and they are traditional fuse-based devices. The PD4s marked as (4) are the protection devices for the DG units.

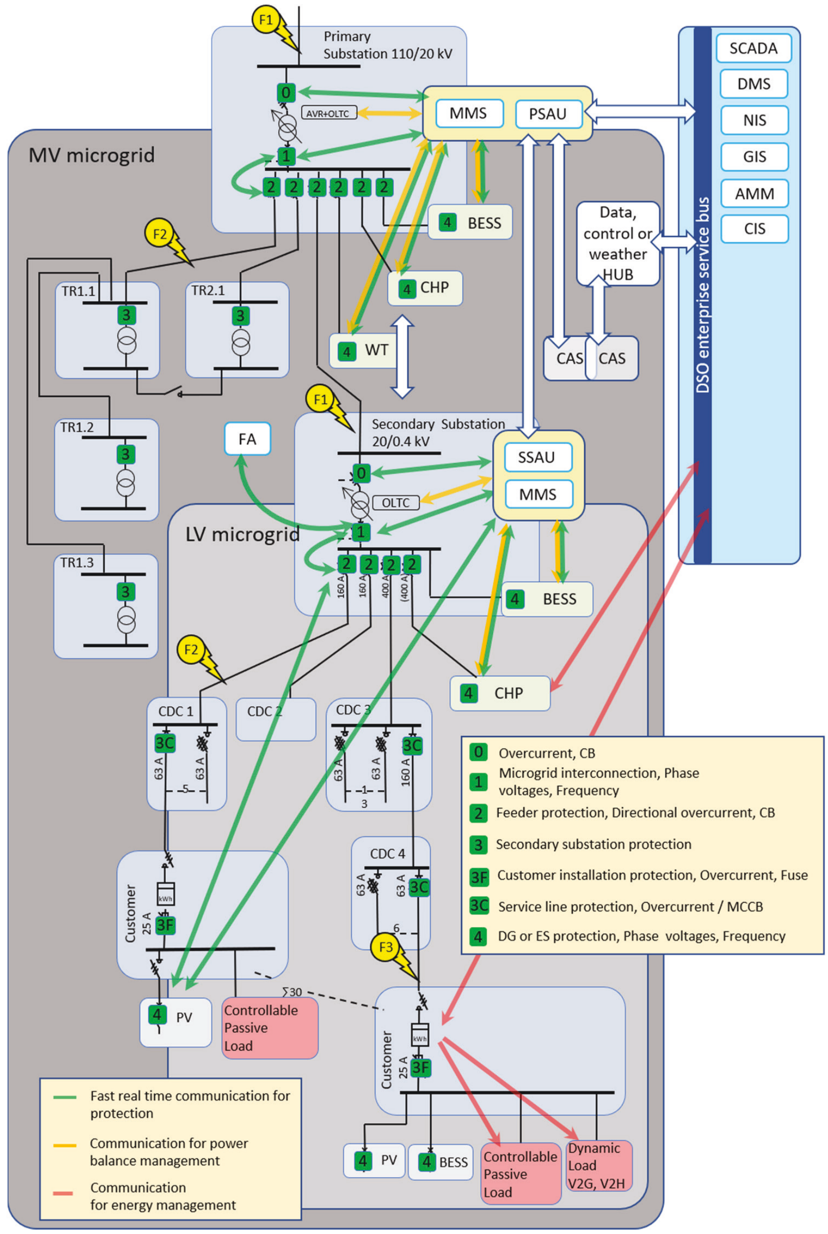


Figure 5. The suburban distribution network in the microgrid phase. Adapted from [13].

The selectivity of the protection system in the MV (and LV) distribution network is established as follows [43,96,103,104]:

- The function of the PD0 is to isolate the substation from the utility grid during the line fault (F1) conditions. The PD0 is connected to the transformers' secondary side relay PD1. PD0 sends a transfer trip command to PD1 to isolate the secondary side of the transformer.

- The secondary side relay PD1 is part of the MV (or the LV) busbar protection and also operates as the POI of the microgrid. The PD1 includes the loss-of-mains (LOM) protection, an islanding detection algorithm in the F1 situation. When the HV (or MV) is feeding line-voltage drops under the acceptable limit, the PD1 disconnects the microgrid from the utility grid. In addition, the PD1 can receive a disconnection command from the PD0 in the primary substation (or the MV feeder automation (FA) system in the secondary substation). In the F2 or the F3 situations, the PD1 receives an interlocking signal from the PD2 after the pick-up limit is reached.
- The PD2s operate only in the F2 situations, and they include directional OC protection, which is selective with the PD1 and the PD3s in the MV grid (or the PD3C in the LV grid). After the PD2 is operated, it sends a disconnection signal to all PD4s of the corresponding feeder.
- The PD4 has to be voltage selective with the PD1 and the PD2 and frequency selective with the PD1. In the F2 situation, PD4 receives the disconnection signal from the PD2. In the F1 case, if the microgrid is not capable of islanding, the PD4′s LOM protection operates, or the PD4 receives the disconnection signal from the MPMS.
- The PD3Cs are selective with the PD2 and the PD3F, and PD3Cs protection settings are fixed and based on the microgrid island mode (more critical). Thereby, the communications between the PD3Cs and the MPMS are not necessary.
- The PD3Fs operate in the F3 situations and the customer grid fault situations, and they are selective with the PD2 and the PD3C. No communications are required.

The studied OC protection HL-UCs of the MV and the LV distribution network in the microgrid phase are described in Table 7.

Table 7. Protection management high-level use cases in the microgrid phase.

HL-UC Name	Events in the MV and/or LV Distribution Network
Fault in the supplying feeder (F1), microgrid transfer to the island operation mode	In the fault F1 situation at the HV feeder, the MV (or the LV microgrid) is required to disconnect from the faulted feeder line, so an islanding detection method, such as the rate of change of frequency (ROCOF) relay, is required. The PD0 disconnects the transformer's primary side, and the microgrid switch (by the PD1) at the secondary side isolates the microgrid from the utility grid. The PD2s adapt to the protection settings of the island operation mode. The MPMS's adaptive protection calculation algorithm calculates new protection setting values for the PD2s based on the type, the state, and the production capacity of the DG units.
Fault F1 cleared, microgrid transfer to the parallel operation mode	After clearing the F1, the DMS sends the permission of utility grid reconnection to the MPMS (MMS). The PD1 measures the reliable recovery of supply (voltage amplitude, phase, and frequency) and sends this information to the MPMS. The MPMS sends to the PD1 the permission for synchronized reconnection (based on the permission, the reliable voltage recovery information from the DMS). After the synchronized reconnection, the MPMS sends commands to the PD2s to apply the renewed protection settings.
Fault in the MV or LV feeder line (F2) in the parallel or the island operation mode	In the fault F2 situations, the PD2 detects the directional fault current and other PD2s see the fault in the backward direction. After that, it sends disconnection commands for the PD4s connected to the faulted feeder line. The PD2 operates to isolate the fault after a short (20 ms) delay after sending the disconnection commands for the PD4s. Finally, the PD2 sends the event data with timestamps to the MPMS. Settings for the PD2s in the MV and LV feeder need to be properly selective.
Service restoration after F2 repair in the parallel operation mode	After the repair of the F2 is completed, the serviceman checks the protection settings for the PD2 from the MPMS. For example, setting the PD2 to the test position requests the set values from the MPMS. After receiving the latest protection setting values, the PD2 can be connected to the line, and the MPMS sends the connection request to the PD4s.

Table 7. *Cont.*

HL-UC Name	Events in the MV and/or LV Distribution Network
Service restoration after F2 repair in the island operation mode	This function is similar to the parallel operation mode. In addition, the MMS coordinates the operation between the MPMS and MEMS and permits the PD2 to reconnect the feeder.
Fault in the LV customer service line (F3)	The PD3Fs operate to isolate the customer installation from the faulted LV distribution line. The LOM of PD4s operates, disconnecting the DG and BESS units from the grid.
Service restoration after F3 repair in the parallel and island operation modes	After clearing the F3, the customer installation, the DG units, and the BESSs can be reconnected to the grid.

6. Structural Description of the Future Electricity Distribution Networks

The actors represented in the UCs can be the persons, devices, systems, and events presented in Section 2. However, in this section, actors are studied more closely: an actor represents a role, and a role is a kind of position in a task. The previously defined actors are classified to generalize their roles, and further, the classified actors with their associations are presented with the class diagrams. Table 8 presents the classified actors based on HL-UCs of the energy management, power balance management, and OC protection in the developing electricity distribution network from state of the art (traditional) to the intelligent microgrid network phase. Only the new classes are presented compared to the previous phase, and the classes are aligned with the NIST conceptual domains.

Further, the classified actors are presented in more detail with their associations in Figure 6, which presents the class diagram that is developed by combining the following class diagrams of the microgrid phase: Figure A1, presenting energy management, in which white classes exist in the traditional phase, light blue classes emerge in the self-sufficient phase, and blue classes emerge in the microgrid phase; Figure A2, presenting the power balance management system; and Figure A3, presenting the OC protection system of the microgrid phase.

The classes, which are illustrated in blue, are classes participating in energy management. The green classes are for power balance management, and the red classes are for protection. The classes illustrated in white present the other classified actors associated with the basic distribution system and operations. The classes are assigned to the conceptual domains defined in [16] and [18]. The classified actors have attributes and operations; the attributes define values attached to a class. The operations are the operations that a classified actor can perform or can be addressed to them. For example, in the UML terms, a customer object in the customer class (classified object/actor) has its value of the connection capacity, that is, an attribute. Further, a customer's operations can be: consume energy, produce energy, and assign loads for DR purposes. Furthermore, the static relationships between the classes, that are, the associations, are presented briefly in the class diagrams.

In the class diagrams, similar classes are combined in a more general class by generalization, identifying common elements of entities. Therefore, a superclass (a parent) has the most general attributes (−), operations (+), and relationships that can be shared with/inherits to subclasses (children). Hence, a subclass may have more specialized attributes and operations. Different types of relationships between the actors are present. Aggregation (◊) implies a relationship where a subclass can exist independently of the superclass. Composition (⧫) implies a relationship where a subclass cannot exist independent of the superclass [105].

By examining Figure 6, the study case of the microgrid phase of the Sundom smart grid, the following can be concluded. The consumer, load, PV unit, BESS, and inverter superclass have several subclasses. The MMS consists of MEMS, PMS, tertiary controller(s), and secondary controller(s), and it is aggregated with the DMS and SCADA.

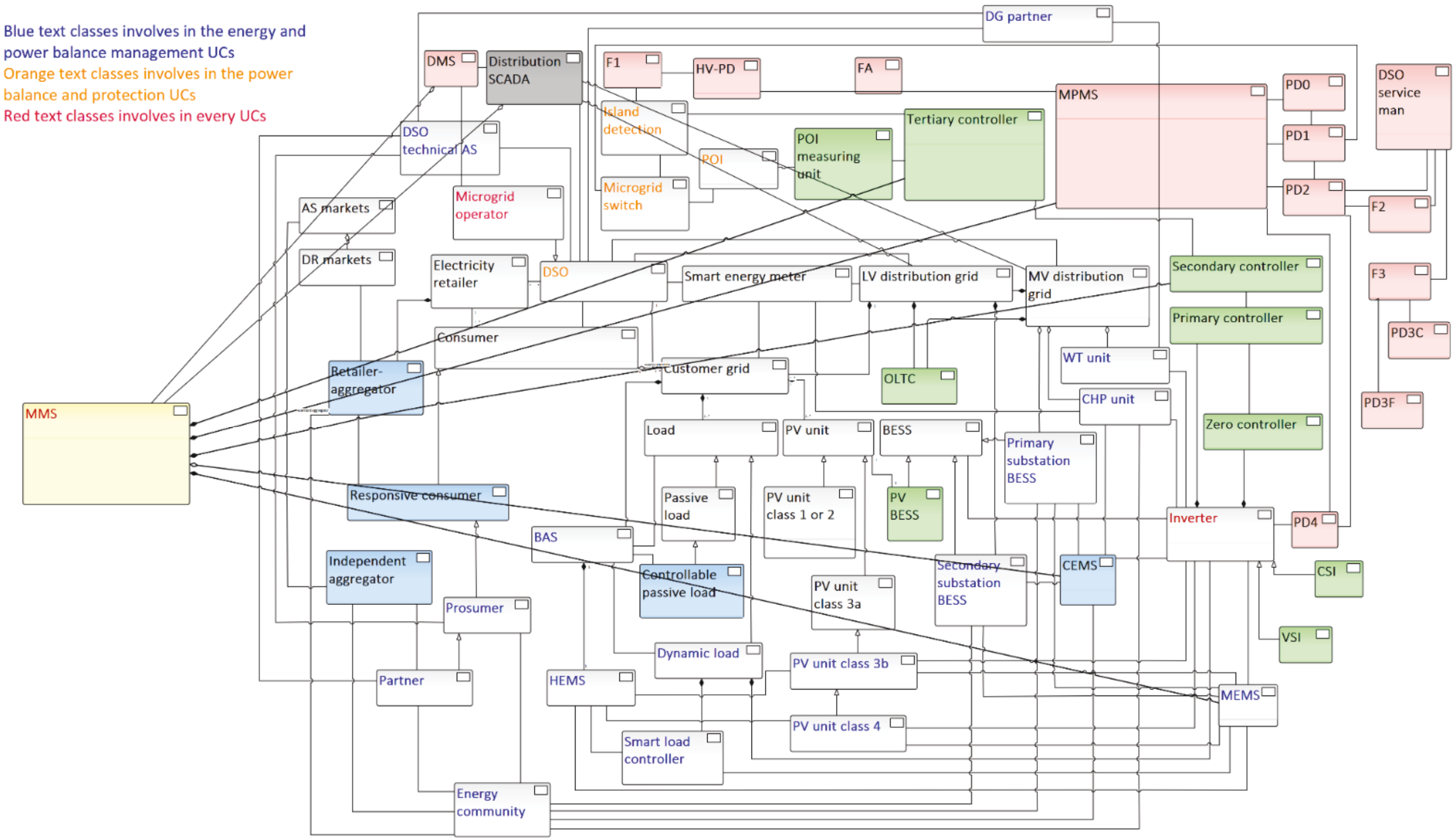


Figure 6. Class diagram of the suburban distribution network management of the microgrid phase.

Table 8. Classified actors of the evolving electricity distribution networks.

	Traditional	Self-Sufficient	Microgrid	Intelligent Microgrid Network	
ENERGY MANAGEMENT	Person roles: consumer Equipment: PV unit class 1, 2, and 3a, controllable passive loads	Person roles: responsive consumer, prosumer, energy community Equipment: PV unit class 3b and 4, inverter Systems: BAS, HEMS	Person roles: partner Equipment: dynamic load, smart load controller	person roles: strategic partner	Customer (C)
	Person roles: DSO Equipment: WT unit	Equipment: SS-BESS, PS-BESS, CHP unit, inverter Systems: CEMS	Person roles: microgrid operator Systems: MMS, MEMS	systems: CMMS	Distribution (D)
	Systems: DSOs SCADA, DMS, and MDMS	Systems: DSOs AS system			Operation (O)
		Person roles: retailer-aggregator, DG partner	Person roles: independent aggregator		Service Provider (SP)
	Person roles: electricity retailer Systems: DR markets	Systems: DR markets (Elspot, Elbas, FCR-N, FCR-D)	Systems: AS markets, DR markets (FFR)		Markets (M)
POWER BALANCE MANAGEMENT			Person roles: responsive consumer, prosumer, partner, the energy community Equipment: controllable passive load, dynamic load, and smart load controller, PV unit class 3b and class 4, PV-BESS Systems: BAS, HEMS, primary controller of the DER		C
			Person roles: microgrid operator Equipment: CHP unit, WT unit, microgrid switch, OLTC, PS-BESS, LV-OLTC, SS-BESS Systems: MEMS, primary controller, secondary controller, tertiary controller		D
			Systems: DSO's TAS		O
			Person roles: independent aggregator		S
			Systems: AS market systems		M

Table 8. *Cont.*

	Traditional	Self-Sufficient	Microgrid	Intelligent Microgrid Network	
PROTECTION			Equipment: PD4, PV inverter, BESS inverter		C
			Person roles: DSO, microgrid operator, DSO service man Equipment: microgrid switch, POI measuring unit, CHP unit inverter, WT unit inverter, PS-BESS inverter, SS-BESS inverter, PD1, PD2, PD3, PD3C, PD3F Systems: DMS, MMS, MPMS, primary controller, secondary controller, tertiary controller, island detection Phenomenon: fault F1, F2, and F3		D
					O
					SP
					M

7. Discussion—Derivation of Class Diagrams from Use Cases

This paper uses a UML-based method to analyze the future electricity distribution network evolution, where the UCs or operational scenarios are a starting point for developing (i) a joint roadmap and (ii) a control and management system scheme for various stakeholders' use. Four network evolution phases forming a road map were recognized: the traditional, self-sufficient, microgrid, and intelligent microgrid phases. For analyzing the electricity distribution network development by their operation, various UCs were developed related to energy management, power balance management, and protection, associated with the network evolution phases, as presented in Figure 7. The HL-UCs were developed concerning the high-level functions for:

1. Energy management: electricity supply, electricity consumption, load control, electricity generation, generation control, and Volt/Var control.
2. Power balance management: regulate the output voltage and control the current of the inverter-connected DER, regulate the active and reactive power, and control power flow at the POI, and seamless switching between the operation modes.
3. OC protection: a fault in the supplying feeder (F1), fault F1 cleared, fault in the MV or LV feeder line (F2), service restoration after F2 repair, fault in the LV customer service line (F3), and service restoration after F3 repair.

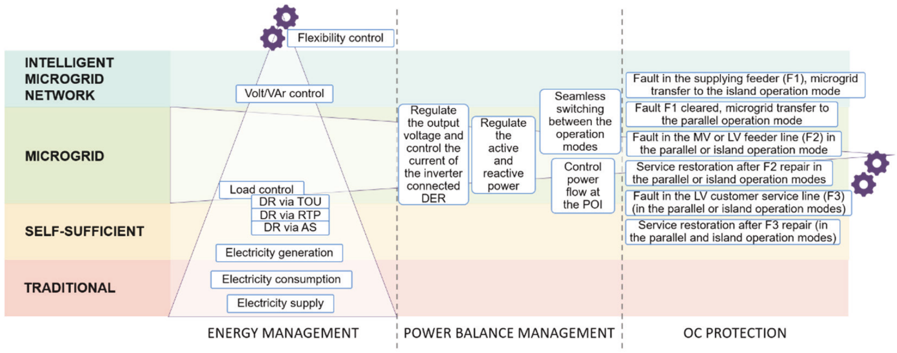


Figure 7. Analysis of the electricity distribution network evolution by the high-level use case studies.

The HL-UCs were developed for the energy management of the self-sufficient, microgrid, and intelligent microgrid network phases following the previous studies [13,70]. The power balance management and the OC protection HL-UCs were developed for the microgrid phase. The conceptual level (HL-UCs) and more practical level (PUCs) were developed concerning the Sundom smart grid's evolution, representing a typical network in the suburban and rural areas in the Nordic countries.

As an outcome of the UC analysis, the outline of the future network management architecture scheme was developed for the microgrid phase. In this instance, the classified actors based on the UCs formed the management system frame. Combining the class diagrams of the energy management, power balance management, and protection of the microgrid phase, a total system management architecture scheme was produced. In this circumstance, with the help of the developed class diagrams, the static structure related to the studied operational scenarios (UCs) is illustrated.

The research findings from the energy management UCs analysis are following. The load control function was studied further regarding the DR functions in DSM and voltage support functions in the Volt/VAr control for the DSO's local ASs. In the self-sufficient phase, the customers' DSM is related to cost savings in electric energy. The means that load controlled via load curtailment (DR via TOU), consumption curtailment according to the energy market prices (DR via RTP), and DR functions through the aggregated customers' load control (DR via AS marketplaces). In DR via ASs, the retailer-aggregators collect demand flexibility and shape bids for the base power (Elspot), balancing energy (Elbas), and reserve markets (FCR). In the microgrid phase, DR in DSM is exploited for the frequency support AS, such as in the self-sufficient phase and DR using generation. The retailer-aggregators and independent aggregators can offer flexibility via the enhanced PV units and the dynamic and smart loads to the FFR market in addition to previous evolution phase options. In the self-sufficient and microgrid phase, voltage support services can be provided for the DSO's (or the microgrid owner's) local ASs through the inverter-connected DER units. DR programs could also be exploited during local disturbances in the microgrid phase to avoid service interruptions by load shedding or by direct load control. This operational scenario was left to future research. In the intelligent microgrid network phase, various DR programs are used among various stakeholders: electricity utilities, markets, aggregators, and customers, and their different roles interlinked together. In this evolution phase, DR can be used regionally as a local AS, for example, in the disturbance situations' supply restoration. A single microgrid can be used for local ASs or ASs in many ways by giving the optimization target of active and reactive power or even dispatch. A single microgrid could be described as a dynamic DER. For its nature, we consider a new HL-UC function for the intelligent microgrid network phase that is the flexibility control combining responsive generation control and responsive demand control.

For analyzing the development of the electricity distribution network management structure, actors defined in the UCs operating the system were classified, whereby class diagrams of energy management, power balance management, and protection were developed. Figure 6. presents the whole system in the microgrid phase in which the class diagrams of energy management, power balance management, and protection are combined. This class diagram gives a static illustration of the system that is the active management architecture scheme. It can be noticed from Figure 6 that several new actors are present compared to the previous evolution phases. The functions, which can serve in other actor's operations, could be discovered, and actors, which can be combined.

Compared to the traditional phase, the new operations or the new attributes of the energy management actors in the microgrid phase are in the customer class. Responsive customer's operation: assign loads for DR, and attribute: controllable loads volume, inherits to prosumers, partners, and strategic partners. Both the LV and the MV distribution grid classes have attributes: generation capacity and load control capacity compared to the traditional phase, which information can be used in future network control and management. The DG inverter attributes: status and type, and operations: measure current, measure voltage, and receive reference value, are aimed to serve the energy, power balance, and protection management. Various inverter types can be classified differently depending on the system's operational scenario and technology. Therefore, in this study, just the general inverter class is used. The diagram also illustrates that the measuring unit at the POI could be integrated, or it could be a module of the microgrid switch or the PD. Most importantly, the diagram shows the essential modules required for an MMS to be integrated or distributed with the outlined communications (association lines). For example, the CEMS can be integrated into the MEMS and further to the MMS.

A similar analysis performed by more detailed UCs, functional and structural analysis could indicate the operations that could be combined or integrated and into the decentralized autonomous operations. For further behavioral analysis, the operations in the system can be described by the activity diagrams (kind of extended flowcharts), the sequence diagrams (interaction between the objects from the classified actors), and the state diagrams (representing the system states) of the dynamics in the system. Such analysis would result in new designs of the management system for the studied scenarios, a mix of centralized and decentralized management systems.

8. Conclusions

With the help of the generated pathway's operational and structural description, an overview of the evolving electricity distribution networks is obtained (in the suburban or rural areas, at least). Furthermore, with the pathway's help, the UCs, the management scheme(s), and the potential RDI topics can be indicated for understanding the critical and missing elements and the potential business cases. Doubtless, the analysis method used in this research applies to various levels of UCs, which could be used from defining a problem from the pre-studies to the piloting stage.

The presented analysis method using UML is a powerful tool for describing the main actors, system operations, and structure for developing the ADN management system. A notable feature is that by combining several class diagrams, the operations can be detected, serving other actors' operation(s), and synergies between different actors can be identified.

Author Contributions: Conceptualization, K.H.S.; methodology, K.H.S.; software, K.H.S.; validation, K.H.S.; formal analysis, K.H.S.; investigation, K.H.S.; resources, K.H.S.; data curation, K.H.S.; writing—original draft preparation, K.H.S.; writing—review and editing, K.H.S., K.K., H.L., and N.H.; visualization, K.H.S.; supervision, K.K. and H.L.; project administration, K.K. and H.L.; funding acquisition, K.K. and H.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was carried out in the SolarX research project with financial support provided by Business Finland, 2019–2021 (grant No. 6844/31/2018). This work was undertaken as part of the FLEXIMAR project (novel marketplace for energy flexibility) with financial support provided by Business Finland (grant No. 6988/31/2018) as well as Finnish companies. (https://www.univaasa.fi/en/tutkimus/hankkeet/fleximar-novel-marketplace-energy-flexibility (accessed on 20 March 2021)).

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A

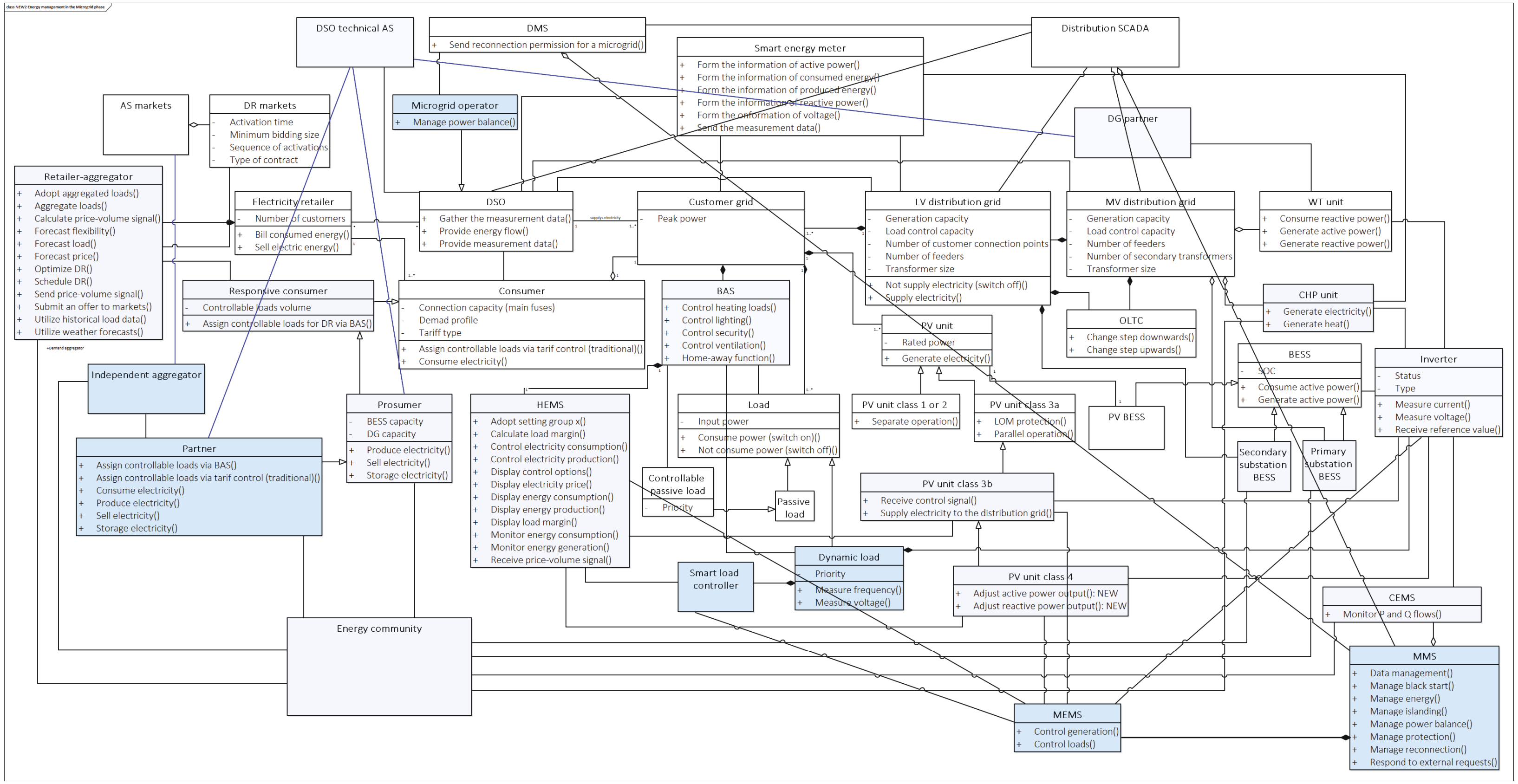


Figure A1. Class diagram of the energy management of the microgrid phase.

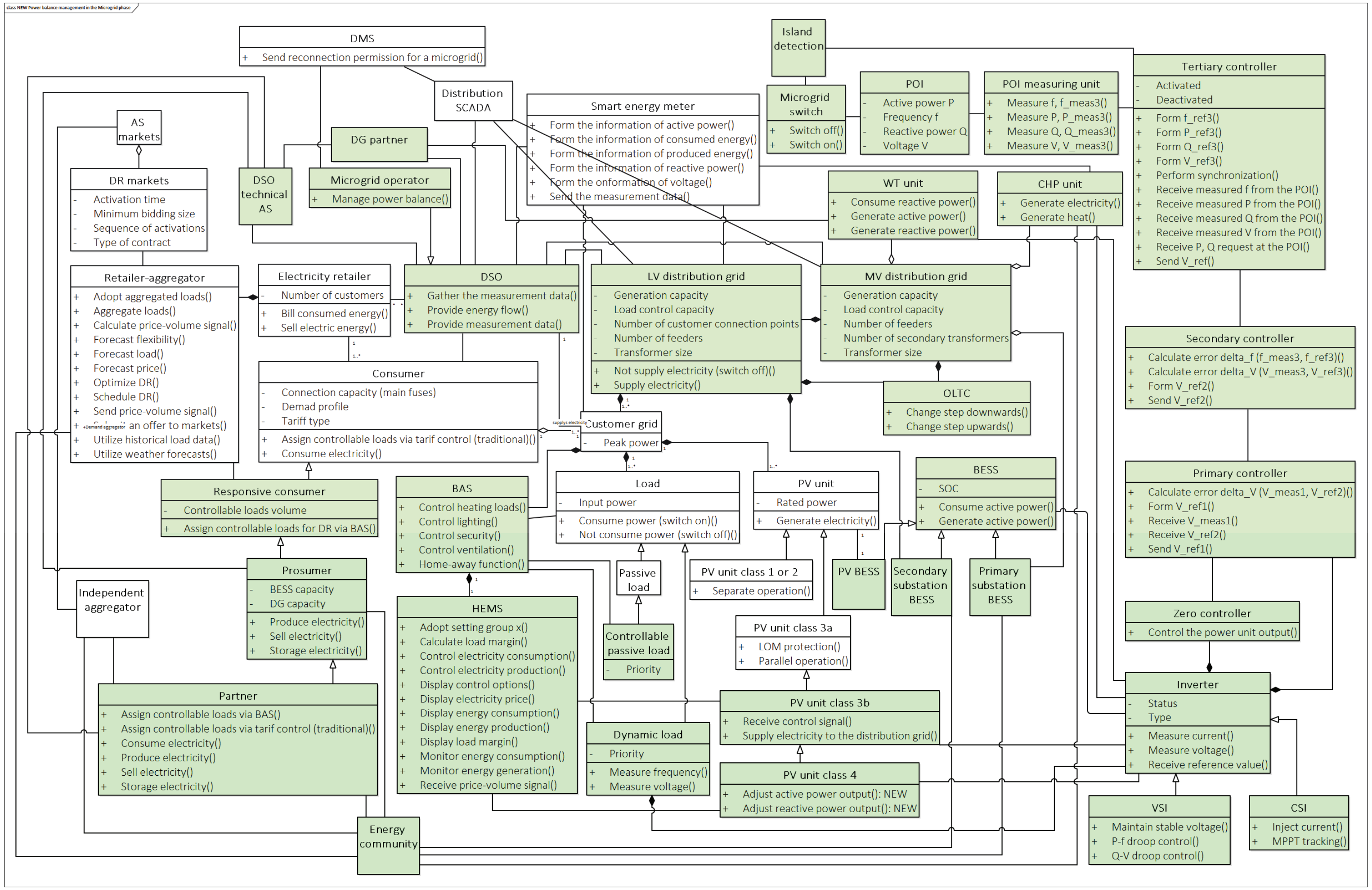


Figure A2. Class diagram of power balance management of the microgrid phase.

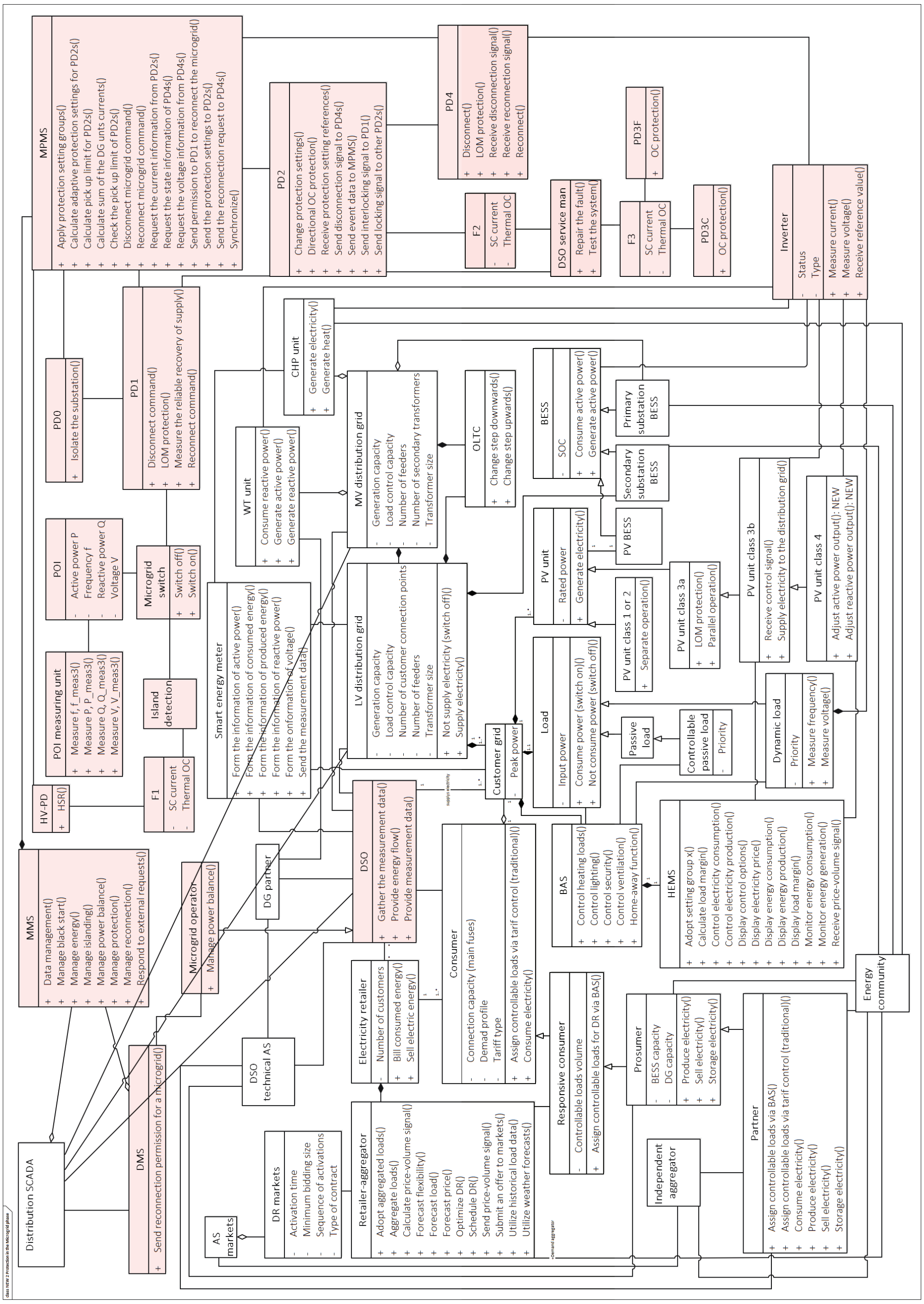


Figure A3. Class diagram of the overcurrent protection of the microgrid phase.

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