UNIVERSITY OF VAASA

THE SCHOOL OF TECHNOLOGY AND INNOVATIONS

ELECTRICAL ENGINEERING

Samuli Aflecht

SIMULATION STUDY OF TECHNICAL ANCILLARY SERVICES IN ELECTRICITY DISTRIBUTION SYSTEMS

Master's thesis for the degree of Master of Science in Technology submitted for assessment, Vaasa, 28 August 2018.

Supervisor	Kimmo Kauhaniemi
Instructor	Hannu Laaksonen

TABLE OF CONTENTS

SYMBOLS AND ABBREVIATIONS

U	voltage
I	current
I_P	active component of the current
I_Q	reactive component of the current
R	resistance
P	active power
Q	reactive power
S	apparent power
φ	phase angle (phi)
$cos(\varphi)$	power factor
j	imaginary unit (electrical engineering)
W	unit for active power
VA	unit for apparent power
var	unit for reactive power

ANM	active network management
DCC	demand connection code
DeCAS	demonstration of coordinated ancillary services covering different voltage levels and the integration in future markets
DER	distributed energy resource
PV	photovoltaic
DSO	distribution system operator
ENTSO-E	the European network of transmission system operators
flexibility	controllable reactive/active power resource
SSG	Sundom smart grid
TSO	transmission system operator
IC	innovation cell
$Q(U)$-control	reactive power is controlled by the function of voltage
$P(U)$-control	active power is controlled by the function of voltage
$P(f)$-control	active power is controlled by the function of frequency
PI-control	proportional-integral control
SV	sampled values
GOOSE	generic object oriented substation event
IEC61850	data transfer protocol
ESS	energy storage system
RES	renewable energy source
CHP	combined heat and power
IGBT	insulated gate bipolar transistor
PCC	point of common coupling
HV	high voltage

MV	medium voltage
LV	low voltage
p.u.	per unit value
EV	electric vehicle

UNIVERSITY OF VAASA		
The School of Technology and Innovations		
Author:	Samuli Aflecht	
Topic of the Thesis:	Simulation study of technical ancillary services in electricity distribution network	
Supervisor:	Professor Kimmo Kauhaniemi	
Instructor:	Professor Hannu Laaksonen	
Degree:	Master of Science in Technology	
Major of Subject:	Electrical engineering	
Year of Entering the University:	2015	
Year of Completing the Thesis:	2018	**Pages:** 97 + 27

ABSTRACT

This thesis was done as part of the research project DeCAS. The EU-funded project aims to analyze technical ancillary services crossing traditional boundaries from high voltage, medium voltage to low voltage, also with regard to their respective market integration concepts. The goal is to achieve an active control concept of the future distribution network where the unnecessary reactive power flows are avoided.

The studied network is located in Sundom, Vaasa. Sundom Smart Grid is a living laboratory done in collaboration with ABB, Vaasan Sähkö, Elisa and the University of Vaasa. The main target of this thesis was to examine by PSCAD simulations the addition of distributed generation and to manage the possible network interactions by the means of active network management.

An existing simulation model of the SSG was utilized. Some simplifications were made to the model to reduce the simulation time. The simulations consisted of 72 simulation cases, 36 cases with both Fingrid and ENTSO-E reactive power windows. The idea was to start from a basic model without DER-units connected and then make additions of wind turbines, photovoltaics and utilize different control scenarios for them.

The results offer information on possible interactions between different voltage levels. DER-units have capabilities for providing the ancillary services. By using ANM to control the flexibilities the amount of distributed generation can be increased significantly in an electricity network. Aggregating will be needed to sum up the smaller production portions and to ease up the marketing process. Also a type of 'flexible database' will be needed for the overall coordination of available resources. The database could include real time information about the free production capacities, sizes, distances, scheduling etc.

KEYWORDS: **technical ancillary services, reactive power control, voltage control**

VAASAN YLIOPISTO
Tekniikan ja innovaatiojohtamisen yksikkö

Tekijä:	Samuli Aflecht
Diplomityön nimi:	Simulointitutkimus teknisistä lisäarvopalveluista sähköverkossa
Valvojan nimi:	Professori Kimmo Kauhaniemi
Ohjaajan nimi:	Professori Hannu Laaksonen
Tutkinto:	Diplomi-insinööri
Oppiaine:	Sähkötekniikka
Opintojen aloitusvuosi:	2015
Diplomityön valmistumisvuosi:	2018 **Sivumäärä:** 97 + 27

TIIVISTELMÄ

Tämä opinnäytetyö tehtiin osana DeCAS-tutkimushanketta. Tässä EU:n rahoittamassa hankkeessa pyritään tutkimaan ja analysoimaan teknisiä lisäarvopalveluja yli perinteisten jänniterajojen, korkeajännitteestä aina pienjännitteelle saakka, unohtamatta niiden markkinoille saattamista. Tavoitteena on kehittää tulevaisuuden sähkönjakeluverkolle aktiivinen ohjauskonsepti ilman tarpeetonta loistehon siirtoa.

Tutkittu verkko sijaitsee Sundomissa, Vaasassa. Sundom Smart Grid on elävä laboratorio, joka on tehty yhteistyössä ABB:n, Vaasan Sähkön, Elisan ja Vaasan Yliopiston kanssa. Työn päätavoitteena oli tutkia PSCAD-simulaatioiden avulla hajautetun tuotannon lisäämistä sekä selvittää voidaanko mahdollisia verkon yhteisvaikutuksia hallita aktiivisen verkonhallinnan keinoin.

Simulaatiot tehtiin hyödyntäen olemassa olevaa simulointimallia, johon tehtiin joitakin yksinkertaistuksia simulointiajan lyhentämiseksi. Simuloinnit koostuivat 72:sta simulaatioajosta, 36 ajoa sekä Fingridin että ENTSO-E: n loistehoikkunalla. Ajatuksena oli aloittaa perusmallista ilman hajautetun tuotannon yksiköitä ja lisätä vähitellen tuuliturbiineja, aurinkokennoja sekä niiden eri ohjaustapoja.

Tulokset tarjoavat tietoa mahdollisista yhteisvaikutuksista eri jännitetasojen välillä. DER-yksiköillä on pätevät mahdollisuudet teknisten lisäarvopalvelujen tarjoamiseen. Käyttämällä ANM: ää joustoresurssien hallintaan hajautetun tuotannon määrää voidaan lisätä merkittävästi sähköverkoissa. Aggregaattoreita tarvitaan pienempien tuotantojen tai niiden osien yhteen kokoamiseen, joka helpottaa niiden myymistä. Tarvitaan myös nk. ”joustava tietokanta”, joka sisältäisi tarkat ja reaaliaikaiset tiedot käytettävissä olevista resursseista. Tietokanta voisi sisältää reaaliaikaista tietoa vapaista tuotantokapasiteeteista, niiden ko’oista, etäisyyksistä, ajoituksesta jne.

AVAINSANAT: tekniset lisäarvopalvelut, loistehon säätö, jännitteen säätö

1 INTRODUCTION

The EU has the most ambitious energy policy in the world. The objectives of the policy are to provide secure, inexpensive and climate-friendly energy for the residents, businesses and industry. The EU has set itself ambitious goals for the forthcoming decades. For 2020 placed so called 20-20-20 –goal aims to get 20 % of all energy from renewable sources, cut greenhouse gasses by 20 % compared to 1990 levels and increase energy efficiency by 20 %. By the year 2030 it is targeted to reduce greenhouse gasses by 40 %, get at least 27 % of EUs energy from renewable sources, increase energy efficiency by 27-30 % and reach 15 % electricity interconnection which means energy transport between EU countries. The above targets are waypoints for the 2050 main target which is 80-95 % reduction in greenhouse gasses compared to 1990-levels. Europe seriously aims to become sustainable, low-carbon and environmentally friendly (European Union 2018.)

Renewable and energy efficient technologies are in key role when approaching to fulfill above targets. The coal-based energy production has to be replaced with different types of sustainable energy resources. Nuclear power is not considered to be a green alternative although it produces affordable energy efficiently and free of emissions. The problem is nuclear waste that is highly toxic and has very long half-life. Instead, wind- and solar power are acknowledged to be valid sources of green energy.

The growth of distributed generation set multiple requirements for the electricity networks. For example voltage rise and reactive power management are considered to be major issues. In addition the growth of underground cabling increases the potential of these issues. The fact is that the electrical system is not initially designed from the perspective which takes into account the effects of distributed generation. These issues have to be solved before they come every day reality. Fortunately, there are different solutions for the management of the oncoming energy transition.

The other aspect of growing distributed generation is the possibility for them to participate in energy and ancillary service markets. The traditional producer and consumer boundaries fade when network operators would be able to utilize smaller customers’ production capacities or parts of them for electricity grid’s support functionalities and on the contrary compensate customers for the provided services.

In this thesis reactive power management is studied from ancillary services’ viewpoint. By simulating different control scenarios of distributed energy resources on different voltage levels their suitability for ancillary services will be evaluated.

1.1 Background and objectives

The background of the thesis is the EU-funded ERA-Net Smart Grids Plus initiative. It consists of 21 European countries and regions with a mutual vision to create an electric power system that integrates renewable energies and enables flexible consumer and production technologies. This thesis is done as part of the research project DeCAS. The project aims to research and analyze system services such as demand response and coordination of individual voltage and reactive power control concepts crossing traditional boundaries from high voltage, medium voltage to low voltage, also with regard to their respective market integration concepts (ERA-Net 2017a.)

The main objective of this thesis is to study the possibility of providing different ancillary services by distributed generator units connected at LV and MV networks and chosen active network management scheme as well as potential interactions between ancillary services provided by DG units connected at different voltage levels. The smart grid under examination is Sundom Smart Grid and it is located in Sundom, Vaasa. It is a living laboratory done in collaboration with ABB, Vaasan Sähkö, Elisa and University of Vaasa. The goal is to discover solutions for reactive power- and voltage management considering islanding detection functionality and coordinated ancillary services across different voltage levels.

1.2 DeCAS project

DeCAS is an abbreviation of the words ‘demonstration of coordinated ancillary services covering different voltage levels and the integration in future markets’. The project launched in February 2016 and it has partners from four European countries Austria, Germany, Finland and Slovenia. There are three existing demonstration projects (DeCAS Innovation Cells) whose present status will be improved and where the developed solutions will be transferred and validated.

The voltage levels and controls under evaluation are shown in Figure 1. The project aims to research and analyze system services such as demand response and coordination of individual voltage and reactive power control concepts crossing traditional boundaries through different voltage levels considering their respective market integration concepts. It will further include the integration of related monitoring and controls in process-control systems (ERA-Net 2017b.)

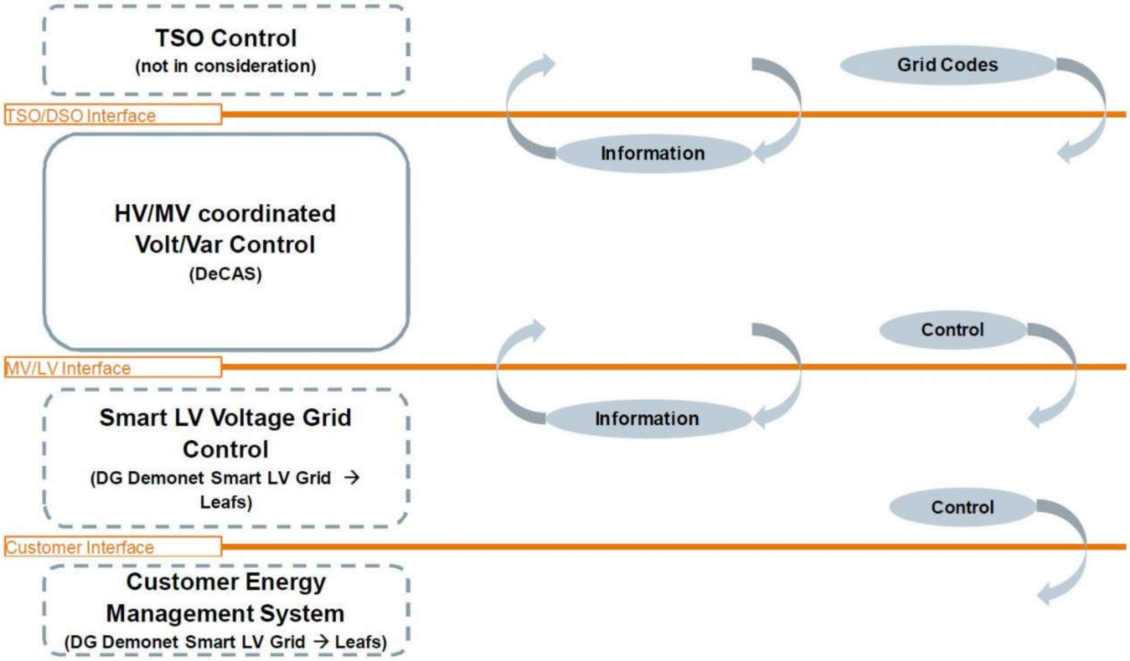


Figure 1. DeCAS schematics (ERA-Net 2017b).

2 ACTIVE DISTRIBUTION NETWORKS

Distributed generation has been around long before modern day smart technologies. At the beginning of inventing electricity production the first production equipment was usually small-scale and the centralized large-scale production took place at later times. In the 1990's distributed generation was in its lowest point. The main reason for this was that the financial benefits of large power plants outweighed the supplemental costs of electricity transportation. These large and centralized systems had long transfer distances, notable losses, they were passive, unidirectional and trivial to control (IET 2006: 3.) Table 1 presents a characteristics comparison between centralized- and distributed generations.

From the 1980's to 2000 energy production was not crucial at all in residential construction in Finland. The main reasons for this were the strong status of centralized district heating and the availability of affordable electricity. After the 1970's oil crisis had been forgotten and the energy was inexpensive. Ecological values didn't restrain the growth of energy consumption. There were some local renewable projects, for example Viikki, Helsinki, where a wide spectrum of renewable technologies were introduced (Motiva 2010: 8.)

In 2000's the climate change discourse has brought energy saving and coal-neutral energy production solutions to the midst of the construction. The development has swayed to the other end of the scale and ecological values are now in the center of all new construction planning. The fact was that distributed renewable generation had become a considerable option for climate friendly and efficient energy production (Motiva 2010:9.)

In Finland it is typical that in one region there are multiple types of energy sources i.e. an energy palette in use (Motiva 2010:9). The traditional transmission grid is still in use and it can be considered as the backbone of the whole electric system. It has been enhanced with automation and communication tools to minimize losses and increase controls. The distributed generation is mostly added to LV-level and nowadays more and more to MV-level. Thus, the need for local control is increased. Also the fact that distribution network is being dug underground in many areas increases the need for control even more.

Table 1. Characteristics comparison between centralized and distributed generation (Björklund 2010: 4).

CENTRALIZED GENERATION	**DISTRIBUTED GENERATION**
Large production plants	Distributed and mainly renewables-based production, also traditional energy sources (in all sizes)
Large transfer networks	Smart transfer considering consumption
Unidirectional power flow	Controllable, bidirectional power flow
Traditional metering and billing	Advanced metering based on real time information
Production far away from consumption	Production near or in touch with consumption for the local or regional demand
Connection to main utility grid necessary	Connection to main utility grid not necessary, island operation in critical situations

2.1 Microgrid

The development of microgrids got started from a need to get distributed generation closer to customer instead of adding them to traditional radial power grid more farther from customers. It was a new systemic approach in which the power grid was divided into smaller proportions called microgrids. The concept of microgrid introduced more flexible use of distributed generation and more efficiency since the reduction of transmission losses (M. Khan et al 2017: 1.)

Microgrid is a small-scale electric grid which uses distributed generation and usually renewable energy sources (RES) as its driving force. It can also be equipped to cogeneration with combined heat and power (CHP) production. Usually, electricity is produced for one's own use and a portion of it is fed into the main grid. On the other hand, heat is always consumed locally because of the pricy transport and fairly large transportation losses (van Gerwen 2006: 4).

Figure 3 presents a basic diagram of a microgrid. From main utility grid's point of view microgrid is seen as an independent controllable entity. It has two main operation modes: grid-connected and island-mode. In the grid connected-mode microgrid operates as part of the traditional electric grid and in the island-mode the connection to main grid is offline and microgrid becomes islanded for self-sufficient operation. Of course, microgrid is designed for seamless transition between the modes. The high level of power electronics enables the power to flow bi-directionally from and to the traditional electric grid (M. Khan et al 2017: 1, van Gerwen 2006: 4).

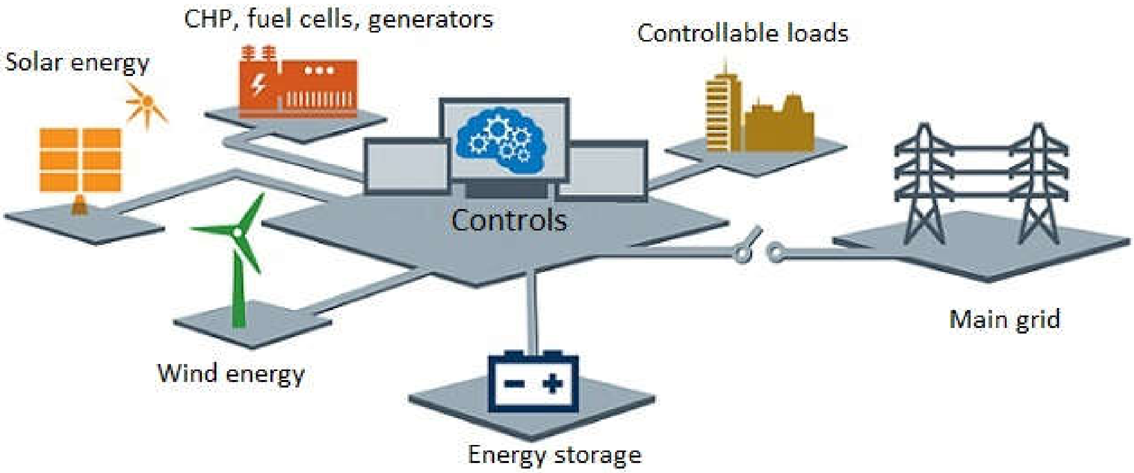


Figure 2. Microgrid (modified from Microgrid knowledge 2015).

2.2 Active Network Management

Distribution networks have traditionally been passive and the flow of electricity has been from producers through transmission system to customers connected to the lower level networks. The growth of distributed generation (DG) and smarter technologies throughout all voltage levels have generated a need to control the power flow more actively. The basic problem with the growth of DG is that traditional networks aren't designed for the increased capacity and voltage increase.

Active network management uses variability of electricity to optimize the use of network's assets. The aim is to reduce contingencies and cut costs by maximizing the use of existing network's resources. The ways to control voltage actively are intermittent limiting of production, adjusting the power factors of generating units, compensation of reactive power and an OLTC based wide area voltage control with or without voltage regulators (ENA 2017.) The control methods used are based on real-time or almost real time measurements and communication protocols.

Active network management combines existing electric grid structure to separate smart grid components such as smaller energy generators, renewable generation and storage devices. It implements data capture, analysis, automation and control capabilities of these devices. (Nines 2017).

The cost saving aspect of ANM is significant. For example in Britain's first smart grid on Orkney it was reviewed that the cost of the ANM scheme was only one sixtieth $(\frac{1}{60})$ of the cost of alternative network reinforcement (Nines 2017). Of course, when the network's DG penetration level grows significantly ANM might not be sufficient i.e. there's a tipping point in the network capacity after which the system has to be reinforced instead. Still, in many cases active network management is a viable choice for controlling the network's voltage and power flow.

2.3 Demand response

Traditionally, electric grid control has been based on adjusting the generating units at the feeding side and the loads have been almost entirely un-controlled. In Finland, a two-tariff system has been on place which balances the grid's load between night- and day-time. The idea of the system is to shift heavier loads to night-time when the overall demand and price of electricity is lower. This type of balancing system is getting outdated because the production structure is shifting towards more weather dependent and volatile entity where the status of the electricity market changes more rapidly than before (Pahkala et al 2017: 20.)

Demand response is a means to make the load-side of a network more flexible. For example at peak load hours customers' equipment can be adjusted to shed or shift the loads to lower the electricity demand and this way make the whole electricity system more stable. Another example is to increase customers' electricity consumption at times of high availability and low price. Of course, customer's load altering functionality has to be done in response to time-based rates or other types of financial incentives.

Demand response programs are used as resource options for balancing supply and demand. The use of these programs can lower electricity rates in wholesale markets, and in turn, lead to lower retail prices. The ways to engage customers in demand response services include different rating-based pricing such as time-of-use pricing, critical peak pricing, variable peak pricing, real time pricing, and critical peak price compensation. Also, direct load control programs are included in which the power companies are given the ability to cycle bigger demand loads, for example air conditioners and water heaters on and off in the times of high demand in exchange for a financial inducement and decreased cost of electricity (Office of electricity delivery & energy reliability 2018.)

2.4 Utilization of energy storage systems

Another highly interesting point of view for demand response is the utilization of energy storage systems (ESS). With the use of ESS the production timing can be shifted in a way like the load shifting mentioned earlier. This way not only the demand but also supply would be more flexible. This would benefit the systems using distributed generation which is varying and weather dependent. Customers would also benefit from the use of BESS by storing energy at the times of high availability and then use it for own consumption or for sale at the times of high demand.

From TSOs/DSOs standpoint one effective way to utilize energy storing would be to place an ESS to HV/MV-substation (or MV/LV-substation). The benefits are as presented below (Laaksonen 2017.):

1) Local compensation of reactive power produced by underground cables which then would decrease the reactive power flow in MV-network. This would lead to decreased losses in MV-network and increased capacity to transfer active power and also the need for reactors at substations would be reduced.

2) Continuously control the reactive power flow through the MV/LV distribution transformer (possibly avoid the cost of an OLTC when the amount of flexibilities in the network is high)

3) Increase the capacity to transfer active power by storing the energy at times of high contingencies, this way possibly avoid the cost of additional transfer capacity.

4) Secure reliable LV-network distribution to all or the most critical customers in cases of MV-network fault by utilizing intended island operation.

5) In cases of problems or challenges the storage capacity in MV/LV distribution substation can be increased

2.5 Ancillary services

The ancillary services are type of services that help grid operators maintain a reliable electricity system. Traditionally ancillary services have been provided by the spinning generating units in transmission networks. The key tasks of ancillary services are to maintain the convenient flow and direction of electricity, deal with the instabilities between supply and demand, and help system recovery after a power system event. In power systems with significant high rate of variable renewable energy, additional ancillary services may be required to manage increased variability and uncertainty (U.S. Government 2017.)

Essential ancillary services listed that can be provided by inverter-connected DERs (Xiaoyan & Tolbert 2006: 2-6.):

- Voltage control

  Use of reactive power injection/absorption to maintain transmission system voltages within desired ranges or for maintaining the bus voltage of essential loads.

- Frequency Regulation

  Regulate frequency by utilizing online generation units equipped with governors and automatic generation control and that can change promptly. In some systems responds to rapid load fluctuations while load following is dedicated to slower changes.

- Load Following

  Partly track the load which is similar to frequency regulation and partly sell power to the utility.

- Spinning Reserve

  Use of online and grid-synchronized generating equipment that can immediately response to frequency change by increasing output. Full capacity utilization in seconds to < 10 minutes.

- Supplemental Reserve (Non-spinning)

  Use of generating equipment and interruptible load with the capability to full availability for correction of generation/load unbalance incurred by generation or transmission outages.

- Backup Supply

  A service for a customer against forced outages by the generating units that provide their energy or against loss of transmission between their normal supply and load.

- Harmonics Compensation

  Use of online generation equipment for harmonics compensation which is caused by non-linear loads. Harmonics affect to power quality, cause voltage imbalances and excessive zero-sequence currents.

- Network Stability

  Similar to frequency control but more rapid response time is required.

- Seamless Transfer

  Ability for online generation to transition among various ancillary services without the disruption of power delivery.

- Peak Shaving

  Use of generation equipment during certain peak load periods.

2.6 Aggregators

Often the small-scale production, for example household size energy production, is too insignificant for direct business with DSOs or TSOs and an intermediary is needed. Aggregator is the third market participant between customer and company. Aggregator gathers multiple customers' resources (consumption, production, storage) to a larger entity which is then marketed to different electricity markets. Aggregating increases the customer's options, enhances the possibilities to participate in electricity markets and gives them the opportunity to affect to their electricity costs (Pahkala et al 2017: 24.)

3 REACTIVE POWER

Sinusoidal AC power consists of three components: apparent-, active- and reactive power. The power triangle in Figure 3 is used to clarify the relation of the three power quantities. Active power P lies on the horizontal real-axis. Reactive power Q is located on the vertical imaginary-axis. Complex power $\bar{S}$ is the vector sum of active- and reactive power. Apparent power S is the absolute value of complex power. The angle between apparent power and active power is called φ (phi). It is a phase angle which represents the phase shift between the voltage and the current.

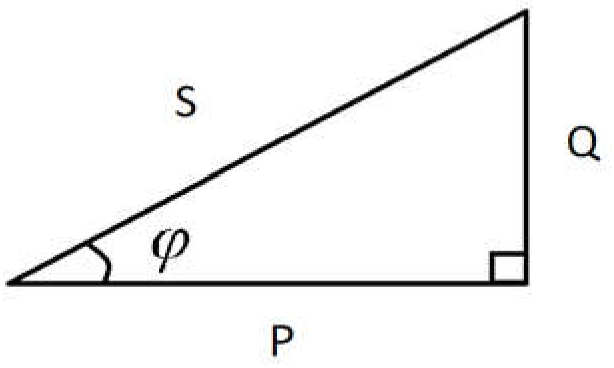


Figure 3. Power triangle (inspired by Silvonen 2004: 175).

The term *cos(φ)* is called power factor which is a dimensionless number used to explain the ratio of active and apparent power in a power system. Generally it varies between 0…1 (Silvonen 2004: 175.) The closer the number is to 1 the less reactive power there is in the system. The following equations clarify the relations of the power quantities:

$$\bar{S} = P + jQ, \tag{1}$$

$$S = \sqrt{P^2 + Q^2}, \tag{2}$$

$$P = U \cdot I \cdot \cos\varphi, \tag{3}$$

$$Q = U \cdot I \cdot \sin\varphi, \tag{4}$$

where $\bar{S}$ stands for complex power, S is apparent power, P is active power, Q is reactive power, j is imaginary unit, U is voltage, I is current and φ is phase shift.

As it can be seen above reactive power is the imaginary part of complex power and therefore it does not do any actual work or transmit any net energy. Active power is the real part and it does all the work and the net energy transmission. Still, in practice the dimensioning of power systems and devices has to be done by using apparent power as a reference.

It is important to remember that the power theory above only applies for sinusoidal quantities. If there are harmonics included the above Equations 1-4 only apply for fundamental values of current and voltage (Siemens 2013).

3.1 Reactive power charasteristics

Reactive power is generated in electric circuits by non-resistive loads or -parts of load. It pulsates back and forth in a circuit between energy source and energy storing components e.g. inductances and capacitances. Reactive power is a calculative quantity which in practice has no distinct equivalent (Silvonen 2004: 176.)

In addition to active power reactive power is needed by many electrical devices to function properly. In these devices for example transformers and squirrel-cage motors the actual work is done by active power and reactive power is needed to create and maintain the magnetic field (Korpinen 1998: 14.)

Reactive power can be either capacitive (positive) or inductive (negative) depending on the load and also on the reference point of examination. Often a lowercase notation *cap.* or *ind.* is used to tell the difference. A capacitor produces reactive power and an inductor consumes it (Silvonen 2004: 177.) Both capacitive and inductive reactive power has its own effect on the electric grid which will be explained in the next section.

3.2 Effects on power system

Reactive power causes losses to the power systems. When reactive power is not produced locally near the point of consumption it will be taken from the grid in which case the current taken by the load will increase. This is why transferring reactive power is harmful. The current I consists of active I_P and reactive I_Q components as it can be seen in the following equation,

$$I = \sqrt{I_P + I_Q}, \tag{5}$$

where, I stands for (overall) current, I_P is the active component of current and I_Q is the reactive component of current.

If reactive power would be produced near the load i.e. compensated the overall dimensioning current could be decreased. The decreased current would have many advantages. First, the capacity to transfer active power would be increased essentially. Second, the active power losses would be decreased. By reactive power compensation the I_Q component in Equation 5 is decreased. This would lead to contraction of overall current and losses and also to decreased temperatures of cables, transformers and switchboards (Korpinen 1998: 14-15.)

It is also crucial to understand the effect that reactive power has on the voltage of the grid. Inductive reactive power tends to lower the voltage and capacitive reactive power raises the grid’s voltage. For aforementioned reasons the reactive power balance has to be maintained to ensure that voltage stays in permissible limits.

3.3 Traditional compensation methods

As mentioned earlier compensation is used to try to diminish the reactive power Q to zero which would lead to a purely resistive circuit and only active power would be consumed or produced (Silvonen 2005: 177).

The compensation methods used will depend on the level of operation. Transmission and distribution networks have different objectives of compensation and voltage regulation. In transmission and sub-transmission networks the aim is to retain the voltage at the highest possible level considering the line losses and the compatible equipment behavior. In the distribution side of operation the voltage is kept within the contractual limits to ensure the voltage quality and the optimal use of customer equipment (Crappe 2008: 31.)

Traditionally shunt (~parallel) compensation is used to provide reactive power for maintaining a good voltage profile. Compensation is done near the loads by parallel placed capacitor banks. Thus, the power factors of the loads are improved and reactive losses are compensated in lower level networks (Crappe 2008: 199.)

In long transmission lines series compensation is an effective way to reduce line impedance and the associated voltage drops. Yet, this kind of equipment is not cost effective and it can make the protection more intricate. Also, it can act as a source of sub-synchronous resonance (Crappe 2008: 199.)

Power generation units can generate or consume reactive power i.e. an overexcited synchronous machine produces reactive power just like a capacitor and when under excited it consumes reactive power like an inductance. Because of the long distances between synchronous generators and loads they are used to meet the reactance requirements of the network (Crappe 2008: 33.)

A synchronous machine without load is called synchronous compensator which is designed specifically for reactive power compensation. Consumption or production of reactive power is done by adjusting the excitation (Crappe 2008: 34.)

Static compensator is enabled by power electronics and it consists of capacitor banks or inductances controlled by back to back mounted thyristors (Crappe 2008: 34).

OLTC (on-load tap changer) adjusts the transformation ratio of a transformer. The number of turns of the winding is increased or decreased within a fixed range. A tap change can be compared to an extra voltage injection which equals reactive power generation in the concerned zone (Crappe 2008: 35.)

3.4 Inverter-based control methods

The growing phenomenon in the field of distributed generation is the connecting of DERs through inverters. Most of the DERs and networks benefit from inverter-type connection by the increased control possibilities provided by power electronics. The inverters make the adjusting of DERs highly flexible.

For reactive power control by inverters there are three considerable methods: *Q(U)*-droop for the control of local voltage profile; *P(U) cos(φ)*-constant for the compensation and *cos(φ)(P)*-control for controls near the transformer (Laaksonen 2017.)

Voltage control by controlling reactive power in LV networks is not highly efficient because of the high R/X-ratio (resistance / reactance) of LV cables (resistance R is bigger than reactance X). MV/LV cables have bigger R-value (than HV cables) so transferring active power has a bigger impact to the voltage level of LV-network than transferring reactive power. When the amount of DG-units has increased significantly (for example in Germany) it has come to attention that the flow of reactive power has increased. This has caused a significant increase in losses in LV-networks, not necessarily be able to avoid overvoltage situations and the increase of fast voltage fluctuations caused by different voltage control schemes of different manufacturers' inverters. One efficient way is to limit the active power of DG-units in overvoltage situations, but it is not desirable because of the lost production capacity. For these aforementioned reasons a need for an active voltage (~ reactive power) control method in MV/LV-level has come up (Laaksonen 2017.)

4 REGULATIONS FOR REACTIVE POWER

Finland is part of the European Union and the electricity network regulations in place are passed by the European commission. The legislation and requirements are introduced to the commission by ENTSO-E which consists of 43 electricity transmission network operators from 36 countries across the Europe. The EU's Third Legislative Package for the Internal Energy Market started ENTSO-E and gave it legal mandate in 2009. The aim of the legislative package is to advance the liberalization of gas and electricity markets in the EU (ENTSO-E 2017.)

Fingrid Oyj is a Finnish transmission system operator which is part of ENTSO-E. It maintains the Finnish transmission grid which consists of 14600 kilometers of transmission line and nearly 120 substations. Fingrid applies the EU's regulations and adapts them into practice (Fingrid 2018.)

4.1 Finnish TSO reactive power fees today

The reactive power window by Fingrid which is presented in Figure 4 describes the allowed volume of reactive power exchange without fees. The limits are placed depending on the active power exchange in the point of common coupling. When producing (delivering) active power the allowed reactive power is presented by Q_G and Q_{G1} and when consuming (receiving) by Q_D and Q_{D1}. The point (P_m, Q_m) is the measured hourly output of active and reactive power and it is used to define the reactive power fee. There is an exception to billing that in the period of one month the 50 largest hourly excesses of these limits are not taken into account (Sirviö et al 2017: 7.)

The price of reactive power seems to have an increasing trend which is an important matter when dealing with reactive power management. For example for consumption and production the reactive power fee has doubled from last year's 333 €/Mvar, month to 2018's 666 €/Mvar, month. In 2019 reactive power fee will be 1000 €/Mvar, month.

Instead, reactive energy fee remains at 5 €/Mvarh for both input (consumption) and output (production) (Fingrid 2018.)

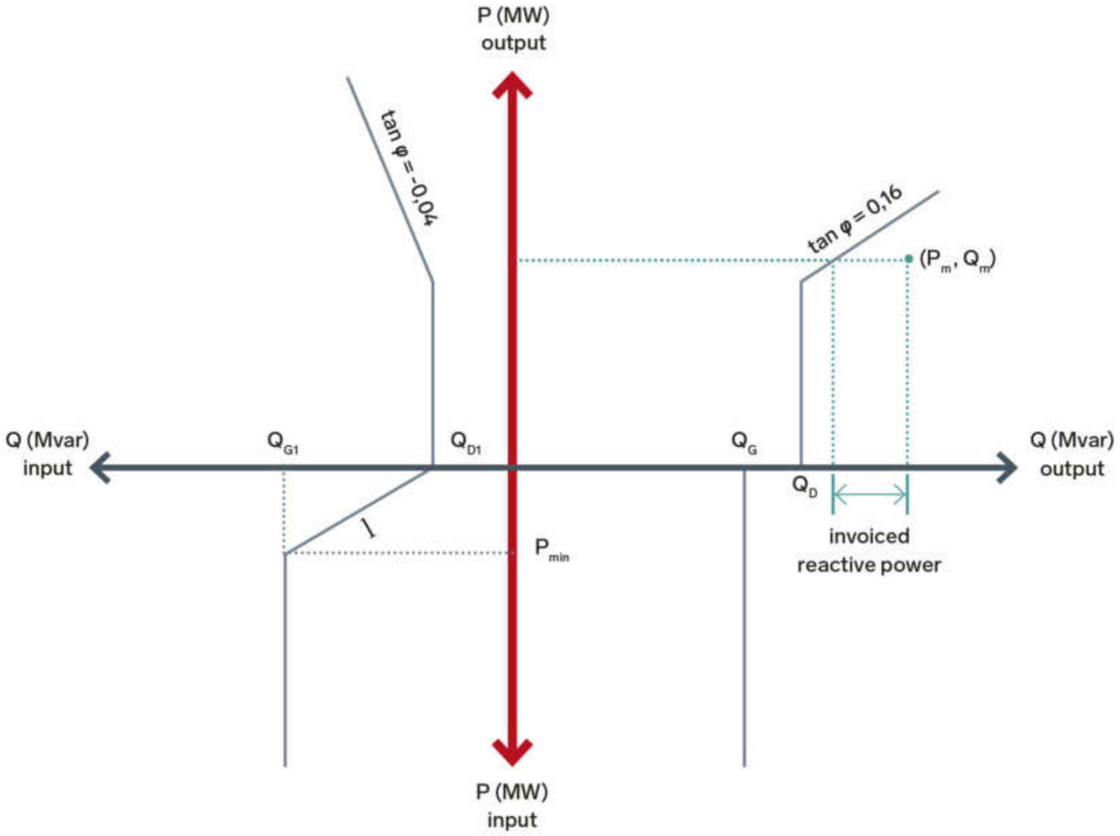


Figure 4. Reactive power window by Fingrid (Fingrid 2017).

4.1.1 Reactive power window when consuming active power

When consuming active power the reactive power limits Q_D and Q_{D1} are applied. The reactive power limits in the point of common coupling are calculated as follows (Fingrid 2017):

$$Q_D = 0{,}16 \cdot \frac{w_{taken}}{t_k} + 0{,}1 \cdot \frac{P_{net}}{0{,}9}, \tag{6}$$

where Q_D is the limit for reactive power consumption, w_{taken} [MWh] stands for the yearly energy in PCC, t_k [h] is peak load time and P_{net} [W] stands for the sum of power plants' net powers below the PCC. If the maximum power of the power plant is 1 MW then $P_{net} = 0$. If the sum of power plants' net powers $P_{net} > 450$ MW the limits of reactive power window won't be increased which means that the maximum value equals to $(0{,}1 \cdot \frac{P_{net}}{0{,}9}) = 50$ Mvar.

Equation 6 gives the Q_D-value in megavars [Mvar].

The limit for reactive power production Q_{D1} [Mvar] is calculated as follows (Fingrid 2017),

$$Q_{D1} = -0{,}25 \cdot Q_D. \tag{7}$$

4.1.2 Reactive power window when producing active power

When producing active power the reactive power limits Q_G and Q_{G1} are applied. The reactive power limits in the point of common coupling are calculated as follows (Fingrid 2017.) The following equation gives the Q_G-value in megavars [Mvar]:

$$Q_G = 0{,}1 \cdot \frac{P_{net}}{0{,}9}, \tag{8}$$

where Q_G is the limit for reactive power consumption and P_{net} [W] stands for the sum of power plants' net powers below the PCC.

The limit for reactive power production Q_{G1} [Mvar] is calculated. as follows (Fingrid 2017):

$$Q_{G1} = -Q_G \ . \tag{9}$$

4.2 Forthcoming ENTSO-E grid codes relating to reactive power control requirements

EU commission regulates reactive power management for the transmission-connected distribution systems by the Network Code of Demand Connection. Among European Union ENTSO-E sets the directive guidelines for reactive power control but some authority is left to the member countries. The final EUs reactive power window is presented in Figure 5. The reactive power limit is 48 % of the maximum capacity to import or export active power P_{max}. Therefore the power factor limit for importing (consuming) reactive power is $cos\ (\varphi)_{max} = 0{,}9_{ind}$ and for exporting (producing) $cos\ (\varphi)_{max} = 0{,}9_{cap}$. Also, it may be required by the TSO that reactive power is not allowed to be exported when active power import (consumption) is below the limit of $0{,}25 \cdot P_{max}$. The points P_i and Q_i are hourly average values of power with the reviewing period of 12 months (Sirviö et al 2017: 8; Commission regulation 2016: 13.)

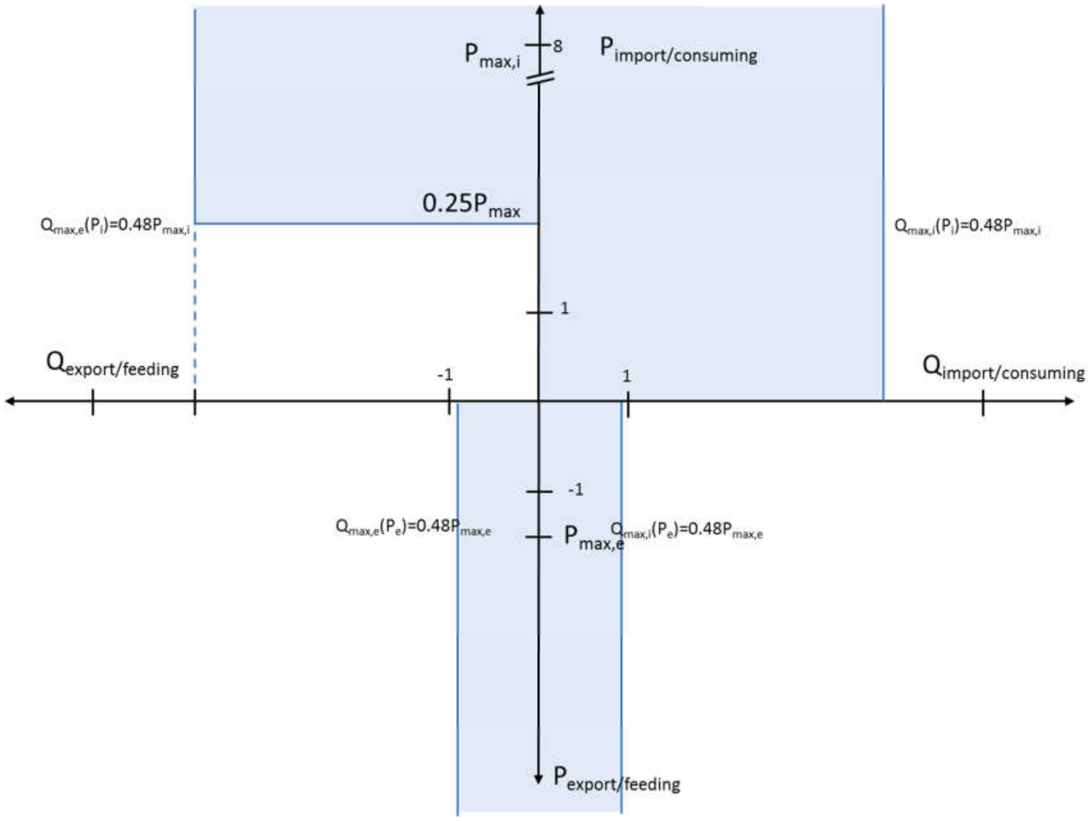
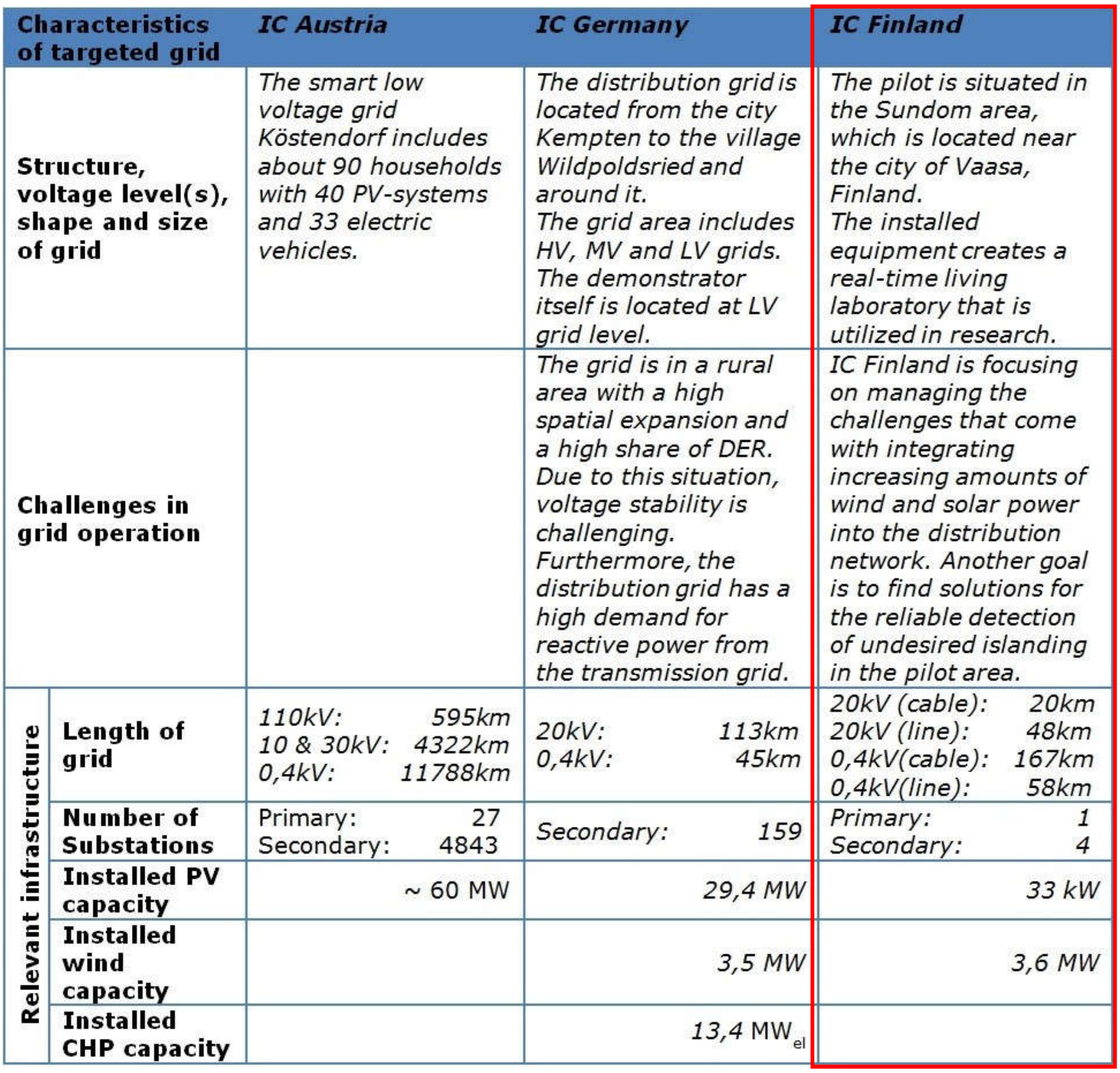


Figure 5. European Commission regulations for reactive power (Sirviö et al 2017: 8).

5 REACTIVE POWER CONTROL PRINCIPLES AS PART OF ANM SCHEME APPLIED TO SUNDOM SMART GRID

This chapter contains Sundom Smart Grid's specifications and control architectures. DeCAS-project aims to find viable control methods for smart grids and overall examine the interactions of these controls through different voltage levels. As mentioned earlier this project contains three innovation cells (IC) that are located in Austria, Germany and Finland. The overall specifications of the ICs are presented in Table 2.

Table 2. Innovation cell specifications (ERA-Net 2017c).



Characteristics of targeted grid		***IC Austria***	***IC Germany***	***IC Finland***
Structure, voltage level(s), shape and size of grid		*The smart low voltage grid Köstendorf includes about 90 households with 40 PV-systems and 33 electric vehicles.*	*The distribution grid is located from the city Kempten to the village Wildpoldsried and around it.* *The grid area includes HV, MV and LV grids.* *The demonstrator itself is located at LV grid level.*	*The pilot is situated in the Sundom area, which is located near the city of Vaasa, Finland.* *The installed equipment creates a real-time living laboratory that is utilized in research.*
Challenges in grid operation			*The grid is in a rural area with a high spatial expansion and a high share of DER. Due to this situation, voltage stability is challenging.* *Furthermore, the distribution grid has a high demand for reactive power from the transmission grid.*	*IC Finland is focusing on managing the challenges that come with integrating increasing amounts of wind and solar power into the distribution network. Another goal is to find solutions for the reliable detection of undesired islanding in the pilot area.*
Relevant infrastructure	**Length of grid**	*110kV: 595km* *10 & 30kV: 4322km* *0,4kV: 11788km*	*20kV: 113km* *0,4kV: 45km*	*20kV (cable): 20km* *20kV (line): 48km* *0,4kV(cable): 167km* *0,4kV(line): 58km*
	Number of Substations	Primary: 27 Secondary: 4843	*Secondary: 159*	*Primary: 1* *Secondary: 4*
	Installed PV capacity	~ 60 MW	*29,4 MW*	*33 kW*
	Installed wind capacity		*3,5 MW*	*3,6 MW*
	Installed CHP capacity		*13,4 MW$_{el}$*	

5.1 Sundom Smart Grid living lab

Sundom Smart Grid is a living lab-type co-op project between several participants. Living lab can be defined as a test environment in which new technologies can be tested in authentic operating conditions. In Sundom Smart Grid it means that the network interconnects the national grid and actual customers. The project participants with different expertize and scope strive together towards the mutual goal. Figure 6 presents SSG's structure by a single line diagram.

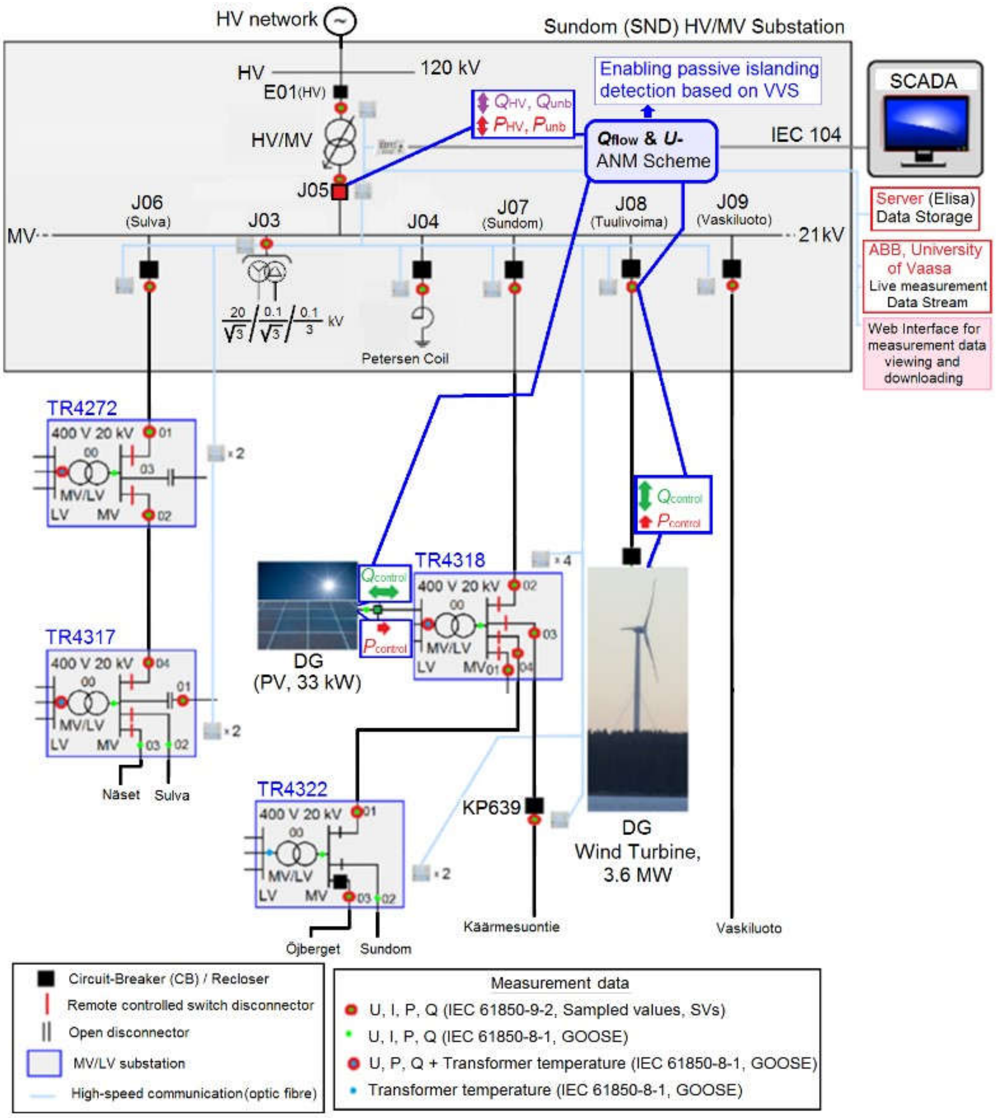


Figure 6. Sundom smart grid single line diagram (Sirviö et. al. 2017: 6).

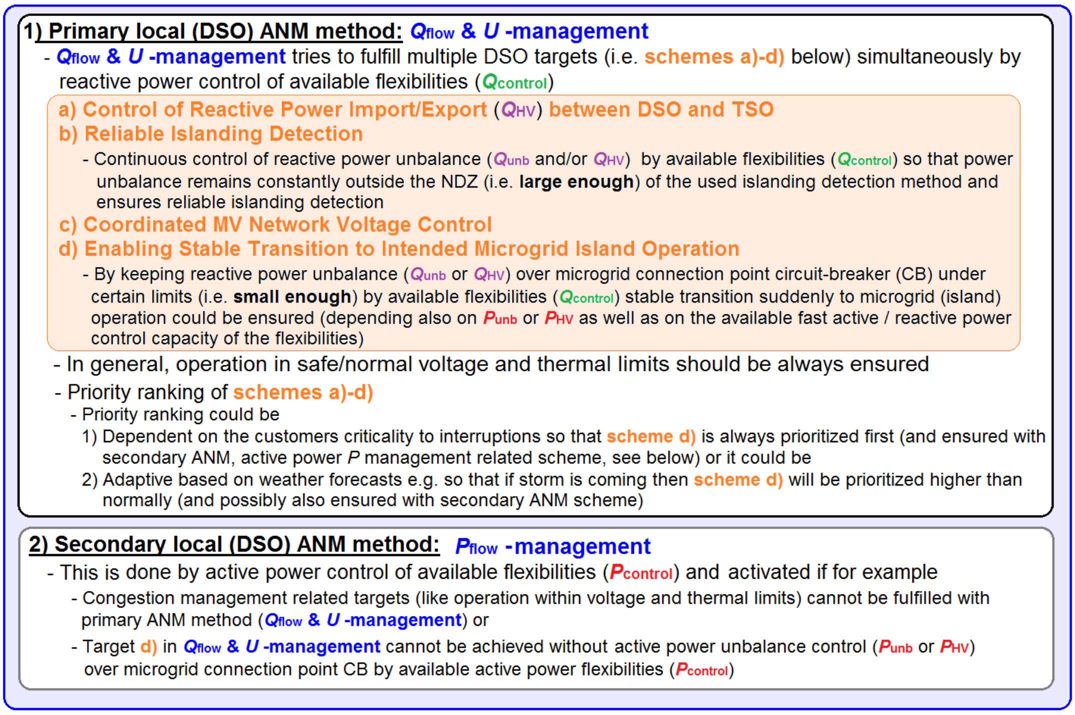
5.2 Structure of the grid

The Sundom substation connects SSG to the main grid via the main HV/MV-transformer. There are total seven feeders connected to the MV-bus, one incoming and six outgoing. An auxiliary transformer is located on feeder J03 which provides electricity for the Sundom substation itself. A Petersen Coil is needed for the compensation of earth fault currents and it is located on feeder J04. The rest four J06-J09 are actual feeders that are connected to lower levels of the network. On both feeders J06 and J07 there are several MV/LV substations on each but only two of them are equipped with on-line measurements. A 3,6 MW wind turbine is located on feeder J08. Another DG-unit, 33 kW photovoltaic, is located on feeder J07's MV/LV-substation.

The measurements are performed in real-time and gathered on-line from MV-network's four feeders at HV/MV-substation and also from three MV/LV-substations. There are total twenty measurement points across the Sundom Smart Grid. The measurement data is IEC61850 stream with current and voltage measurements as SVs (sampled values). The sampling is done by taking 80 samples per cycle at 50 Hz frequency which is equal to 4000 samples per second. Other measured quantities such as power, frequency, RMS-values etc. are transmitted by GOOSE messages. All the measurement data is stored to servers for future use and forthcoming research purposes (Sirviö et al 2017: 6.)

5.3 Studied active network management scheme

Sundom Smart Grid's control methods consist of a two-level system with multiple simultaneous targets. Requirements are met by controlling the reactive and/or active power of available flexibilities. The controls and the targets are presented in Figure 7.



1) Primary local (DSO) ANM method: **Q_{flow} & U -management**

- **Q_{flow} & U -management** tries to fulfill multiple DSO targets (i.e. **schemes a)-d)** below) simultaneously by reactive power control of available flexibilities (Q_{control})

a) Control of Reactive Power Import/Export (Q_{HV}) **between DSO and TSO**

b) Reliable Islanding Detection

  - Continuous control of reactive power unbalance (Q_{unb} and/or Q_{HV}) by available flexibilities (Q_{control}) so that power unbalance remains constantly outside the NDZ (i.e. **large enough**) of the used islanding detection method and ensures reliable islanding detection

c) Coordinated MV Network Voltage Control

d) Enabling Stable Transition to Intended Microgrid Island Operation

  - By keeping reactive power unbalance (Q_{unb} or Q_{HV}) over microgrid connection point circuit-breaker (CB) under certain limits (i.e. **small enough**) by available flexibilities (Q_{control}) stable transition suddenly to microgrid (island) operation could be ensured (depending also on P_{unb} or P_{HV} as well as on the available fast active / reactive power control capacity of the flexibilities)

- In general, operation in safe/normal voltage and thermal limits should be always ensured
- Priority ranking of **schemes a)-d)**
  - Priority ranking could be
    1) Dependent on the customers criticality to interruptions so that **scheme d)** is always prioritized first (and ensured with secondary ANM, active power P management related scheme, see below) or it could be
    2) Adaptive based on weather forecasts e.g. so that if storm is coming then **scheme d)** will be prioritized higher than normally (and possibly also ensured with secondary ANM scheme)

2) Secondary local (DSO) ANM method: **P_{flow} -management**

- This is done by active power control of available flexibilities (P_{control}) and activated if for example
  - Congestion management related targets (like operation within voltage and thermal limits) cannot be fulfilled with primary ANM method (**Q_{flow} & U -management**) or
  - Target **d)** in **Q_{flow} & U -management** cannot be achieved without active power unbalance control (P_{unb} or P_{HV}) over microgrid connection point CB by available active power flexibilities (P_{control})

Figure 7. ANM methods used in Sundom Smart Grid (Laaksonen & Hovila 2016: 23).

As it can be seen the above figure the Q_{flow}- & U–management is the primary local ANM-scheme. It targets to control reactive power exchange between DSO and TSO, ensure reliable islanding detection, apply coordinated MV-network voltage control, enable stable transition to intended island operation and in general, ensure operation in normal voltage and thermal limits. The ranking of above targets depends on prevailing circumstances and customer preferences (Sirviö et al 2017: 8; Laaksonen & Hovila 2016: 23.)

The secondary local ANM-method is P_{flow}-management. It utilizes the active power control of available flexibilities and it is activated if the operation within voltage and thermal limits can't be achieved with the primary ANM-method. Also, if transition to island operation cannot be achieved with reactive power control then active power of available flexibilities will be utilized (Laaksonen & Hovila 2016: 23.)

5.4 Islanding detection

SSG's islanding detection functionality is based on voltage vector shift (VVS). It measures the change in phase angle between DG-unit's and main grid's voltage. If the smart grid is disconnected, the phase angle between it and the main grid will change. For VVS to function reliably at all times a certain active- and reactive power unbalance is needed. Figure 8 presents in the midst of both reactive power windows the b-limits for the needed unbalance. The area inside is called non-detecting zone (NDZ) where the system is too close to power balance. The a-limits are required to ensure the system a stable transition to intended island operation mode without frequency and voltage instabilities (Sirviö et al 2017: 8.)

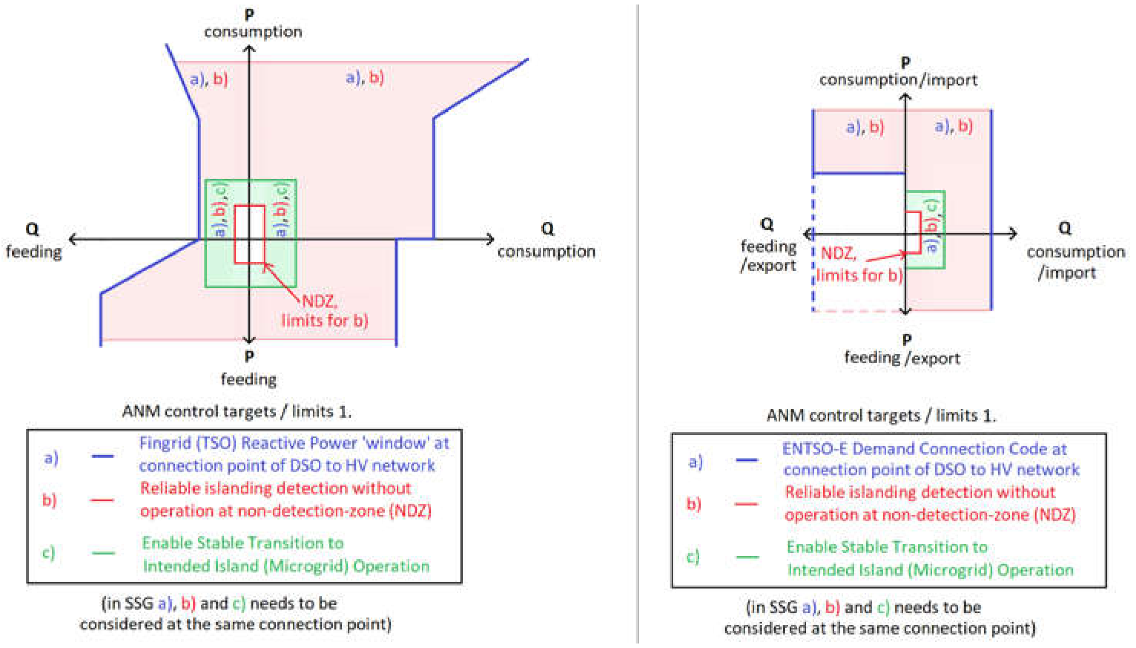


Figure 8. An adaptation of Fingrid's and ENTSO-E's reactive power limits, NDZ- and intended island operation limits (modified from Laaksonen & Hovila 2016)

5.5 Future-proof LV/MV voltage control

A coordinated future-proof LV (and MV) voltage / reactive power control solution is based on OLTC which is located at substation or secondary substation and it tries to keep the voltages within desired limits. If the required voltage level is not achieved the LV/MV inverters controlling the DG-units are given a reactive power set-point. If the two controls above can’t achieve the objective the third option is to limit the active power of the inverters. Of course, for this type of coordinated solution a control device is needed which would be located at the MV/LV-substation (or HV/MV-substation). It would give the active- and reactive power set-points to the inverters (DG-units) by utilizing possibly both state estimation and load flow calculation (Laaksonen 2017.)

6 SIMULATIONS

A formerly made precise PSCAD simulation model of SSG will be utilized to create different scenarios for reactive power control in a smart grid. The basic idea of the simulations is to add possible future enhancements (for example DG-units) to the model and test their utilization for ancillary services and examine the consequent effects on the grid.

These simulations contain nine different PSCAD-workspaces i.e. simulation sets and each set contains eight scenarios, four scenarios with both Fingrid's and ENTSO-E's reactive power window. The workspaces and scenarios are presented in Chapters 6.2 – 6.10. The idea is to start from basic scenarios and gradually increase the level of complexity. Also, basic settings are kept constant throughout the simulation scenarios.

The simulation results are presented in Appendix 1 and in Chapter 7. For each workspace there are usually two result tables (Tables 14-30 in Appendix 1) in which the precursory simulation results are presented. Due to large number of simulations the most notable cases are presented graphically and commented more carefully.

6.1 PSCAD simulation model structure

The simulation model's basic frame is presented in Figure 9. The model adapts the actual SSG's features. The basic model consists of an AC voltage source which enacts as the main HV grid, HV/MV transformer and three MV feeders (J06, J07 and J09) with adjustable loads. There are two wind turbines, one on feeder J06 and the other on feeder J08. The earthing transformer is located on feeder J04.

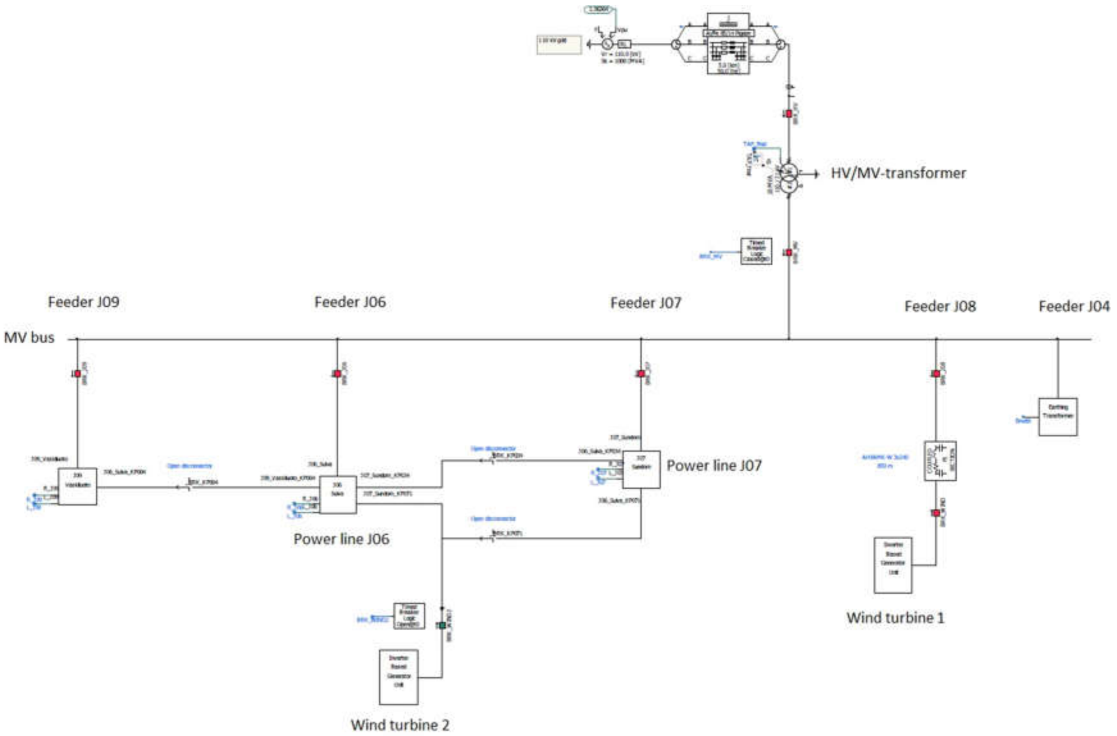


Figure 9. Simplified illustration of the PSCAD-simulation model.

6.1.1 Feeder load configuration

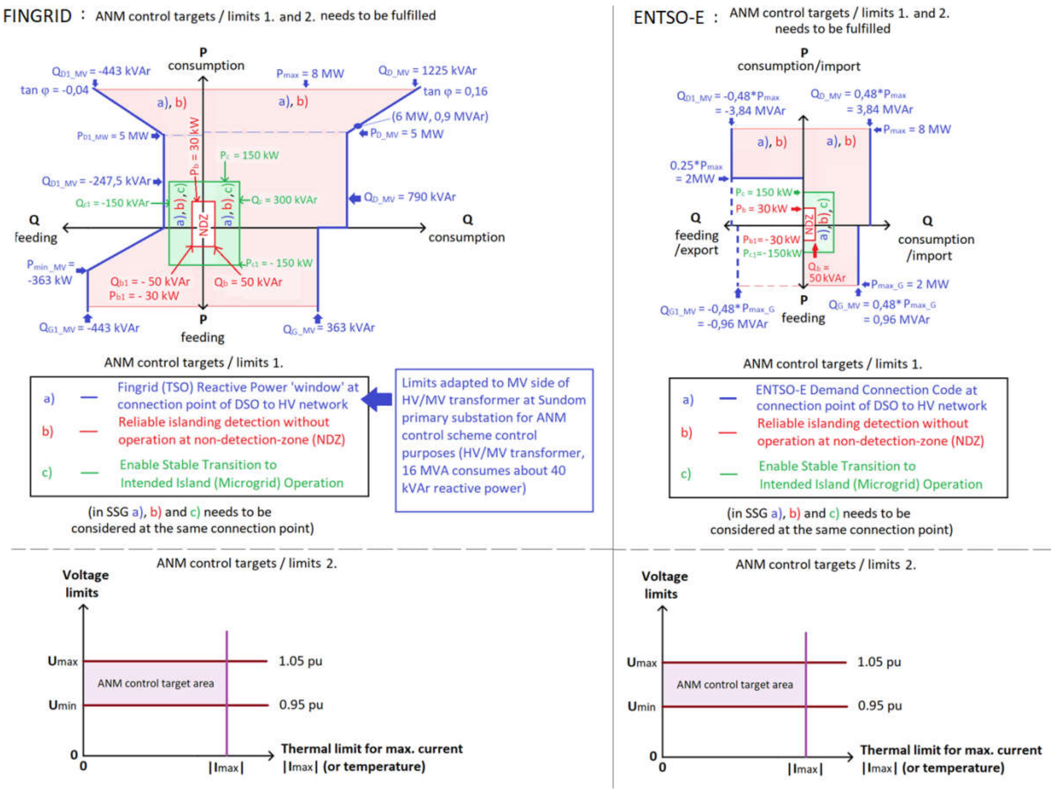
In these simulations the loads used for feeders J06, J07 and J08 are described as 'Very low load' or 'Very high load'. The settings used for feeders J06, J07 and J09 are presented in Table 3. The loads' resistive parts are calculated from the megawatt values. The values 'L_J06', 'L_J07' and 'L_J09' present the inductive parts of the loads.

Table 3. Feeder load settings

SETTINGS	J06 Load (MW)		J07 Load (MW)		J09 Load (MW)		L_J06 (Ω) L_J07 (Ω) L_J09 (Ω)	
Load description	Very Low Load	Very High Load	Very Low Load	Very High Load	Very Low Load	Very High Load	Very Low Load	Very High Load
Cases cos(φ) < 1	0,4	0,93	0,375	0,87	0,085	0,21	0,0042	0,0023
Cases cos(φ) = 1	0,4	0,93	0,375	0,87	0,085	0,21	0	

6.1.2 Controls

The controls for the studied ANM scheme are explained in this chapter. The ANM methods used are Q_{flow}- & U–management and P_{flow}-management that are reviewed thoroughly in Chapter 5.3. The calculated values for the control limits of reactive and active power and also thermal limits are presented in figure 10.



a) — Fingrid (TSO) Reactive Power 'window' at connection point of DSO to HV network

b) — Reliable islanding detection without operation at non-detection-zone (NDZ)

c) — Enable Stable Transition to Intended Island (Microgrid) Operation

Limits adapted to MV side of HV/MV transformer at Sundom primary substation for ANM control scheme control purposes (HV/MV transformer, 16 MVA consumes about 40 kVAr reactive power)

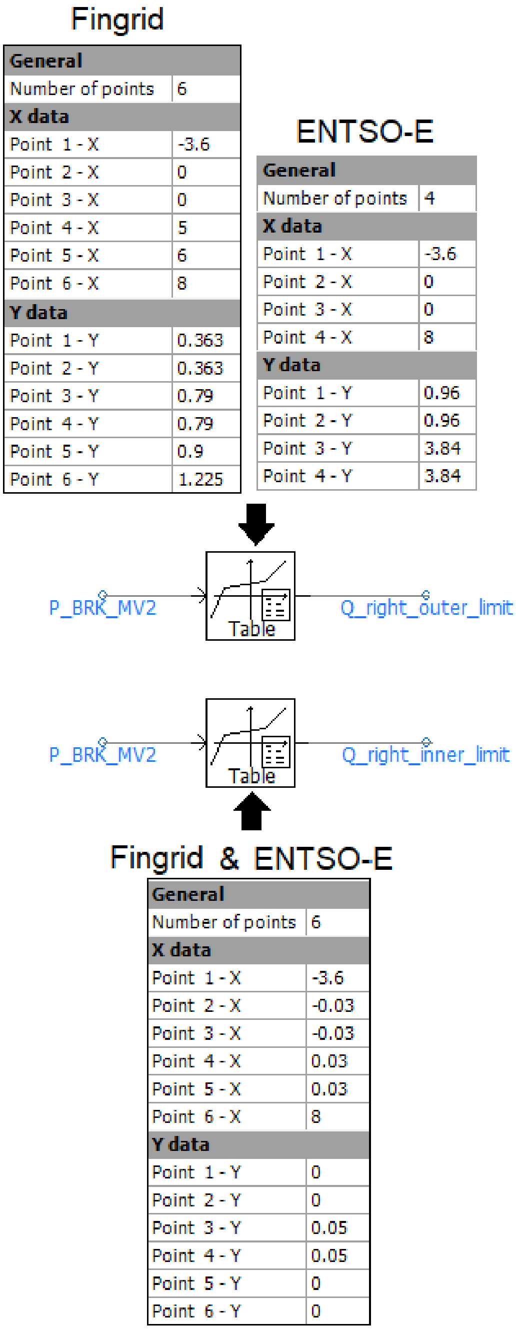
a) — ENTSO-E Demand Connection Code at connection point of DSO to HV network

b) — Reliable islanding detection without operation at non-detection-zone (NDZ)

c) — Enable Stable Transition to Intended Island (Microgrid) Operation

Figure 10. Control targets for primary and secondary ANM methods (Laaksonen 2018b).

The values presented in above figure are introduced to the simulations via table-functions. Figures 11 and 12 present the formation of reactive power limits depending on the active power flow between HV and MV network. The limits are labeled as ‘right’ and ‘left’ depending on the direction of the reactive power flow.



Fingrid

General	
Number of points	6
X data	
Point 1 - X	-3.6
Point 2 - X	0
Point 3 - X	0
Point 4 - X	5
Point 5 - X	6
Point 6 - X	8
Y data	
Point 1 - Y	0.363
Point 2 - Y	0.363
Point 3 - Y	0.79
Point 4 - Y	0.79
Point 5 - Y	0.9
Point 6 - Y	1.225

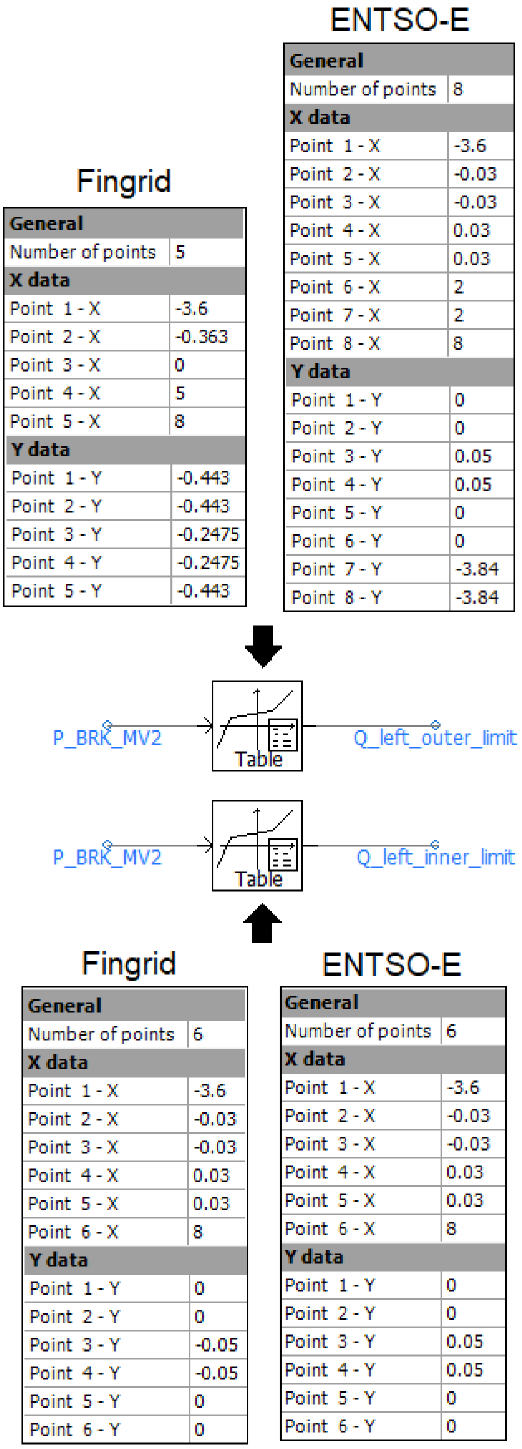
ENTSO-E

General	
Number of points	4
X data	
Point 1 - X	-3.6
Point 2 - X	0
Point 3 - X	0
Point 4 - X	8
Y data	
Point 1 - Y	0.96
Point 2 - Y	0.96
Point 3 - Y	3.84
Point 4 - Y	3.84

Fingrid & ENTSO-E

General	
Number of points	6
X data	
Point 1 - X	-3.6
Point 2 - X	-0.03
Point 3 - X	-0.03
Point 4 - X	0.03
Point 5 - X	0.03
Point 6 - X	8
Y data	
Point 1 - Y	0
Point 2 - Y	0
Point 3 - Y	0.05
Point 4 - Y	0.05
Point 5 - Y	0
Point 6 - Y	0

Figure 11. Reactive power limits (right) depending on the active power flow (Laaksonen 2018b).



Fingrid

General	
Number of points	5
X data	
Point 1 - X	-3.6
Point 2 - X	-0.363
Point 3 - X	0
Point 4 - X	5
Point 5 - X	8
Y data	
Point 1 - Y	-0.443
Point 2 - Y	-0.443
Point 3 - Y	-0.2475
Point 4 - Y	-0.2475
Point 5 - Y	-0.443

ENTSO-E

General	
Number of points	8
X data	
Point 1 - X	-3.6
Point 2 - X	-0.03
Point 3 - X	-0.03
Point 4 - X	0.03
Point 5 - X	0.03
Point 6 - X	2
Point 7 - X	2
Point 8 - X	8
Y data	
Point 1 - Y	0
Point 2 - Y	0
Point 3 - Y	0.05
Point 4 - Y	0.05
Point 5 - Y	0
Point 6 - Y	0
Point 7 - Y	-3.84
Point 8 - Y	-3.84

Fingrid

General	
Number of points	6
X data	
Point 1 - X	-3.6
Point 2 - X	-0.03
Point 3 - X	-0.03
Point 4 - X	0.03
Point 5 - X	0.03
Point 6 - X	8
Y data	
Point 1 - Y	0
Point 2 - Y	0
Point 3 - Y	-0.05
Point 4 - Y	-0.05
Point 5 - Y	0
Point 6 - Y	0

ENTSO-E

General	
Number of points	6
X data	
Point 1 - X	-3.6
Point 2 - X	-0.03
Point 3 - X	-0.03
Point 4 - X	0.03
Point 5 - X	0.03
Point 6 - X	8
Y data	
Point 1 - Y	0
Point 2 - Y	0
Point 3 - Y	0.05
Point 4 - Y	0.05
Point 5 - Y	0
Point 6 - Y	0

Figure 12. Reactive power limits (left) depending on the active power flow (Laaksonen 2018b).

The calculation of difference values of reactive power is executed below. Figure 13 presents the formulation of four differential values of reactive power (Q_diff_1…Q_diff_4).

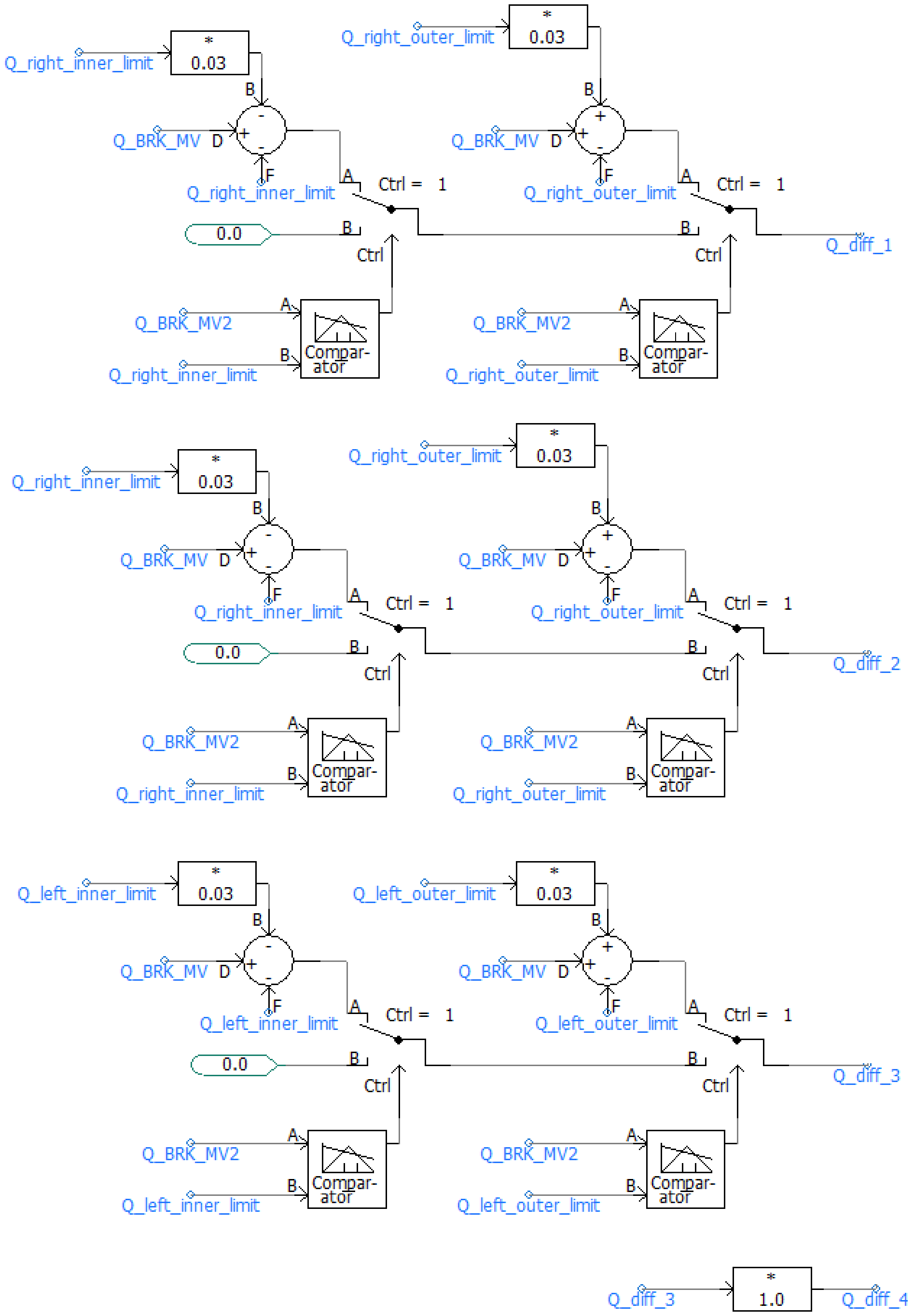
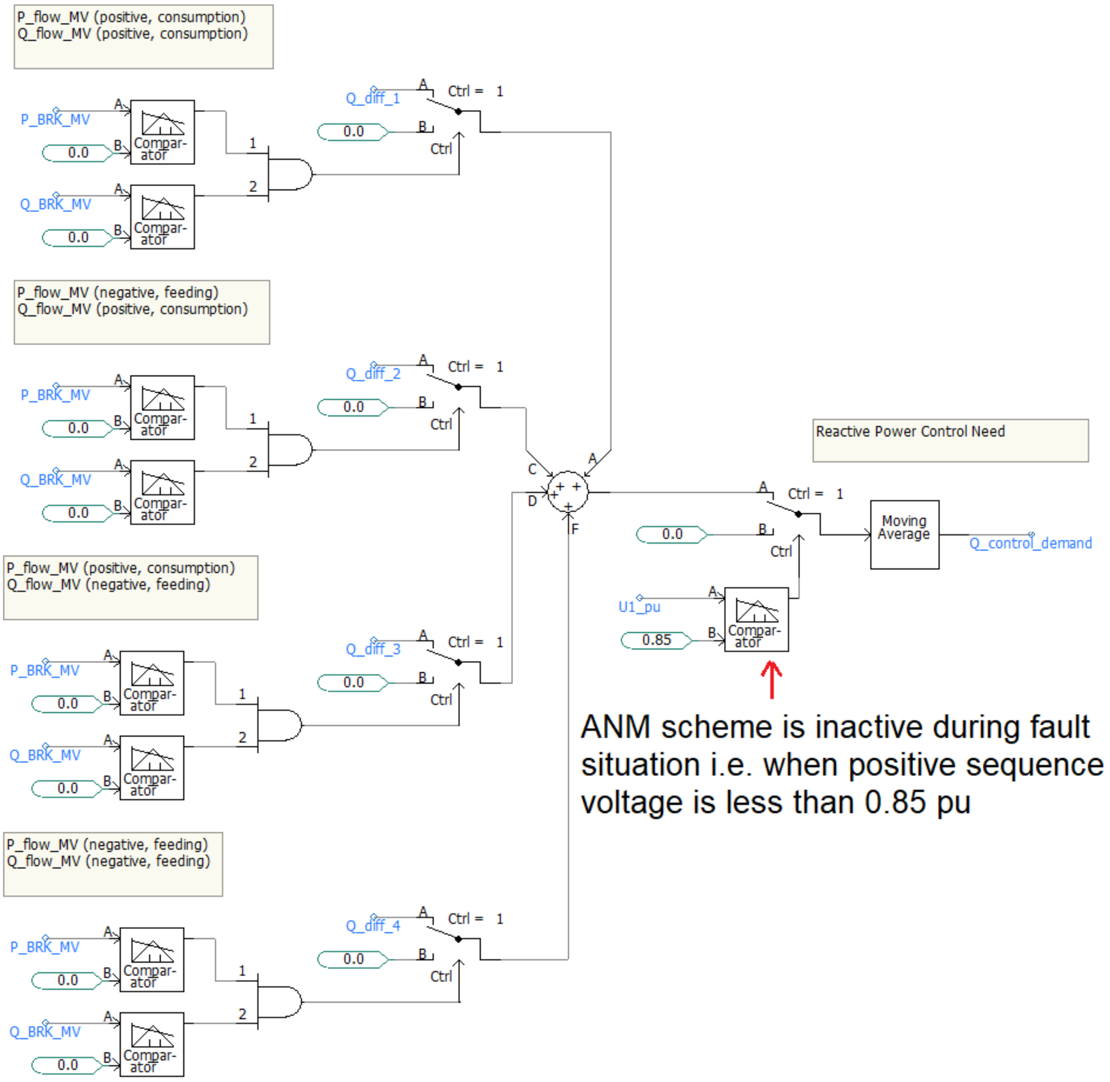


Figure 13. Comparators are used for the calculation of difference values of reactive power (Laaksonen 2018b).

Figure 14 presents the calculation of reactive power control need for DER units. There are four blocks that describe the relation between reactive power and active power flow. There are four possible combinations: 1) Both active power and reactive power are consumed, 2) active power is produced and reactive power is consumed 3) active power is consumed and reactive power is produced, 4) both active power and reactive power are consumed.

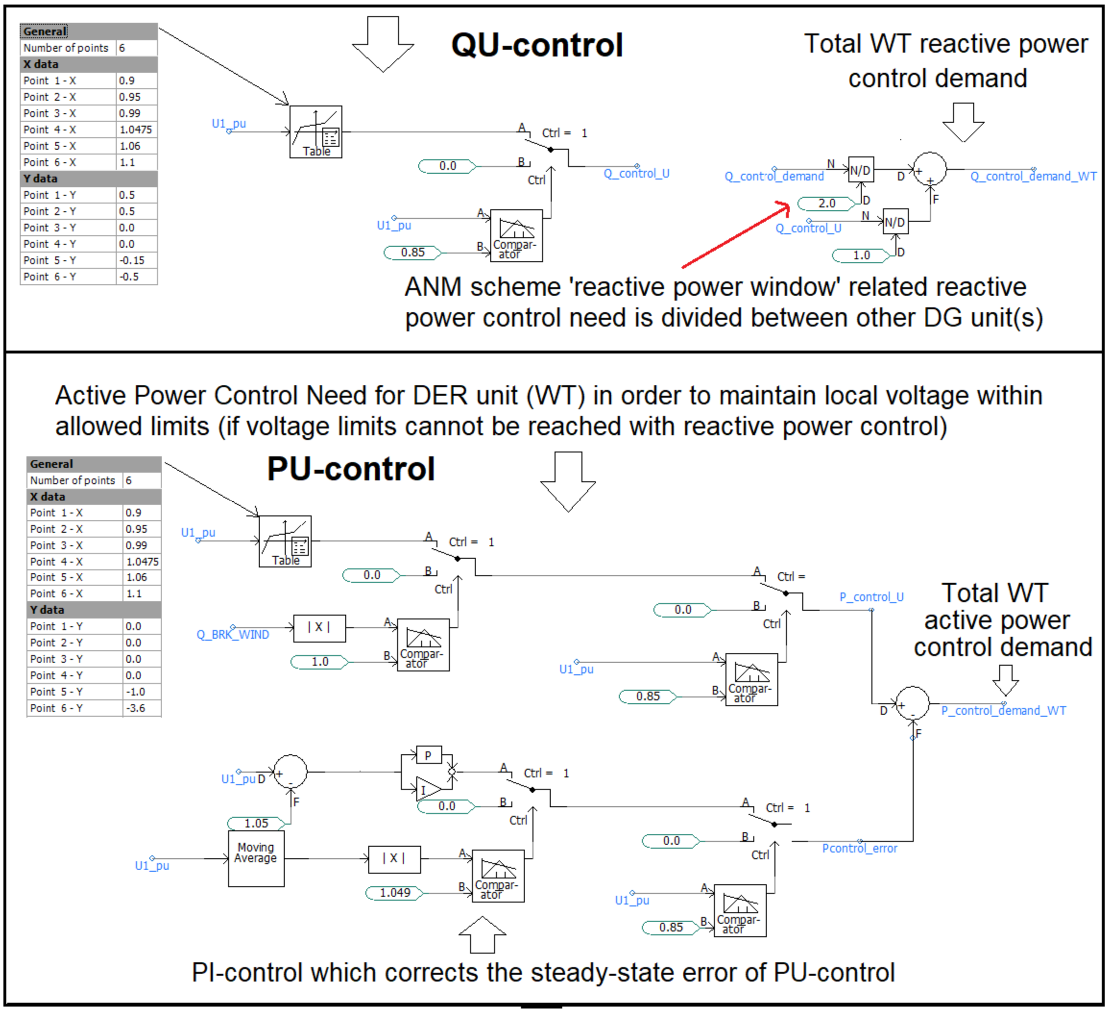


ANM scheme is inactive during fault situation i.e. when positive sequence voltage is less than 0.85 pu

Figure 14. The calculation of reactive power control need for DER units (Laaksonen 2018b).

To prevent undesirable operation the ANM scheme is inactive during fault situations. If the positive sequence voltage declines below 0,85 p.u. the ANM scheme is switched off.

Local voltage controls are presented in Figure 15. Table function is used to input the operating boundaries to both Q_U*-control* and P_U*-control*. Reactive power is adjusted by the function of voltage. If the voltage is less than 0,99 p.u. reactive power is fed to the network and if the voltage gets over 1,0475 p.u. reactive power is taken from the network. P_U*-control* is activated only if the desired voltage control cannot be obtained by Q_U*-control.* The voltage limit for the activation of P_U*-control* is 1,0475 p.u.



QU-control

Total WT reactive power control demand

ANM scheme 'reactive power window' related reactive power control need is divided between other DG unit(s)

General	
Number of points	6
X data	
Point 1 - X	0.9
Point 2 - X	0.95
Point 3 - X	0.99
Point 4 - X	1.0475
Point 5 - X	1.06
Point 6 - X	1.1
Y data	
Point 1 - Y	0.5
Point 2 - Y	0.5
Point 3 - Y	0.0
Point 4 - Y	0.0
Point 5 - Y	-0.15
Point 6 - Y	-0.5

Active Power Control Need for DER unit (WT) in order to maintain local voltage within allowed limits (if voltage limits cannot be reached with reactive power control)

PU-control

Total WT active power control demand

PI-control which corrects the steady-state error of PU-control

General	
Number of points	6
X data	
Point 1 - X	0.9
Point 2 - X	0.95
Point 3 - X	0.99
Point 4 - X	1.0475
Point 5 - X	1.06
Point 6 - X	1.1
Y data	
Point 1 - Y	0.0
Point 2 - Y	0.0
Point 3 - Y	0.0
Point 4 - Y	0.0
Point 5 - Y	-1.0
Point 6 - Y	-3.6

Figure 15. Reactive power control need for DER unit in order to maintain the local voltage within allowed limits (Laaksonen 2018b).

Wind turbine's active and reactive power control loops are presented in figure 16. Reactive and active power control needs of the ANM scheme (Q_control_demand_WT, P_control_demand_WT) are taken into account within the control loops. At this stage the increments to wind turbine's active power output are also introduced.

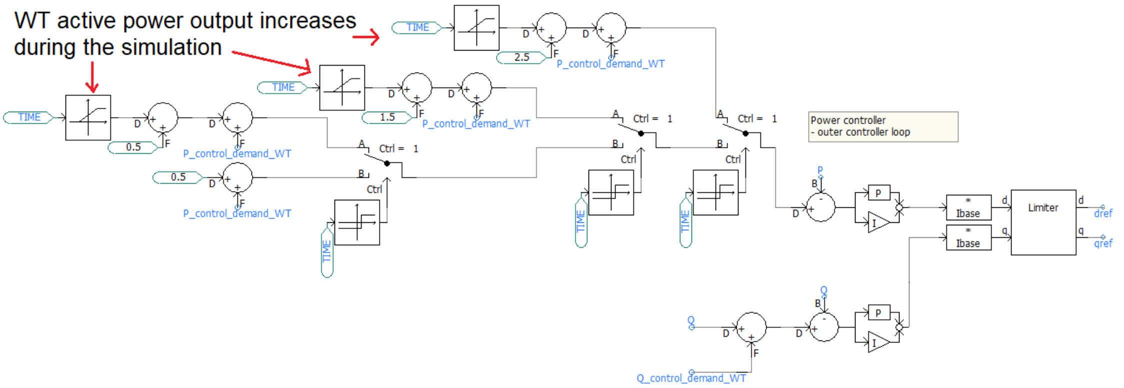


Figure 16. Wind turbine active and reactive power control loops which take into account ANM scheme's reactive and active power control needs (Laaksonen 2018b).

A simplified flow-chart of wind turbine's power control which takes actively part in the studied ANM scheme is presented in Figure 17.

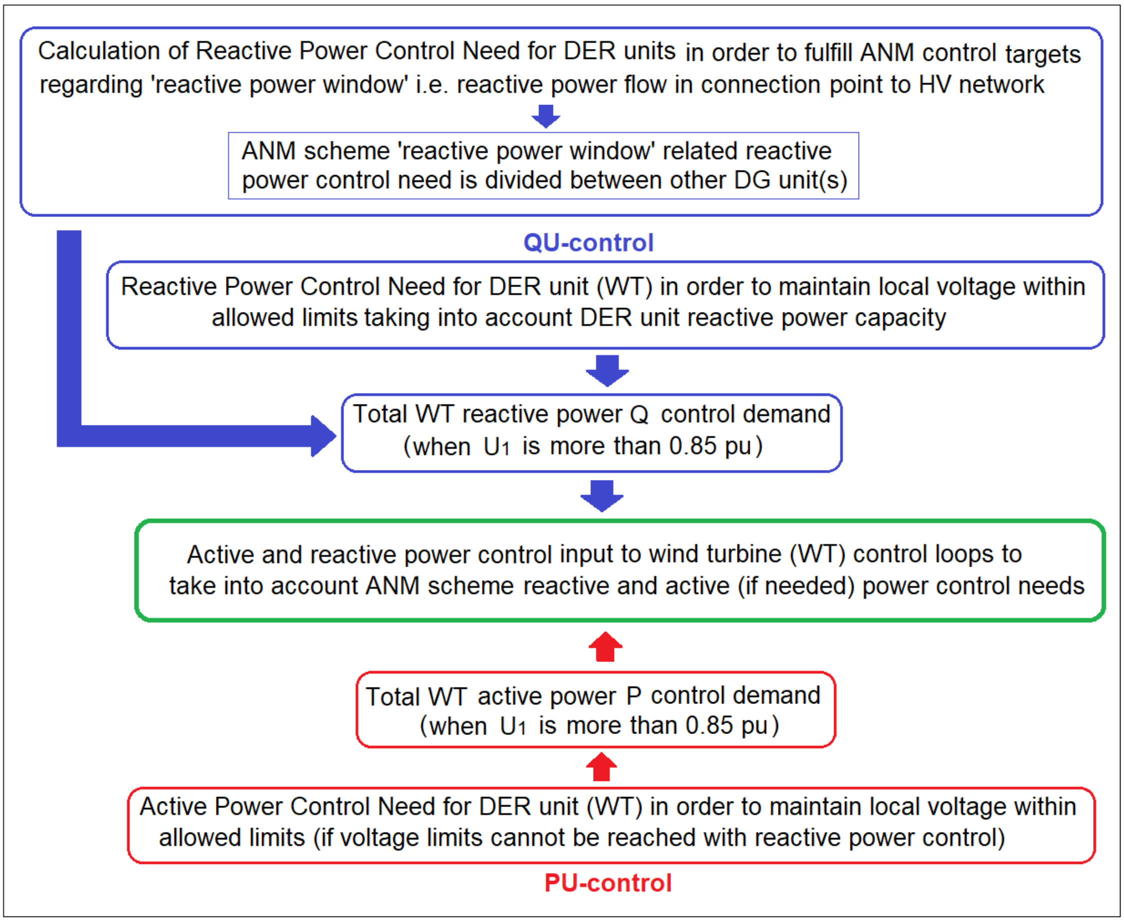


Figure 17. Simplified flow-chart from wind turbine power control which takes actively part in the studied ANM scheme (Laaksonen 2018b).

6.1.3 Simplifications

Because of time limitations three precise inverter models (2 wind turbines and a photovoltaic) were removed from the original simulation model. The two wind turbine models were replaced by voltage source-based inverter models. The principal difference between these models is that the precise model uses solid state components i.e. IGBTs as switches to create the desired voltage level. These switching operations strain the calculating power used by the computer and simulating program. With the use of voltage source-based inverter models the simulation time was reduced significantly.

This simulation model is accurate enough for this type of reactive power and voltage control related studies. Of course, the wind conditions are not considered and the changes in wind turbines' active power output are made by simple and noticeable steps to get an idea of system's response more clearly. The precise wind model would fit better to longer simulations with a different scope. From the ancillary services' point of view this type of simulation setup is more appropriate.

6.2 Base Cases

In these simulation scenarios all DG-units have been disconnected. This is done in order to gain a clear reference point for the comparison of forthcoming simulation cases. This set of simulations contains eight simulations total, same four cases with both Fingrid and ENTSO-E reactive power windows. The loads are kept constant and the operation delay for the OLTC is 60 seconds. Table 4 presents information about the loads, the target voltage at HV/MV substation (OLTC setting) and the number of DG-units.

Table 4. Initial settings for Base Cases.

CASE	**Load**	**Voltage**	**DG-units**
Case 1	Very low	20,7 kV	0
Case 2	Very low	20,0 kV	0
Case 3	Very high	20,7 kV	0
Case 4	Very high	20,0 kV	0

6.3 Cases Wind-A

In this simulation set the same model is used as in previous set but now one 3,6 MW wind turbine (WIND) is added to the feeder J08. The control for reactive power window requirements is also done by the same wind turbine. In these cases active power varies (increases in steps) during the simulation, the loads are kept constant and the operation delay for the OLTC is 60 seconds. Table 5 presents information about the loads, the target voltage at HV/MV substation (OLTC setting) and the number of DG-units.

Table 5. Initial settings for Cases Wind-A.

CASE	Load	Voltage	DG-units
Case 1	Very low	20,7 kV	WT
Case 2	Very low	20,0 kV	WT
Case 3	Very high	20,7 kV	WT
Case 4	Very high	20,0 kV	WT

6.4 Cases Wind-B

The same model is used as previously but now another 3,6 MW wind turbine (WIND2) is added to the end of the feeder J06. The control for reactive power window requirements is done by the wind turbine on feeder J08 alone. In addition, both wind turbines are controlled by *Q(U)*-control. If *Q(U)*-control range is exceeded during the simulations then the wind turbines' active power will be limited by *P(U)*-control. In these cases active power varies during the simulation, the loads are kept constant and the operation delay for the OLTC is 60 seconds. Table 6 presents information about the loads, the target voltage at HV/MV substation (OLTC setting), number of DG-units and the control method of the DG-units.

Table 6. Initial settings for Cases Wind-B.

CASE	Load	Voltage	DG-units	WT Control
Case 1	Very low	20,7 kV	2 WTs	Q(U) ->P(U)
Case 2	Very low	20,0 kV	2 WTs	Q(U) ->P(U)
Case 3	Very high	20,7 kV	2 WTs	Q(U) ->P(U)
Case 4	Very high	20,0 kV	2 WTs	Q(U) ->P(U)

6.5 Cases Wind-C

The same model is used with this set as in the previous set but now the control for reactive power window requirements is done by the wind turbine on feeder J06 alone. In addition, both wind turbines are controlled by *Q(U)*-control. If *Q(U)*-control range is exceeded then the wind turbines' active power will be limited by *P(U)*-control. In these cases active power varies during the simulation, the loads are kept constant and the operation delay for the OLTC is 60 seconds. Table 7 presents information about the loads, the target voltage at HV/MV substation (OLTC setting), number of DG-units and the control method of the DG-units.

Table 7. Initial settings for Cases Wind-C

CASE	Load	Voltage	DG-units	WT Control
Case 1	Very low	20,7 kV	2 WTs	Q(U) ->P(U)
Case 2	Very low	20,0 kV	2 WTs	Q(U) ->P(U)
Case 3	Very high	20,7 kV	2 WTs	Q(U) ->P(U)
Case 4	Very high	20,0 kV	2 WTs	Q(U) ->P(U)

6.6 Cases Wind-D

The same model is used as in the previous set but now the control for reactive power window requirements is divided in half by the wind turbines on feeders J06 and J08. In addition, both wind turbines are controlled by *Q(U)*-control. If *Q(U)*-control range is exceeded then the wind turbines' active power will be limited by *P(U)*-control. In these cases active power varies during the simulation, the loads are kept constant and the operation delay for the OLTC is 60 seconds. Table 8 presents information about the loads, the target voltage at HV/MV substation (OLTC setting), number of DG-units and the control method of the DG-units.

Table 8. Initial settings for Cases Wind-D

CASE	Load	Voltage	DG-units	WT Control
Case 1	Very low	20,7 kV	2 WTs	Q(U) ->P(U)
Case 2	Very low	20,0 kV	2 WTs	Q(U) ->P(U)
Case 3	Very high	20,7 kV	2 WTs	Q(U) ->P(U)
Case 4	Very high	20,0 kV	2 WTs	Q(U) ->P(U)

6.7 Cases PV-A

The same model will be utilized with this set as previously but now again with only one 3,6 MW wind turbine (WIND) on feeder J08. The control for reactive power window requirements is also done by the same wind turbine. The active power of the wind turbine varies (increases in steps) during the simulation. The loads are kept constant excluding the 49,8 Hz under frequency period in Cases 1 and 2 at the time 70-80 s. At that time in light load cases parts of the loads are disconnected due to under frequency.

In addition, there are three 300 kW centralized PV-inverters in the LV-side of both feeders J06 (PVs 6, 7 and 8) and J07 (PVs 2, 3 and 4) that equals 0,9 MW per feeder. These PV-inverters are constantly driven with the nominal power and *cos(φ)*=1. There is also one 250 kW PV-unit on feeder J07 (PV 5) which will not participate in any controls and it is driven with the nominal power of 250 kW. The operation delay for the OLTC is 60 s. Table 9 presents information about the loads, the target voltage at HV/MV substation (OLTC setting), number of DG-units, control methods of the DG-units and the under frequency period.

Table 9. Initial settings for Cases PV-A

CASE	Load	Voltage	DG-units	WT control	PV control	Event
Case 1	Very low	20,7 kV	WT + 6 PVs	Q(U) ->P(U)	cos(φ)=1	49,8 Hz
Case 2	Very low	20,0 kV	WT + 6 PVs	Q(U) ->P(U)	cos(φ)=1	49,8 Hz
Case 3	Very high	20,7 kV	WT + 6 PVs	Q(U) ->P(U)	cos(φ)=1	-
Case 4	Very high	20,0 kV	WT + 6 PVs	Q(U) ->P(U)	cos(φ)=1	-

6.8 Cases PV-B

The same model is used as in the previous simulation set but now the PV-inverters are controlled by *Q(U)*-control. If the *Q(U)*-control range is exceeded then PV-inverters' active power will be limited by *P(U)*-control. At the same time two designated PV-inverters (PV2 and PV4) maintain the reactive power unbalance between LV-microgrid breaker and main grid breaker. The unbalance is needed for the islanding detection functionality to work properly. The operation delay for the OLTC is 60 s. Table 10 presents information about the loads, the target voltage at HV/MV substation (OLTC setting), number of DG-units, control methods of the DG-units and the under frequency period.

Table 10. Initial settings for Cases PV-B

CASE	Load	Voltage	DG-units	WT control	PV control	Event
Case 1	Very low	20,7 kV	WT + 6 PVs	Q(U) ->P(U)	Q(U) ->P(U)	49,8 Hz
Case 2	Very low	20,0 kV	WT + 6 PVs	Q(U) ->P(U)	Q(U) ->P(U)	49,8 Hz
Case 3	Very high	20,7 kV	WT + 6 PVs	Q(U) ->P(U)	Q(U) ->P(U)	-
Case 4	Very high	20,0 kV	WT + 6 PVs	Q(U) ->P(U)	Q(U) ->P(U)	-

6.9 Cases PV-C

The same model is utilized as in the previous set but now in case of over frequency (50,2 Hz for the time period 70-80 s) the PV-inverters are controlled by *P(f)*-control. The operation delay for the OLTC is 60 s. Table 11 presents information about the loads, the target voltage at HV/MV substation (OLTC setting), number of DG-units, control methods of the DG-units and the over frequency period.

Table 11. Initial settings for Cases PV-C

CASE	Load	Voltage	DG-units	WT control	PV control	Event
Case 1	Very low	20,7 kV	WT + 6 PVs	Q(U) ->P(U)	Q(U) ->P(U)	50,2 Hz / P(f)
Case 2	Very low	20,0 kV	WT + 6 PVs	Q(U) ->P(U)	Q(U) ->P(U)	50,2 Hz / P(f)
Case 3	Very high	20,7 kV	WT + 6 PVs	Q(U) ->P(U)	Q(U) ->P(U)	50,2 Hz / P(f)
Case 4	Very high	20,0 kV	WT + 6 PVs	Q(U) ->P(U)	Q(U) ->P(U)	50,2 Hz / P(f)

6.10 Cases PV-D

The same model is used as in the previous set but now the loads are kept constant and their *cos(φ)*=1. Table 12 presents information about the loads, the target voltage at HV/MV substation (OLTC setting), number of DG-units, control methods of the DG-units and the over frequency period.

Table 12. Initial settings for Cases PV-D

CASE	**Load**	**Voltage**	**DG-units**	**WT control**	**PV control**	**Event**
Case 1	Very low	20,7 kV	WT + 6 PVs	Q(U) ->P(U)	Q(U) ->P(U)	50,2 Hz / P(f)
Case 2	Very low	20,0 kV	WT + 6 PVs	Q(U) ->P(U)	Q(U) ->P(U)	50,2 Hz / P(f)
Case 3	Very high	20,7 kV	WT + 6 PVs	Q(U) ->P(U)	Q(U) ->P(U)	50,2 Hz / P(f)
Case 4	Very high	20,0 kV	WT + 6 PVs	Q(U) ->P(U)	Q(U) ->P(U)	50,2 Hz / P(f)

7 RESULTS

In this chapter the most interesting simulation cases are presented. The result tables (Tables 14-30) and also the wind turbines' active power input sequences are presented in Appendix 1.

7.1 Base Cases

The results for Base Cases are presented in Appendix 1, Table 14. In these simulation cases there were no highly deviant events. These cases were simulated to get a baseline for later more advanced cases. In these cases it was notable that with a very low load the reactive power flow was from SSG to main grid and active power flow was the opposite from main grid to SSG. In case of a light load the underground cables are a source of reactive power. In cases with a high load both reactive and active power were taken from the main grid to SSG. The reactive power limits were exceeded in six of total eight cases. This was because there were no actual production units on SSG's side on this simulation model and therefore there was no control for reactive power window requirements either.

In ENTSO-E Cases 3 and 4 the reactive power window limits were not exceeded. The same cases with Fingrid's limits exceeded the reactive power limits because Fingrid has more strict limitations.

Fingrid Case 2 is presented in Figure 18. Reactive power window limits are marked as red (Q_right_outer_limit) and magenta (Q_left_outer_limit) and the reactive power at MV breaker (Q_BRK_MV) does not lie between the aforementioned limits.

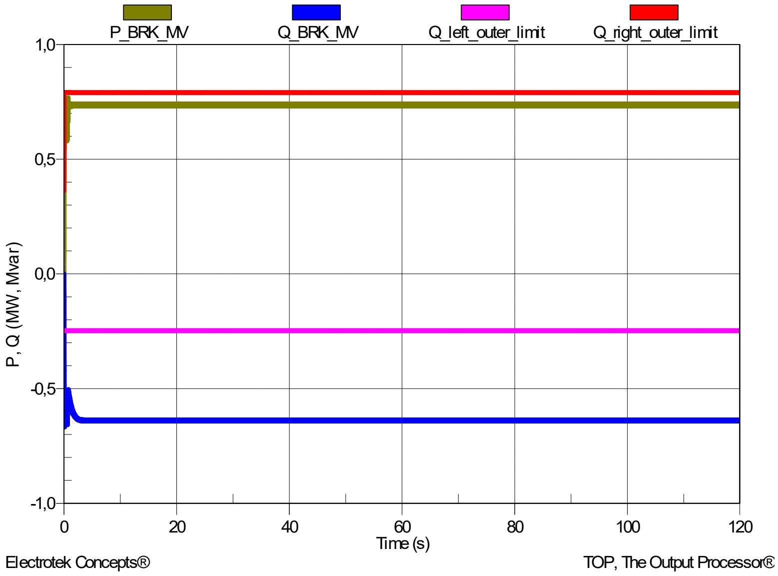


Figure 18. Fingrid Case 2 reactive power limits exceeded.

ENTSO-E Case 2 is presented in Figure 19. Reactive power window limits are marked as in the previous case. Reactive power window was exceeded also in this case.

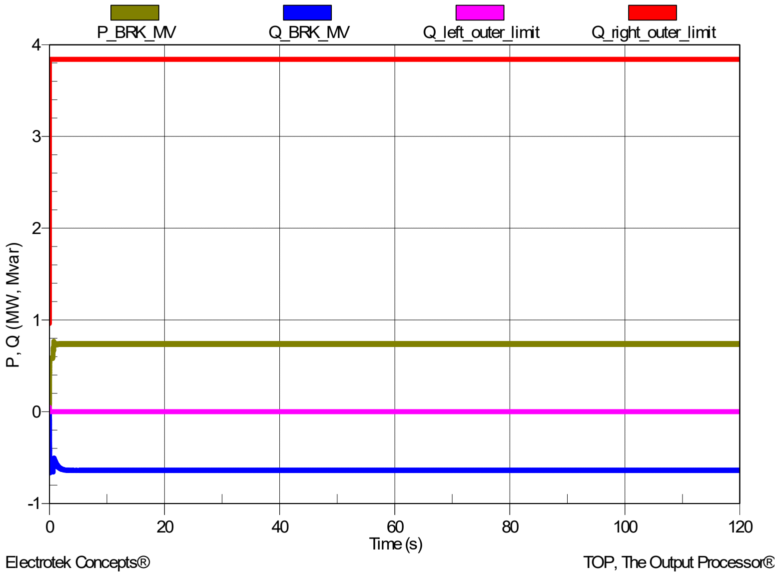


Figure 19. ENTSO-E Case 2 reactive power limits exceeded.

In ENTSO-E Case 2 it was notable that the reactive power limit (Q_left_outer_limit) was at zero i.e. no reactive power was allowed to be exchanged.

7.2 Cases Wind-A

The same model was used as in the first set but a 3,6 MW wind turbine (WT) was added to the model on feeder J08. It was also designated to fulfil the reactive power window requirements. The results for this set are presented in Appendix 1, Tables 15-16.

The reactive power window limits were exceeded in two Fingrid's cases, Case 3 and Case 4. In case 3 MV-network voltage limits were exceeded also. The difference between the cases 3 and 4 is the target value for the OLTC: Case 3's 20,7 kV and Case 4's 20,0 kV. Figure 20 below presents Fingrid's Case 3 and Figure 22 Case 4.

The reactive power window limits are shown as red (Q_right_outer_limit) and magenta (Q_left_outer_limit) curves. The blue curve is the reactive power at MV-breaker (Q_BRK_MV) and it does not lie between the aforementioned limits. 20,7 kV voltage is harder to reach than 20,0 kV and this is the reason for this behavior. The higher the HV/MV target voltage is the more active power is needed to reach it and this also affects to the excess of local voltage limits.

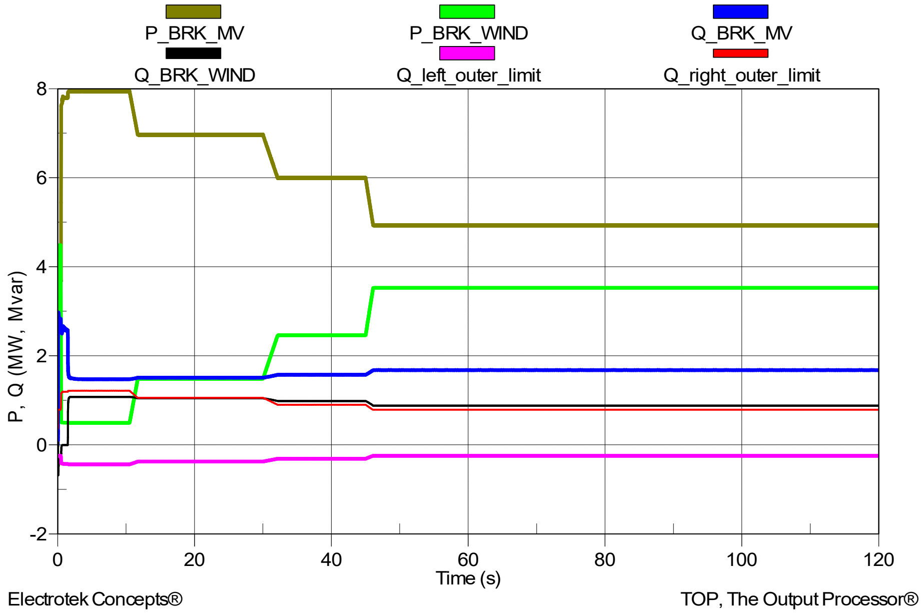


Figure 20. Fingrid Case 3

In both figures 20 and 22 it can be seen that the more the wind turbine's active power output is increased the less active power needs to be taken from the main grid.

Figure 21 presents voltages from Fingrid Case 3. Both LV voltages (U1_pu_end_J06) and (U1_pu_end_J07) are under the maximum allowed limit of 1,0475 p.u. but at 10 s MV voltage (U1_pu) makes the excess due to increased active power output of the wind turbine on feeder J08 (P_BRK_WIND).

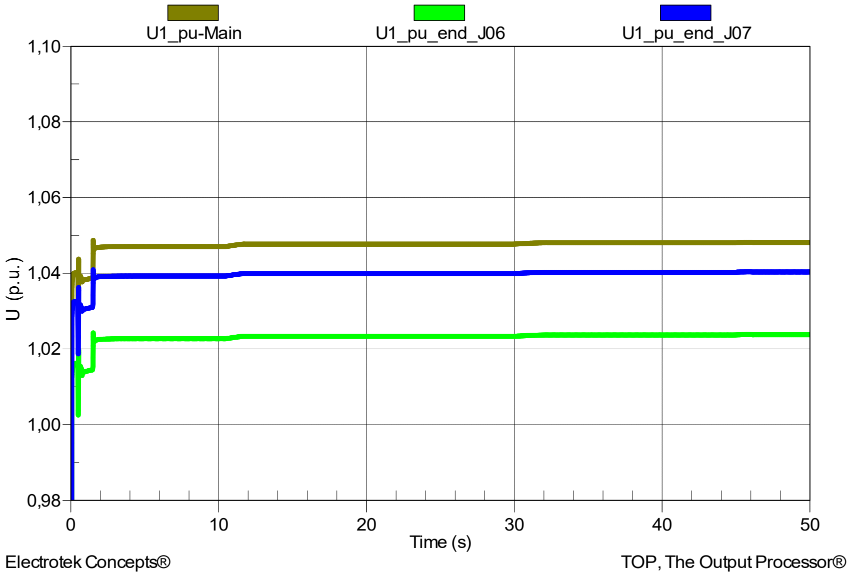


Figure 21. Fingrid Case 3 voltages.

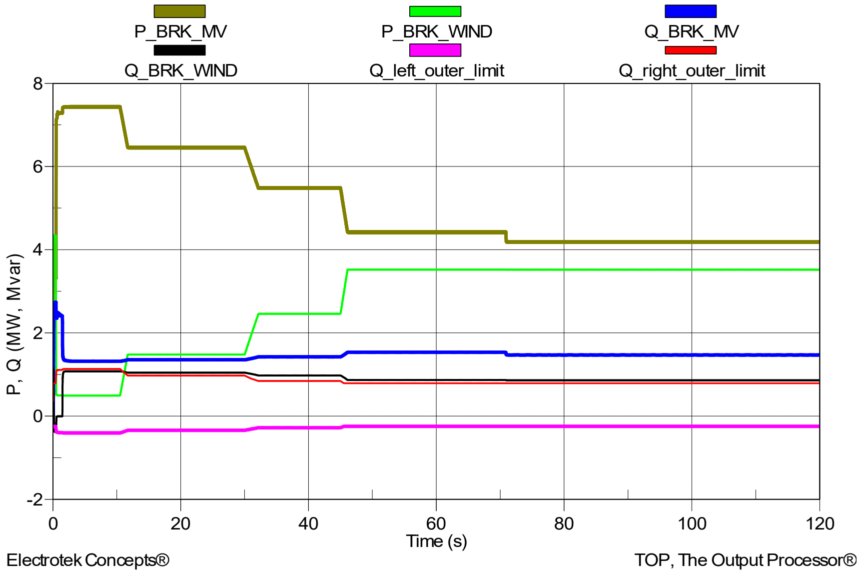


Figure 22. Fingrid Case 4

The J08 wind turbine was able to handle the reactive power limit control in six out of eight cases. In Fingrid Cases 3 and 4 the amount of reactive power taken from main grid was too high in relation to active power. The same cases with ENTSO-E limits seemed to lie inside the allowed limits. ENTSO-E's reactive power limits are more solute than Fingrid's.

7.3 Cases Wind-B

The results for this set are presented in Appendix 1, Tables 17-18. In this set of simulations there were four cases with some deviation. The J06 wind turbine had to restrict its active power output in Fingrid's case 1 and ENTSO-E's case 1. Reactive power window limits were exceeded (again) in Fingrid‘s cases 3 and 4. In Fingrid case 3 the local MV-voltage limits were exceeded also at the times t_1 and t_2. Cases with active power restriction are presented in Figures 23-26 below.

Fingrid Case 1's various power quantities are presented in Figure 23. The active power (P_BRK_MV) flows to the main grid which is common in light load cases. At first reactive power (Q_BRK_MV) flows to same direction but at 25 s the direction changes. After 25 s reactive power is taken from main grid.

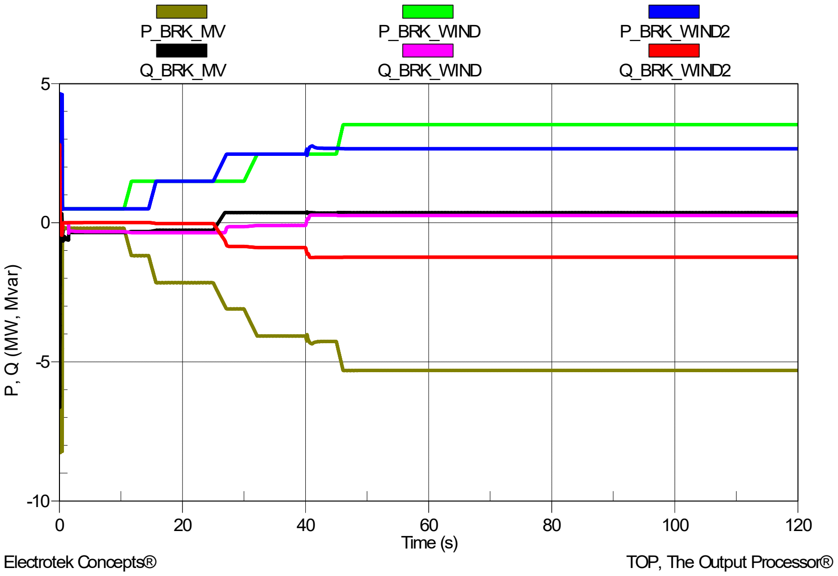


Figure 23. Fingrid Case 1

In figures 24 and 25 active power restriction of J06 wind turbine can be seen in the blue curve (P_BRK_WIND2) just after 40 s. In Fingrid Case 1 the limitation is ca. 900 kW and it effects to active power (P_BRK_MV) which is measured at MV breaker.

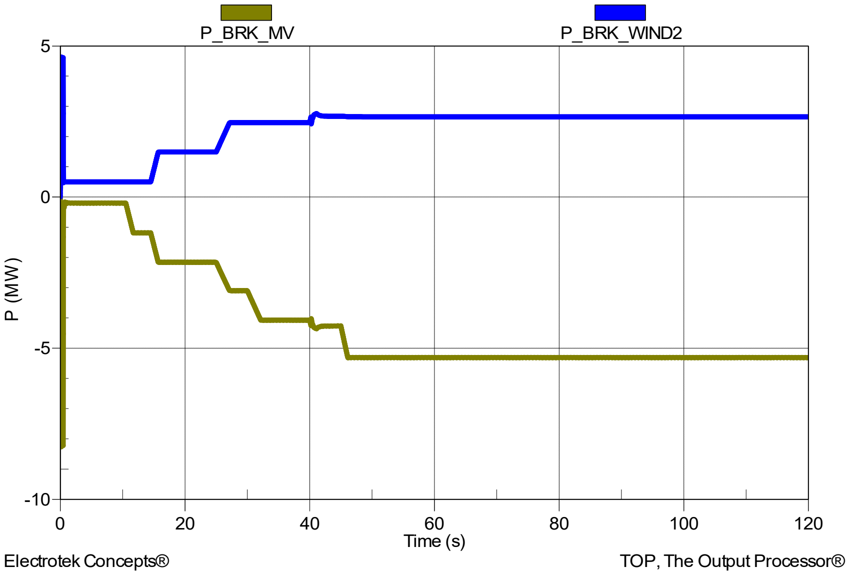


Figure 24. Fingrid Case 1

In ENTSO-E Case 1 which is presented in Figures 25 and 26 the amount of active power restriction is ca. 400 kW. The actual limitation can be seen in the blue curve just after 40 s.

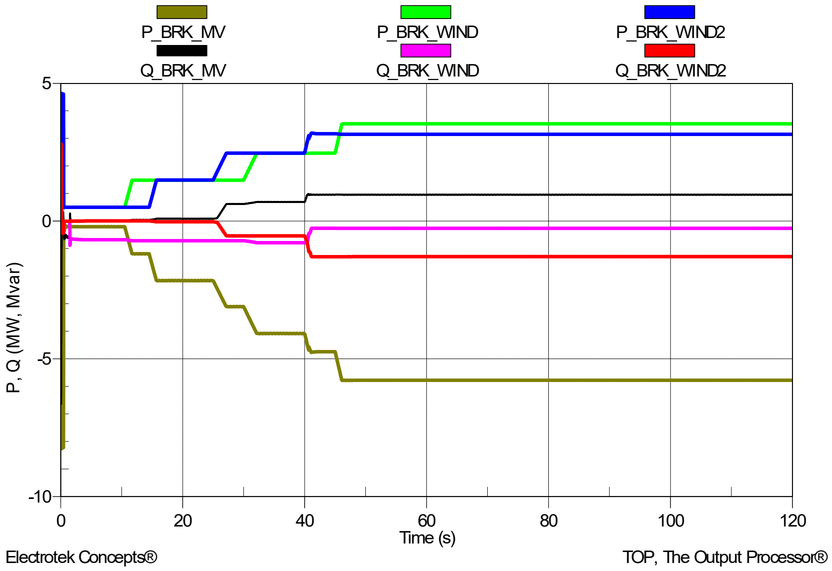


Figure 25. ENTSO-E Case 1

Figure 25 presents various power quantities of ENTSO-E Case 1. The active power (P_BRK_MV) flows to the main grid which is common in light load cases. At first there's no reactive power (Q_BRK_MV) flow but after 15 s the reactive power flow increases and it is taken from the main grid.

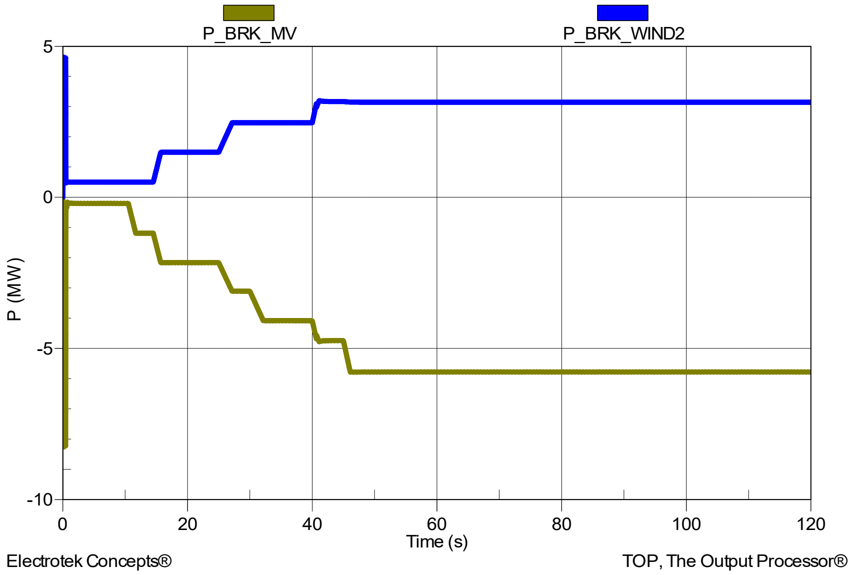


Figure 26. ENTSO-E Case 1

Fingrid Case 3 is presented in Figures 27 and 28. It is presented from 0 to 60 s because the voltages settle to allowed range after 45 s. MV voltage limits were exceeded between 10-40 s and LV voltage limits between 26-45 s.

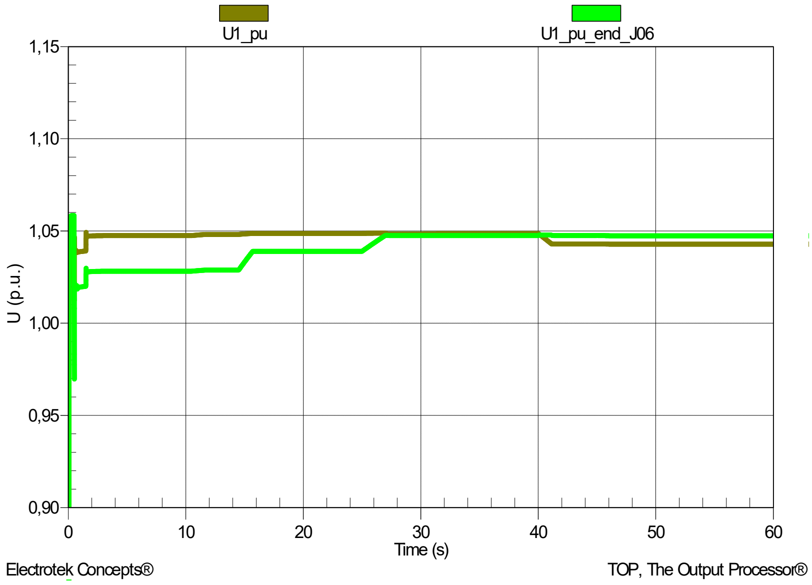


Figure 27. Fingrid Case 3 voltage excess

In this case the reactive power control (*Q(U)*-control) gets both the voltages to allowed limits far before the end of the simulation.

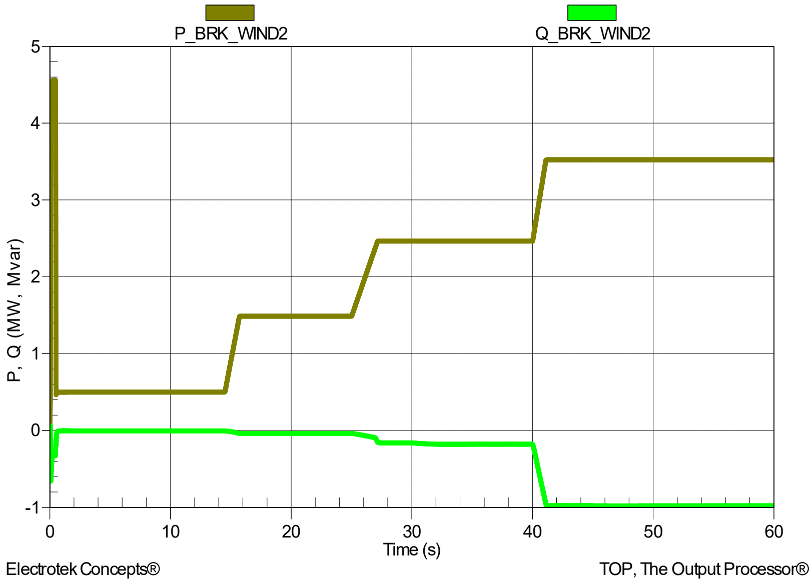


Figure 28. Fingrid Case 3 WIND2 active and reactive power.

Figure 28 presents active- and reactive power curves of J06's wind turbine. Active power curve (P_BRK_WIND2) is clean and it reacts to given power step values. The biggest step in reactive power curve (Q_BRK_WIND2) appears at just after 40 s.

7.4 Cases Wind-C

The results for this set are presented in Appendix 1, Tables 19-20. There were four cases with deviation in this simulation set: Fingrid Cases 1, 3 and 4 and ENTSO-E Case 1. There was active power limitation of J06's wind turbine (WIND2) in two cases, Fingrid and ENTSO-E Case 1. MV voltage limits were exceeded in one case only, Fingrid Case 3. LV voltage limits were exceeded in four cases from which the actual excess could be noticed in only three cases, Fingrid Case 3 and ENTSO-E Cases 1 and 3. Fingrid Case 1's reactive power signal was distorted and therefore the excess could not be determined precisely. Reactive power limits were exceeded in Fingrid Cases 1, 3 and 4.

Fingrid Case 1 is presented in Figures 29-31. Figure 29 presents active- and reactive power curves of J06's wind turbine (WIND2). The control starts to resonate just after the time 40 s when the last increment of active power input is applied to the wind turbine.

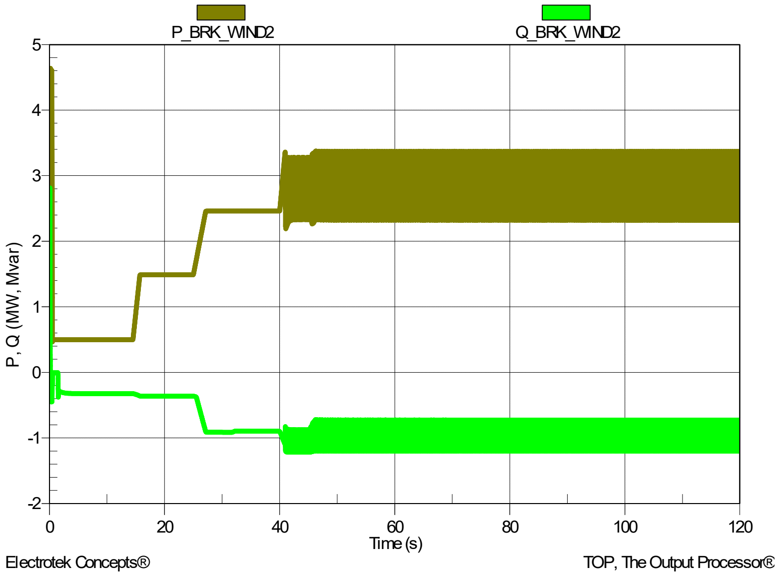


Figure 29. Finrid Case 1 distorted signals.

When looking closer to Fingrid Case 1's controls it could be noticed that there are a couple of reasons affecting to resonated behaviour. The Fingrid's reactive power window limit (Q_left_outer_limit) is on a quite low level (lower than ENTSO-E's).The target voltage at HV/MV substation is also higher (20,7 kV). At the time 40 s the local *Q(U)*-control which is used to prevent the excess of upper voltage limit tries to control the reactive power to opposite direction compared to *Q*-control for achieving reactive power window requirements. From the viewpoint of reactive power control both of these controls can't be fulfilled simultaneously. If the wind turbine on J06 (WIND2) is used alone for controlling the reactive power window requirements the full reactive power capacity (±1,1 Mvar) can't be used for voltage control at the point of common coupling. In this type of situations active power limitation is required (Laaksonen 2018a.)

The used reactive power capacity of J06's wind turbine was decreased by 0,1 Mvar from 1,1 Mvar to 1,0 Mvar. After this decrement the case was simulated again. This time the simulation turned out to be clean. Figure 30 presents the a re-run of Fingrid Case 1.

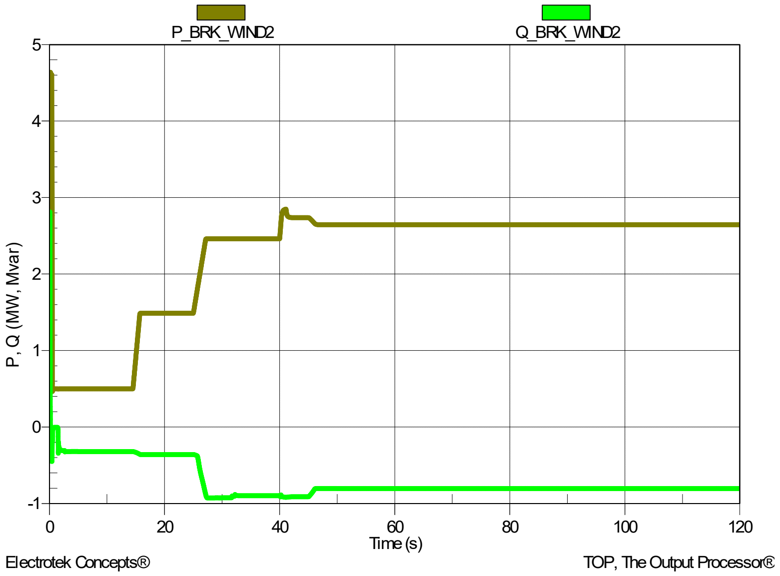


Figure 30. Fingrid Case 1 active power limitation (re-run).

The amount of active power limitation is ca. 880 kW. Reactive power curve doesn’t appear to get affected at 40 s but at about 45 s the reactive power output is decreased slightly. Fingrid Case 1 voltages are presented in Figure 31. The second increment step in active power output of J06’s wind turbine causes the LV voltage limit excess at 25 s. Also the last increment step (which causes the active power limitation to occur) at 40 s makes the voltage to rise even higher.

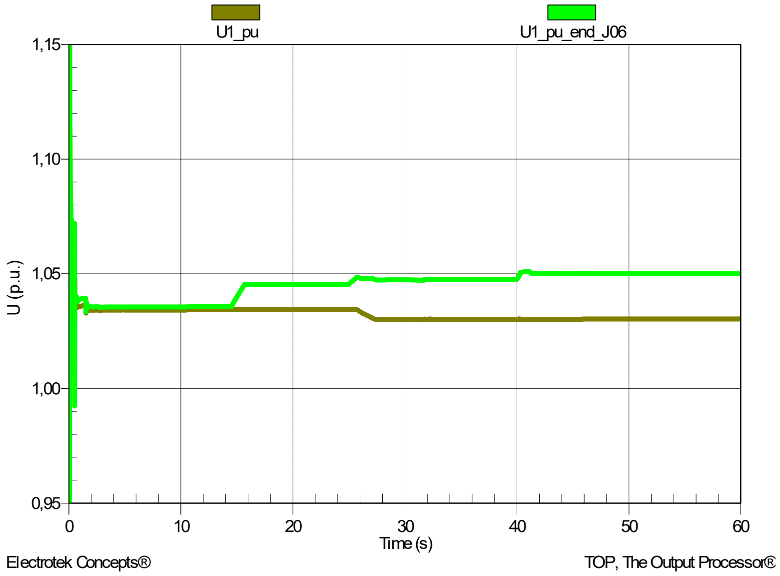


Figure 31. Fingrid Case 1 voltages.

ENTSO-E Case 1 is presented in Figure 32 in which the active power limitation (P_BRK_WIND2) can be seen more precisely at the time 40 s. The limitation was done because of the voltage rise at the end of the feeder J06. LV voltage limit was exceeded slightly regardless of the active power limitation. The voltage excess occurred just after the last increment step in wind turbine's active power and it lasted till the end of the simulation.

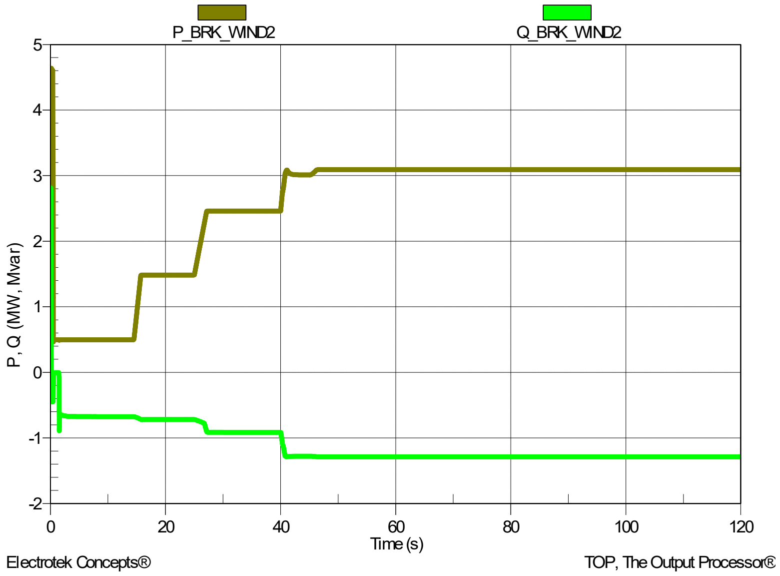


Figure 32. ENTSO-E Case 1 active power limitation.

Fingrid Case 3 is presented in Figures 33 and 34. MV voltage (U1_pu) settles after 26 s which is about at the same time when LV voltage at the end of feeder J06 (U1_pu_end_J06) exceeds the voltage limit.

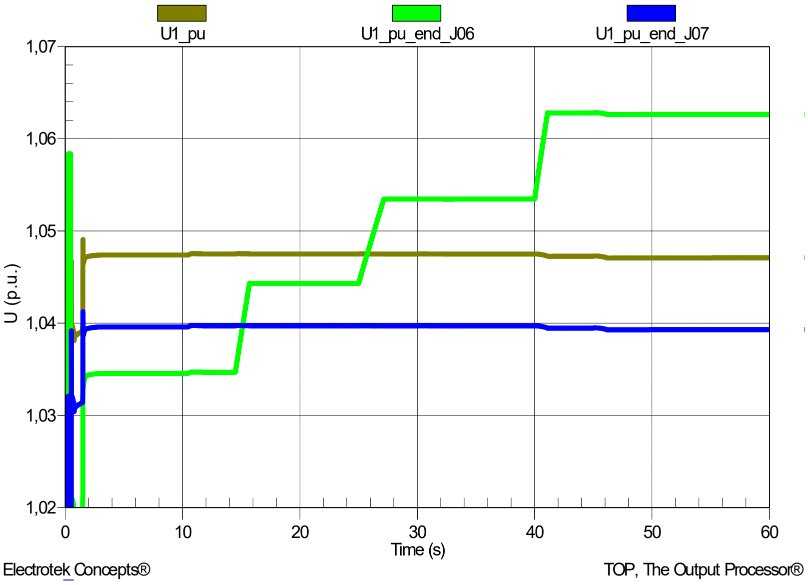


Figure 33. Fingrid Case 3 voltages.

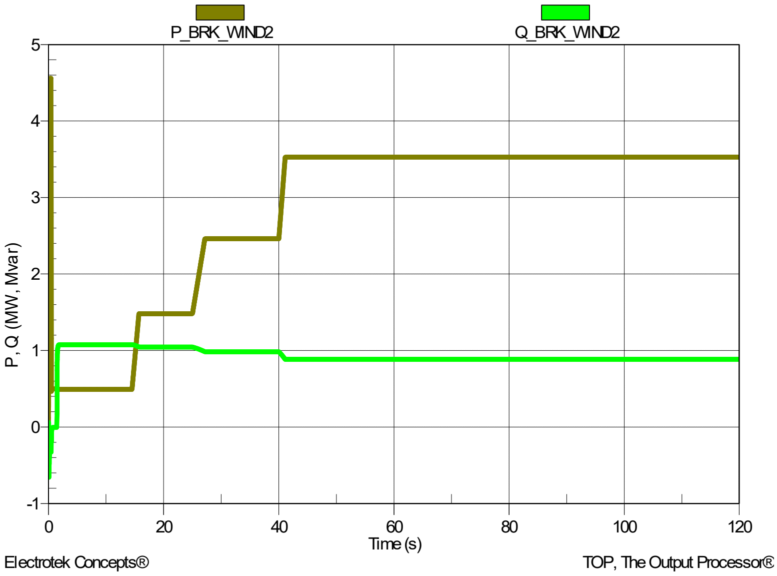


Figure 34. Fingrid Case 3 active- and reactive power curves.

When comparing both figures above it is notable that the active power curve of the wind turbine (P_BRK_WIND2) matches the LV voltage curve (U1_pu_end_J06) almost exactly. This case is a 'very high load'-case with the target voltage of 20,7 kV at HV/MV substation and it seems like a challenging combination from the viewpoint of voltage limits.

7.5 Cases Wind-D

The results for this set are presented in Appendix 1, Tables 21-22. In this set of simulations the control for reactive power window limitation was divided in half between the two wind turbines, WT on J08 (WIND) and WT2 on J06 (WIND2). There are four cases total with some deviation, Fingrid and ENTSO-E Cases 1 and 3. Active power limitation of the wind turbine (WIND2) took place in both Fingrid and ENTSO-E Case 1. LV voltage limits were exceeded also in aforementioned two cases plus in Fingrid and ENTSO-E Case 3. MV voltage limits were only exceeded in Fingrid Case 3. Reactive power limits were exceeded in Fingrid Cases 1 and 3.

Figures 35 and 36 present close-ups of Fingrid Case 1's first 60 seconds. This action is done to get better readability to the figures. In these figures the most interesting section is the 40 s point. Figure 36 shows that at 40 s time LV voltage (U1_pu_end_J06) is already at the 1,0475 p.u. limit and at the same time the last increment step in J06 WT2's (P_BRK_WIND2) active power output occurs. Both *Q(U)*-control and *P(U)*-control react to the situation and the response to these controls can be seen in Figure 35 where both power quantities are decreased.

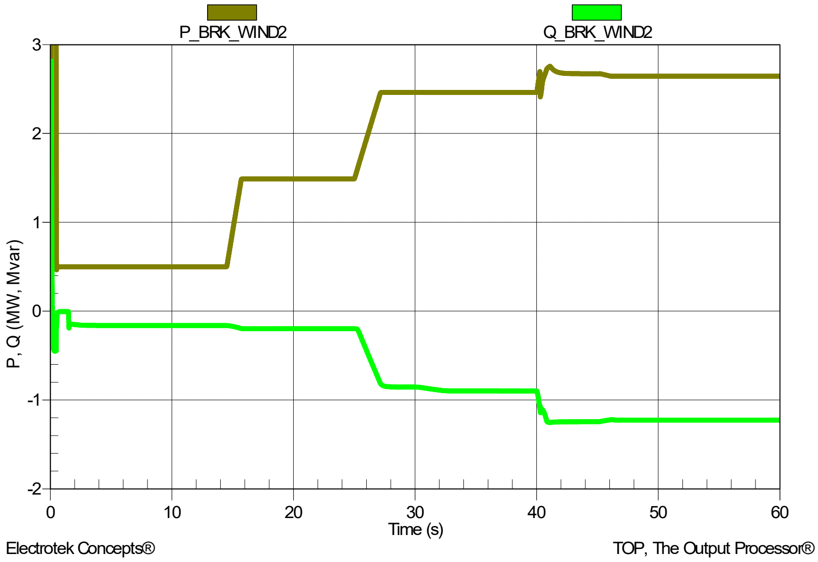


Figure 35. Fingrid Case 1 active- and reactive power curves.

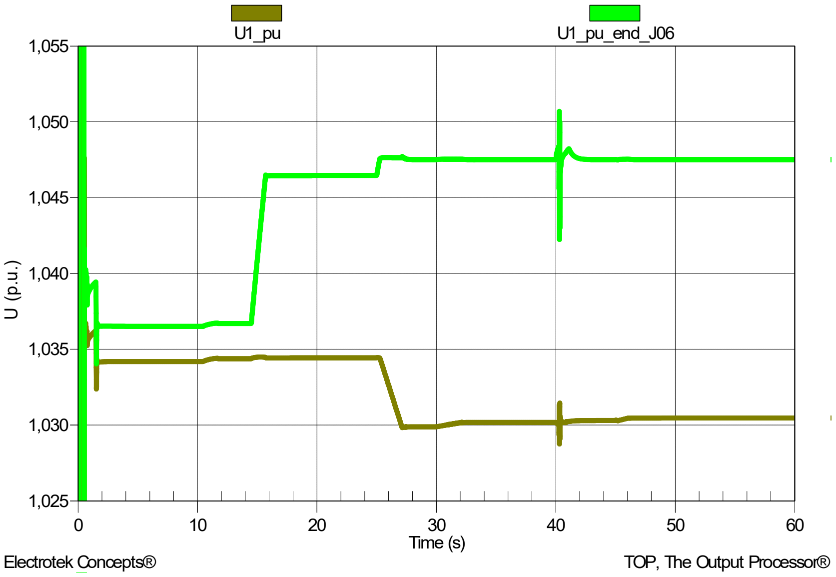


Figure 36. Fingrid Case 1 MV and LV voltages.

In Fingrid Case 3 both LV and MV voltage limits were exceeded. In this type 'very high load' case the limitation of wind turbine's active power output is not a valid option. The voltages for this case are presented in Figure 37. MV voltage (U1_pu) is over the limit during the whole simulation. LV voltage (U1_pu_end_J06) makes the excess at 15 s and stays over the limit to the end of the simulation.

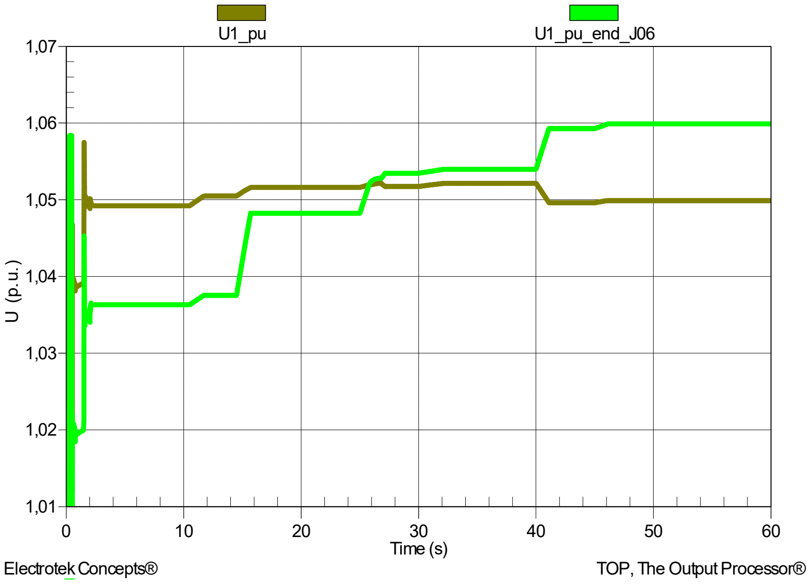


Figure 37. Fingrid Case 3 MV and LV voltages.

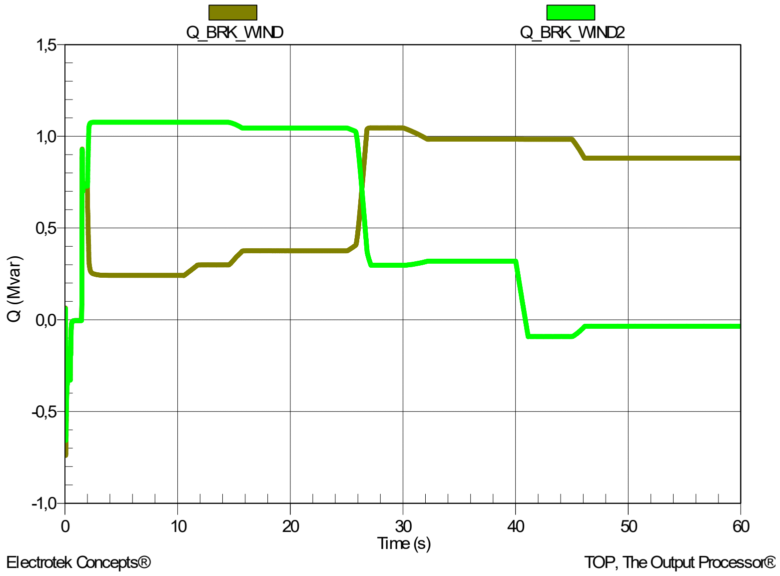


Figure 38. Fingrid Case 3 reactive power curves of both wind turbines.

Figure 38 presents reactive power output of J06 wind turbine (Q_BRK_WIND2) and J08 wind turbine (Q_BRK_WIND). *Q(U)*-control adjusts the reactive power output of WIND2 and tries to get the J06 LV voltage down but obviously in case of this type of combination, ‘very high load’ and 20,7 kV target at HV/MV substation, it is clearly not adequate.

Figure 39 presents ENTSO-E Case 1 active power limitation of J06’s wind turbine (P_BRK_WIND2) caused by the voltage rise at the end of the feeder J06. The limitation occurs just after 40 s. The other wind turbine’s active power output (P_BRK_WIND) is around 3,6 MW at the biggest which is the nominal power for both turbines.

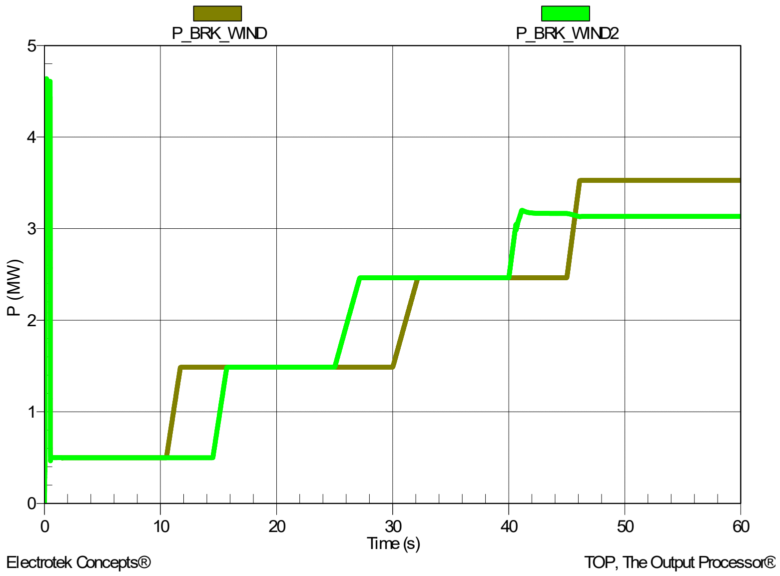


Figure 39. ENTSO-E Case1 active power limitation.

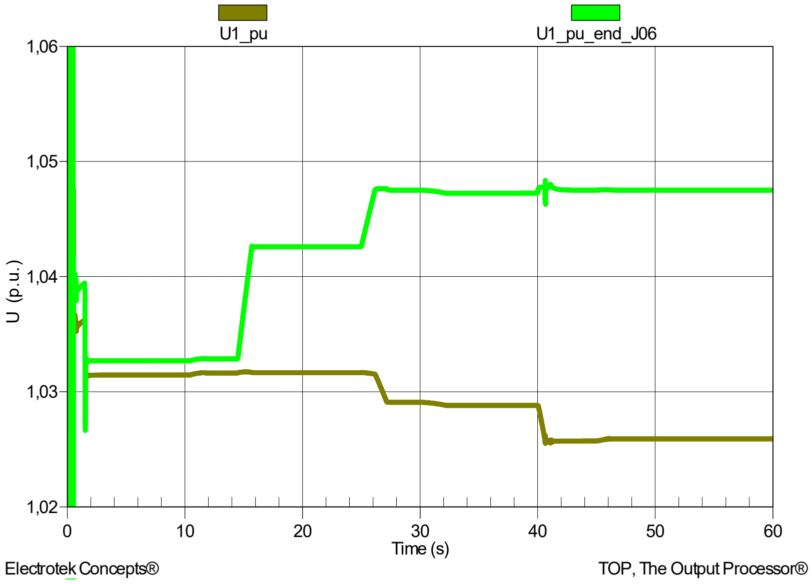


Figure 40. ENTSO-E Case 1 MV and LV voltages.

Figure 40 presents the voltages in ENTSO-E Case 1. MV voltage (U1_pu) stays in allowed range during the simulation. Again, LV voltage (U1_pu_end_J06) causes problems but this time after the active power limitation which occurs at about 40 s the voltage settles to the upper voltage limit 1,0475 p.u.

Figure 41 presents ENTSO-E Case 3 MV and LV voltages. The deviance with this case is a short excess in LV voltage between 40-45 s. After that the voltage settles just under the 1,0475 p.u. limit.

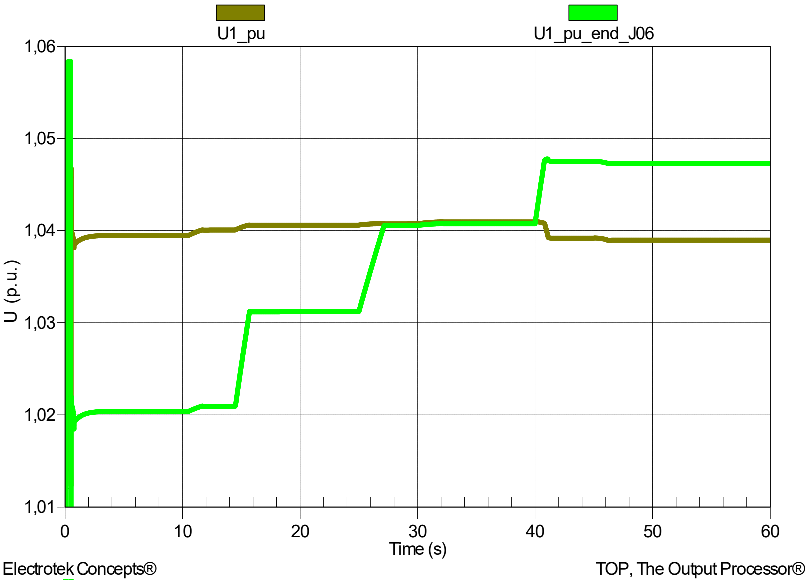


Figure 41. ENTSO-E Case 3 voltages.

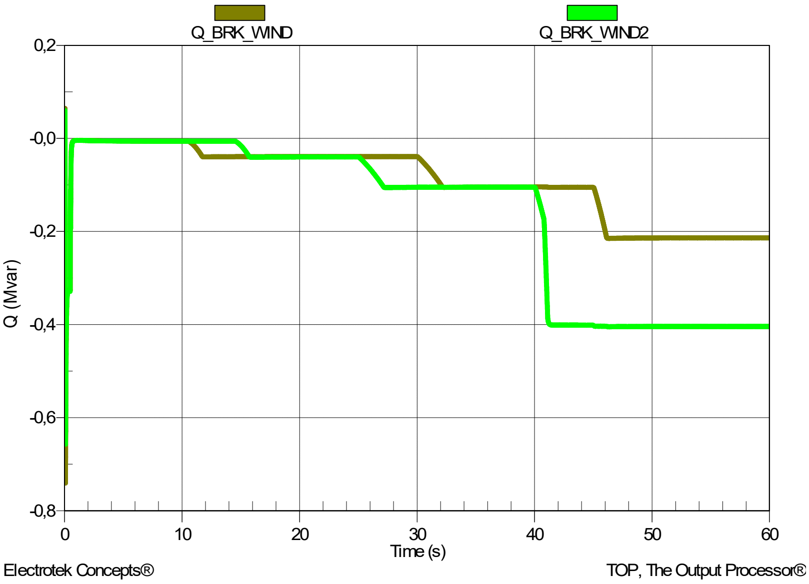


Figure 42. ENTSO-E Case 3 reactive power curves of both wind turbines.

Figure 42 presents the reactive power output of both wind turbines. This time reactive power control alone gets the J06 LV voltage pretty close (but not under) the allowed limit. In this case the active power limitation is not allowed which would be needed to get the LV voltage exactly under the limit.

7.6 Cases PV-A

The results for this set are presented in Appendix 1, Tables 23-24. In this set of simulations in both Fingrid and ENTSO-E Cases 1 and 2 there was an under frequency period during 70-80 s. These were also the cases with LV network interactions to which the reactive power output of certain PVs had a slight reaction. In Fingrid Cases 3 and 4 the reactive power limits were exceeded. Also, in Fingrid Case 3 the MV voltage limit was exceeded.

Fingrid Case 1 is presented in Figures 43-44. The under frequency can be noticed clearly in Figure 43's three power signals between 70-80 s. The active power (P_BRK_MV) flows to main grid during the whole simulation and it is increased during the under frequency period. The reactive power output of J08's wind turbine (Q_BRK_WIND) also responds to under frequency because it is designated to reactive power window control.

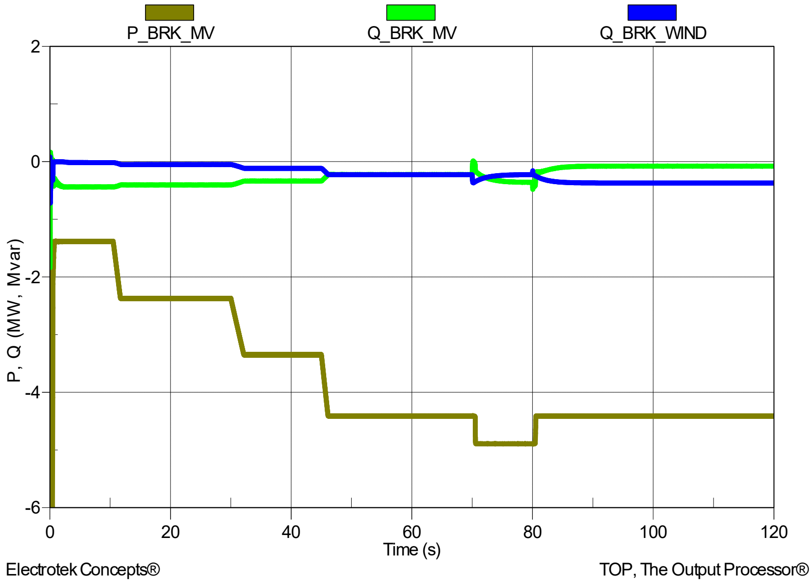


Figure 43. Fingrid Case 1 power curves.

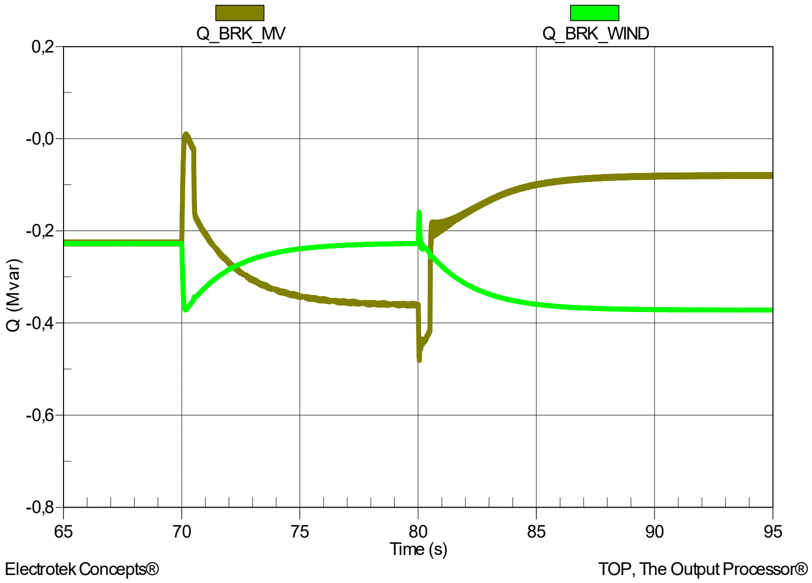


Figure 44. Fingrid Case 1 reactive power flows during under frequency.

Figure 44 presents the reactive power output of J08's wind turbine (Q_BRK_WIND) and the reactive power at MV breaker (Q_BRK_MV) during the under frequency. When comparing the signals before and after the under frequency it can be noticed that the reactive power output of the wind turbine (Q_BRK_WIND) changes from -227 kvars to -371 kvars which means that reactive power production is increased by 144 kvars. On the other hand also reactive power at MV breaker changes from -225 kvar to -80 kvar meaning that reactive power flow to main grid is decreased by 145 kvars.

Also PVs (PV2, PV3, PV4, PV6, PV7 and PV8) react to under frequency slightly even if they are driven with *cos(φ)* = 1. This is presented in Figure 45. The outputs vary between -12 kvar and 12 kvar. The main thing is that even if the outputs vary during the under frequency the final values remain on same level as before the under frequency.

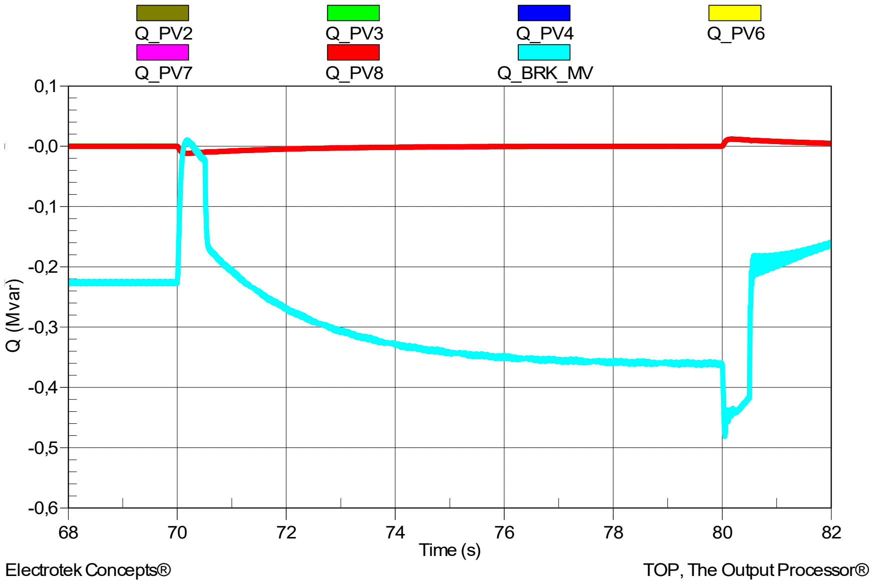


Figure 45. Fingrid Case 1 various reactive power curves.

Fingrid Case 2 is presented in Figures 46-49. The difference between Case 1 and Case 2 is the target voltage at HV/MV substation, 20,7 kV and 20,0 kV, respectively.

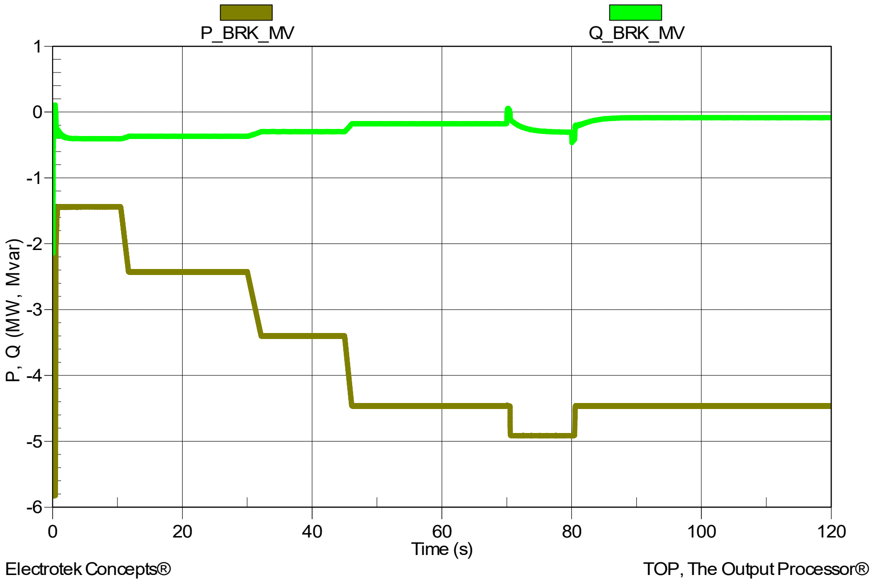


Figure 46. Fingrid Case 2 active and reactive power at MV breaker.

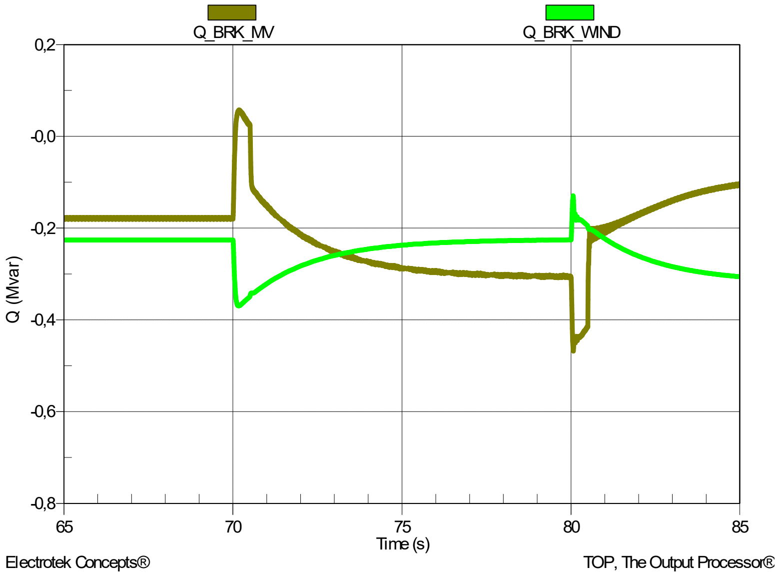


Figure 47. Fingrid Case 2 reactive power signals during under frequency.

Figure 47 presents the reactive power output of J08's WT (Q_BRK_WIND) and the reactive power at MV breaker (Q_BRK_MV) during the under frequency. This is exactly the same situation as was with Case 1. When comparing the signals before and after the under frequency it can be noticed that the reactive power output of the wind turbine (Q_BRK_WIND) changes from -225 kvar to -318 kvar which means that reactive power production is increased by 93 kvars. On the other hand also reactive power at MV breaker changes from -180 kvar to -85 kvar meaning that reactive power flow to main grid is decreased by 95 kvars. In Case 2 less reactive power control is needed because of the lower HV/MV target voltage.

Fingrid Case 3 is presented in Figures 48-49. Again, a case with HV/MV target voltage at 20,7 kV and 'very high load' caused deviance. This time MV voltage exceeded the limit 1,0475 p.u. at the time 10 s and remained at that level till the end of the simulation.

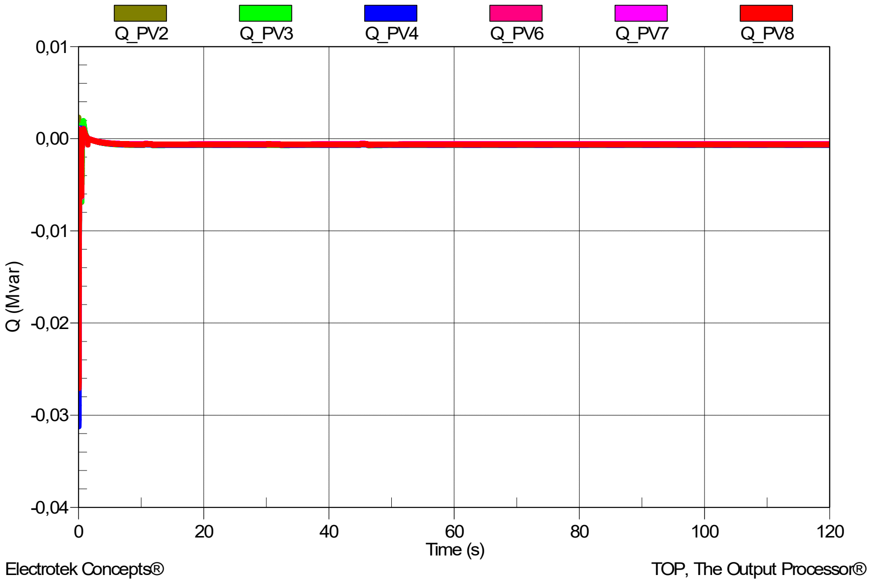


Figure 48. Fingrid Case 3 reactive power output of PVs.

Figure 48 presents the reactive power output of PVs. All PVs signals lie just under zero meaning that reactive power export (production) is insignificant.

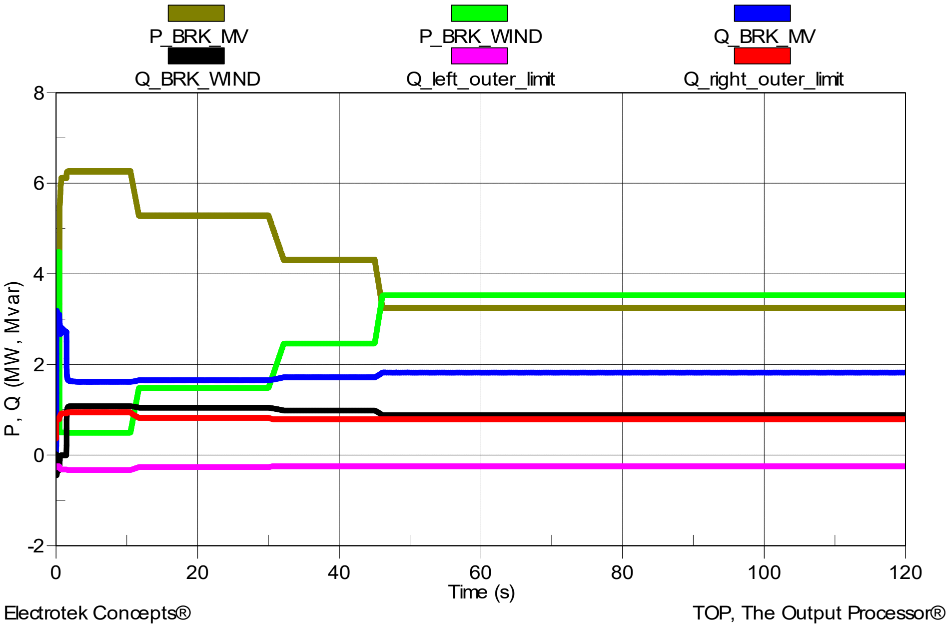


Figure 49. Fingrid Case 3 power quantities and reactive power window limits.

Figure 49 presents various power quantities of Fingrid Case 3. At the time 10 s the active power output of J08’s WT (P_BRK_WIND) was increased which also caused the MV voltage excess. Reactive power exchange (P_BRK_MV) varies between 1500-1800 kvar during the simulation meaning that reactive power is consumed i.e. it is taken from the main grid. When observing the reactive power limit curves (Q_left_outer_limit and Q_right_outer limit) it can be noticed that reactive power at MV breaker (Q_BRK_MV) doesn't meet the reactive power window requirements. The reactive power transfer from the main grid is too substantial compared to active power transfer and this is why the reactive power window limits were exceeded.

Fingrid Case 4 was similar to the previous case. This time only reactive power window limits were exceeded. The lower target voltage of 20,0 kV at HV/MV substation ensured that there were no excess in MV or LV voltages.

7.7 Cases PV-B

The results for Cases PV-B are presented in Appendix 1, Tables 25-26. In this set of simulations in both Fingrid and ENTSO-E Cases 1 and 2 there was an under frequency period at 70-80 s. These were also the cases with slight LV network interactions to which the reactive power output of certain PVs reacted. In Fingrid Cases 3 and 4 the reactive power limits were exceeded. PV3's active power needed to be limited in all eight cases. PV2's active power was limited in Fingrid Case 3 which is a 'very high load' case with higher target voltage 20,7 kV at HV/MV substation.

Fingrid Case 1 is presented in Figures 50-51. There was reactive power control because of the under frequency at 70-80 s and also active power limitation for voltage control. Figure 50 presents reactive power control of certain PVs (PV4, PV6, PV7 and PV8) during the under frequency.

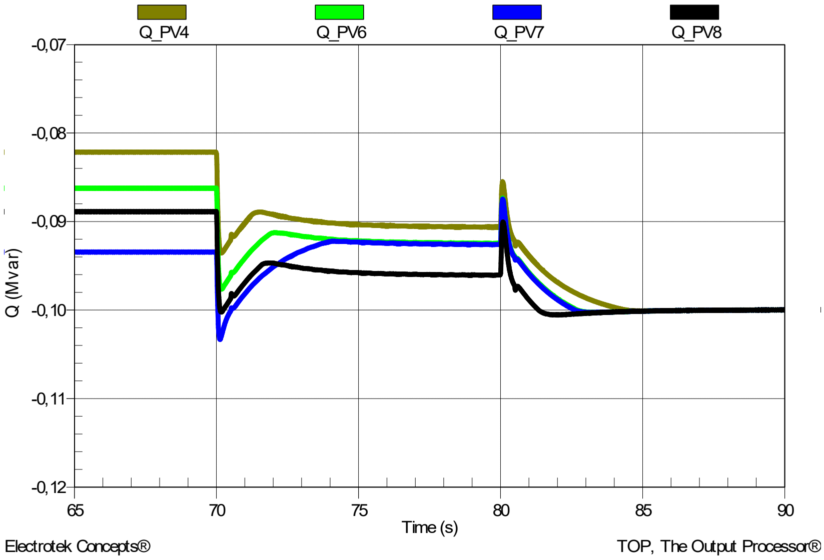


Figure 50. Fingrid Case 1 reactive power output of four PVs.

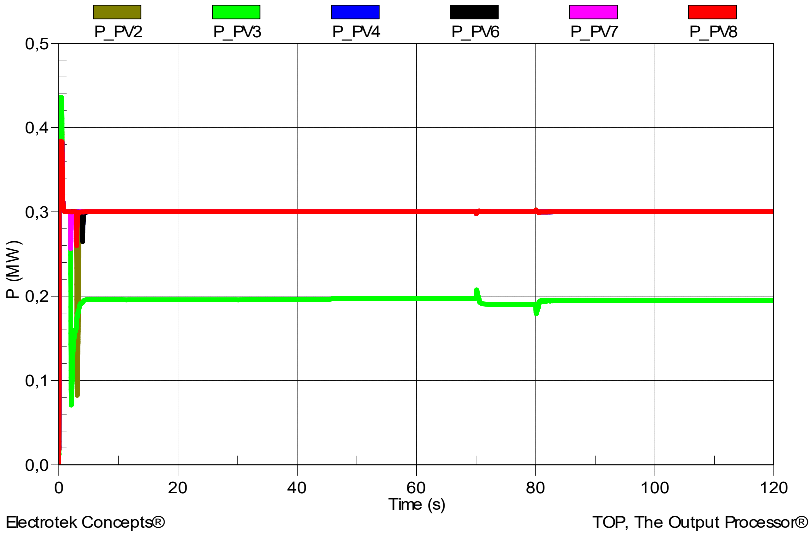


Figure 51. Fingrid Case 1 active power output of the PVs.

Figure 51 presents active power output curves of all the six controlled PVs. All but PV3 are driven at the nominal power of 300 kW. PV3's output has been limited (103 kW) due to *P(U)*-control. The under frequency is barely detectable at PV3's active power curve at 70-80 s.

Fingrid Case 2 is very similar to the previous case. This time five PVs (PV2, PV4, PV6, PV7 and PV8) needed to control their reactive power output during the under frequency. Fingrid Case 2 is presented in Figures 52-53.

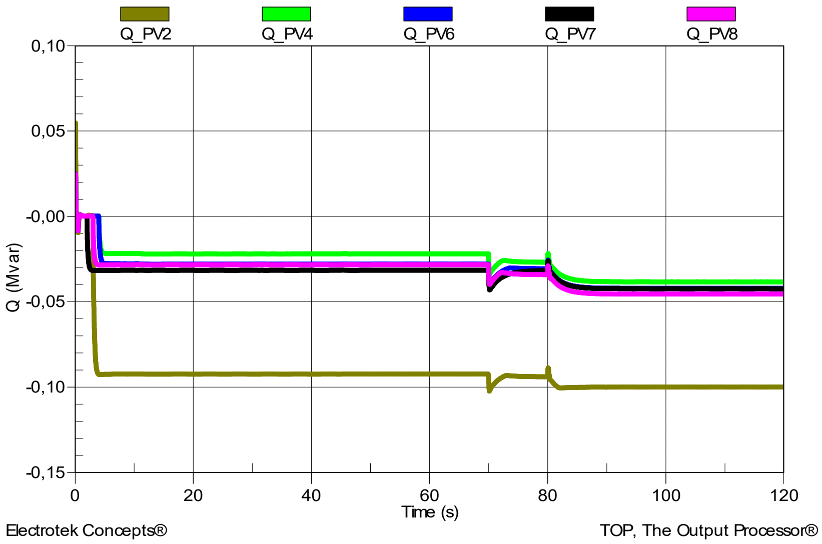


Figure 52. Fingrid Case 2 reactive power output of five PVs.

Active power output curves of the PVs are presented in Figure 53. Compared with the previous case (103 kW) the amount of active power limitation is smaller in this case (30 kW).

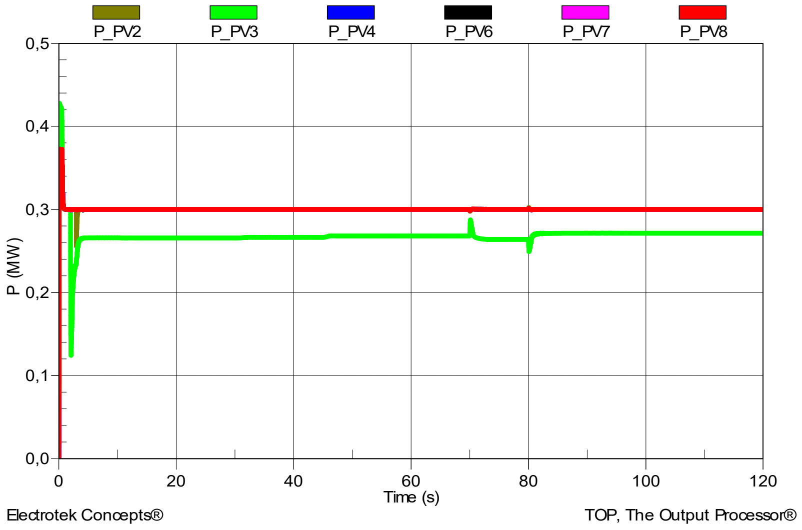


Figure 53. Fingrid Case 2 active power output of the PVs.

7.8 Cases PV-C

The results for this set are presented in Appendix 1, Tables 27-28. In this simulation set there was an over frequency period (50,2 Hz) at 70-80 s in all cases. During the over frequency PV-inverters were controlled by *P(f)*-control in which the active power of PVs adjusted due to changes in frequency. Among these cases there were only two cases in which the reactive power window limits were exceeded, Fingrid Case 3 and Fingrid Case 4.

Table 13. Total active power limitation of PVs by case.

Fingrid Case 1	Fingrid Case 2	Fingrid Case 3	Fingrid Case 4	ENTSO Case 1	ENTSO Case 2	ENTSO Case 3	ENTSO Case 4
800 kW	865 kW	733 kW	841 kW	803 kW	871 kW	785 kW	860 kW

It is logical to notice that in cases with 20,7 kV target voltage at HV/MV substation the total active power limitation of PVs is smaller than in 20,0 kV cases. Fingrid Case 3 is presented in Figures 54-55.

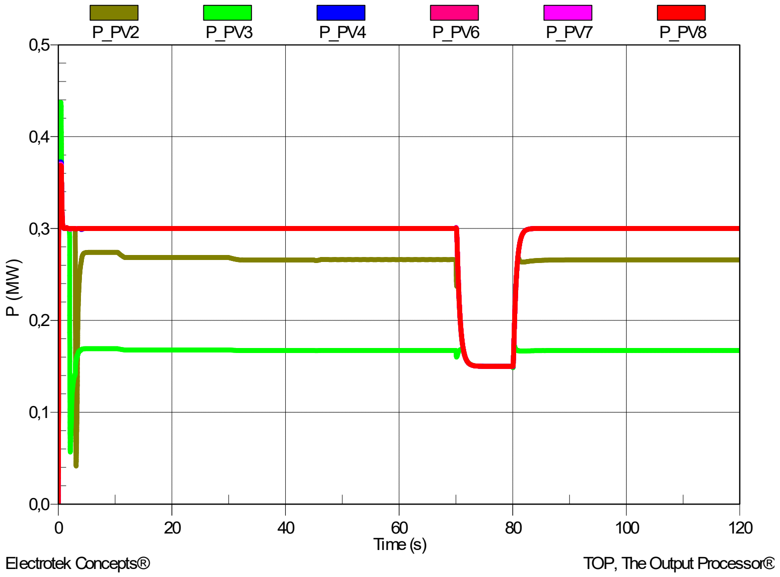


Figure 54. Fingrid Case 3 active power curves of PVs.

In this case the sum of active power limitation during the over frequency is the smallest. PV2 and PV3 are controlled to limit their active power output from the beginning of the simulation i.e. the limitation is done for voltage control. Because of *P(f)*-control all PVs react to the over frequency which can be noticed in Figure 55 at 70-80 s.

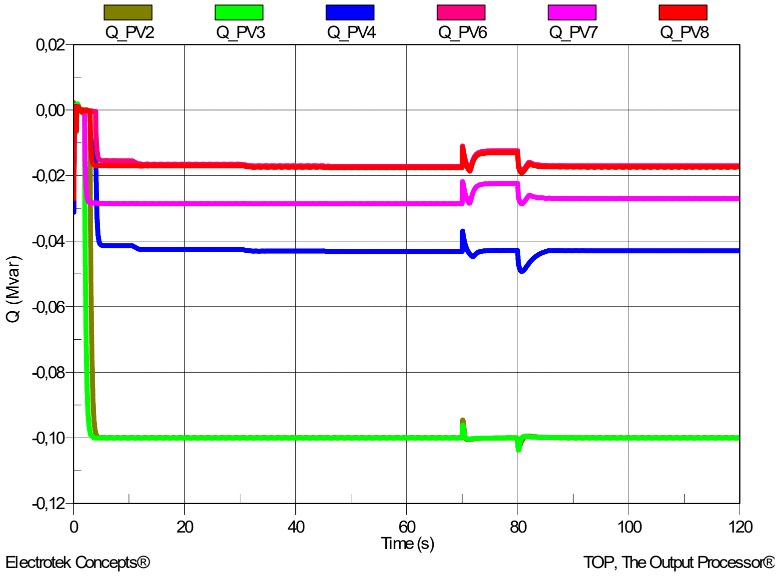


Figure 55. Fingrid Case 3 reactive power curves of PVs.

Figure 55 presents reactive power curves of PVs. A slight reaction to over frequency can be noticed at 70-80 s. PV2's and PV4's reactive power is designated for the purpose of reactive power unbalance which is needed for islanding detection to work properly.

ENTSO-E Case 2 is presented in Figures 56-57. The idea is to do the same examination to this case as in the previous case. In this case the sum of active power limitation during the over frequency is the biggest.

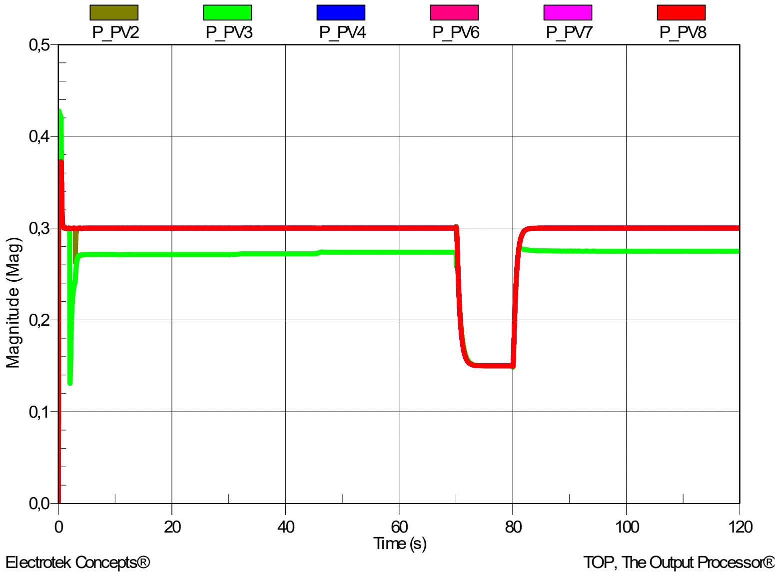


Figure 56. ENTSO-E Case 2 active power curves of PVs.

Figure 56 shows that only PV3's active power was limited because of voltage. Other PVs reacted to over frequency at 70-80 s by limiting the active power output.

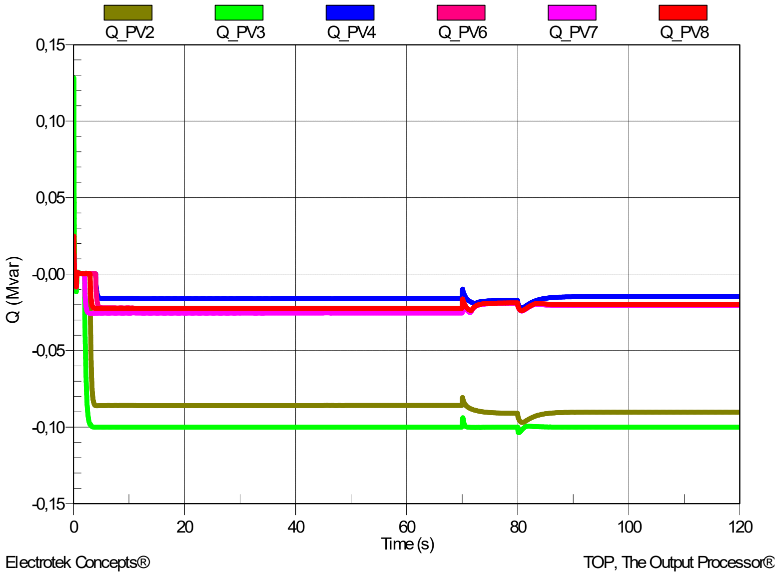


Figure 57. ENTSO-E Case 2 reactive power curves of PVs.

Figure 57 presents reactive power curves of PVs. A slight reaction to over frequency can be noticed at 70-80 s. PV2's and PV4's reactive power is designated for the purpose of reactive power unbalance which is needed for islanding detection to work properly.

7.9 Cases PV-D

The results for Cases PV-D are presented in Appendix 1, Tables 29-30. In this simulation set there was an over frequency period (50,2 Hz) at 70-80 s in all cases. During the over frequency PV-inverters were controlled by *P(f)*-control in which the active power of PVs adjusted due to changes in frequency. In this simulation set the loads of feeders J06, J07 and J09 are purely resistive i.e. their $cos(\varphi) = 1$. In this set there were no excesses in voltage- or reactive power window limits. Next a closer look at the same cases as in the previous set (Cases PV-C: Fingrid Case 3 and ENTSO-E Case 2) to figure out how the change in loads affected the measured quantities.

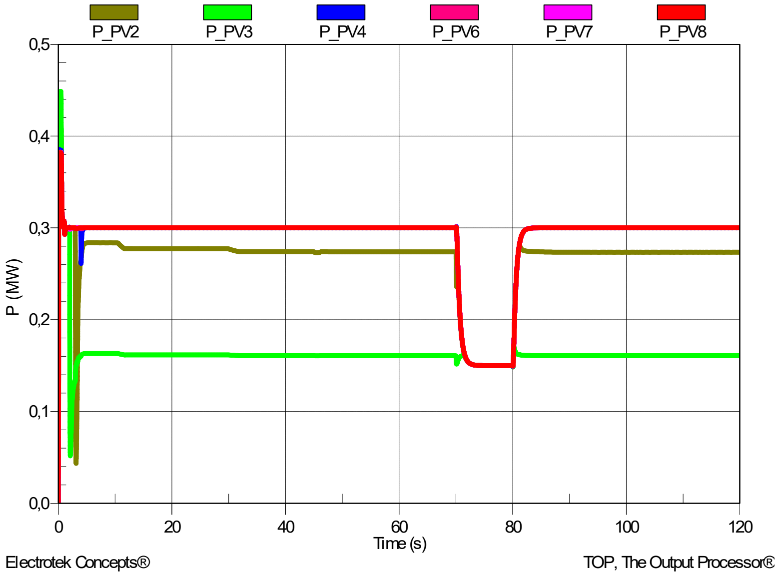


Figure 58. Fingrid Case 3 active power curves of PVs.

Figure 59 presents active power curves of PVs. Compared to Figure 53 the curves look highly similar. Figure 59 presents reactive power curves of PVs. When compared to Figure 55 some deviance can be noticed. If all outputs are summed the total reactive power in previous set's Fingrid Case 3 is -302 kvar and in the current set -402 kvar. More reactive power is produced by the PVs even if the loads' $cos(\varphi) = 1$. This is a 'very high' load case with higher target voltage value 20,7 kV at HV/MV substation.

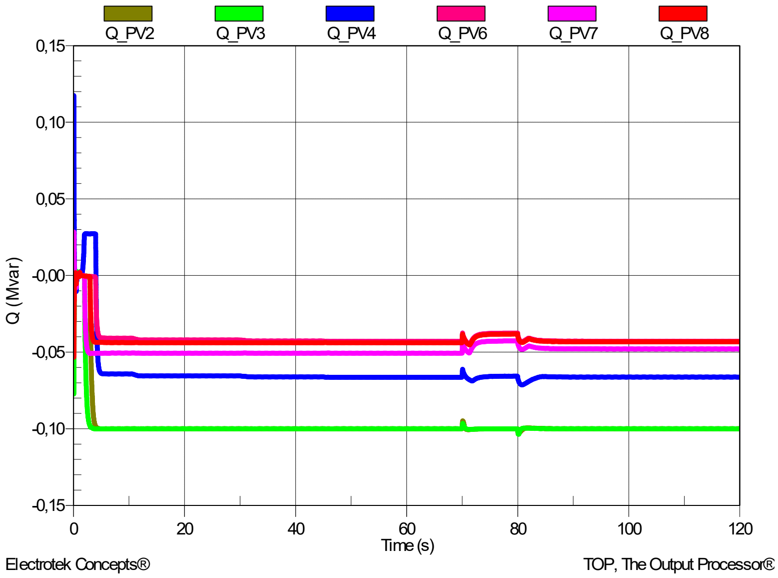


Figure 59. Fingrid Case 3 reactive power curves of PVs.

Figure 60 presents active power curves of PVs for ENTSO-E Case 2. Compared to Figure 56 the curves look again highly similar.

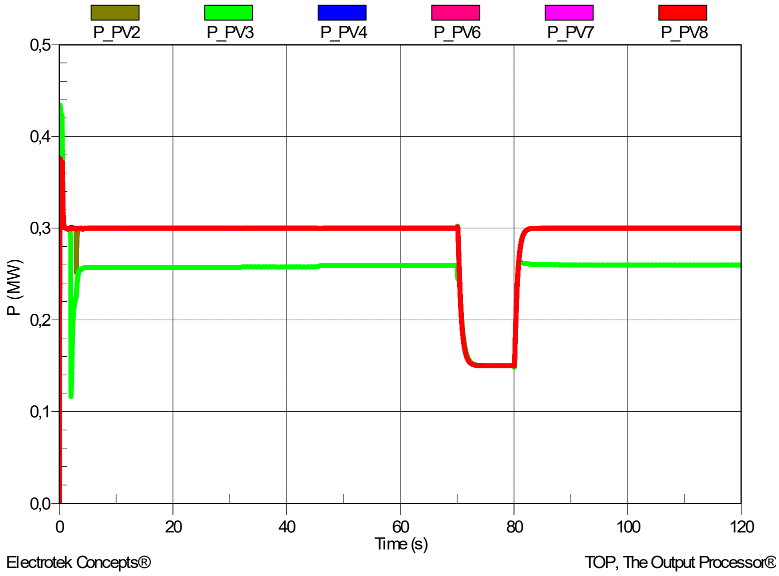


Figure 60. ENTSO-E Case 2 active power curves of PVs.

Figure 61 presents reactive power curves of PVs. When compared to Figure 57 a small deviance can be noticed. If all outputs are summed the total reactive power in previous set’s ENTSO-E Case 2 is -271 kvar and in the current set -284 kvar. Again, more reactive power is produced by the PVs even if the loads' *cos(φ)* = 1. This is a 'very low' load case with lower target voltage value 20,0 kV at HV/MV substation.

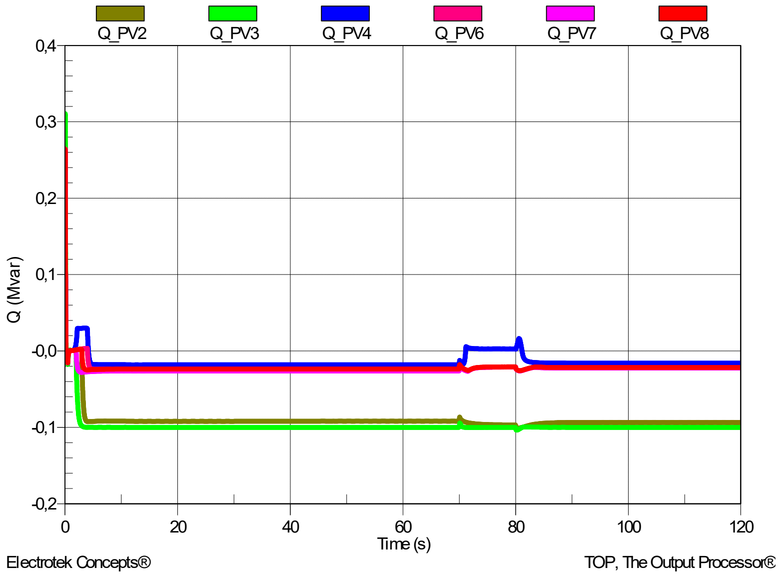


Figure 61. ENTSO-E Case 2 reactive power curves of PVs.

8 CONCLUSIONS

This simulation study contained 72 different cases in total. The best way to examine the results and the conclusions may be to group them up by the type of deviation. There were five types of recorded deviation: the excess of reactive power window limits, the excess of low voltage limits, the excess of medium voltage limits, active power limitation of the wind turbine and active power limitation of the photovoltaics.

There were 61 events in 47 cases among 72 simulations. Figure 62 presents the event distribution of all cases combined.

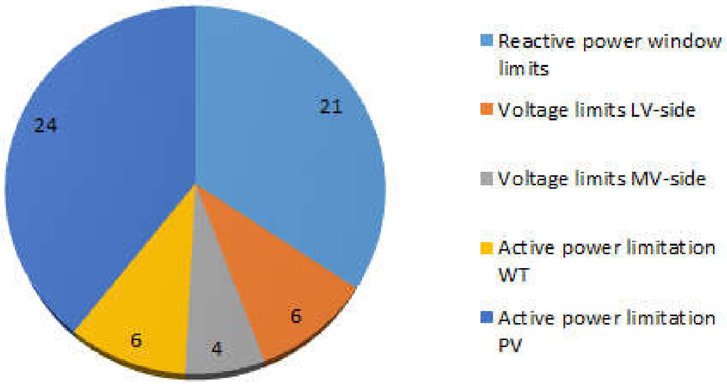


Figure 62. Distribution of interactions by type.

As shown in Figure 62 the most common event or interaction among all simulation cases was the active power limitation of photovoltaics' output. In the last three simulation sets (Cases PV-B, Cases PV-C and Cases PV-D) the active power output of photovoltaics had to be limited in every 24 cases. In Cases PV-B the limitation occurred because of local voltage control. In Cases PV-C and Cases PV-D the limitation was applied by the *P(f)*-control because of the over frequency period. The amount of limitation varied quite significantly which should be taken into consideration. The next three figures (Figures 63-65) explain the vast amount of cases with active power limitation of PVs.

Figure 63 presents a diagram of cases with limit violations. These include violations of reactive power window limits, LV voltage limits and MV voltage limits.

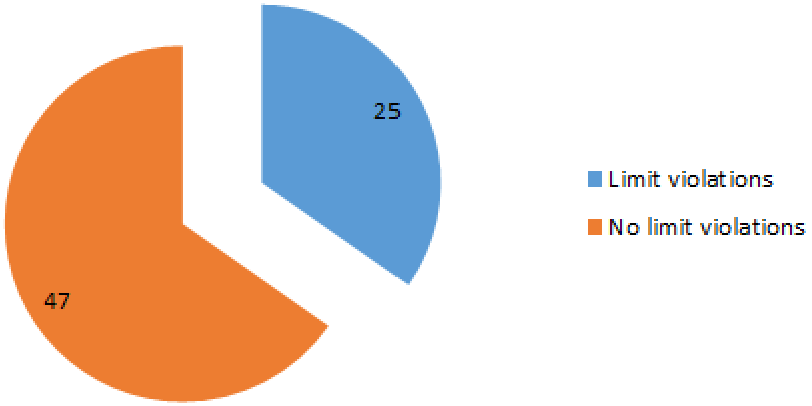


Figure 63. The number of cases with limit violations from 72 cases.

Figure 64 presents the amount of cases with active power limitation needs from 72 cases.

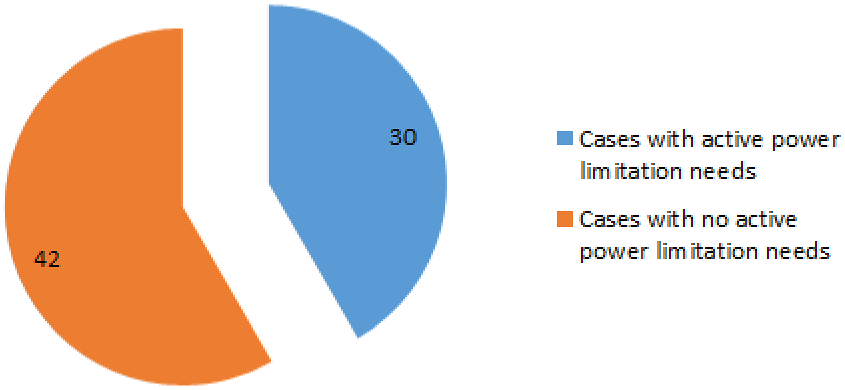


Figure 64. The number of cases with active power limitation needs.

The above 30 cases with active power limitation needs are divided to different types in Figure 65.

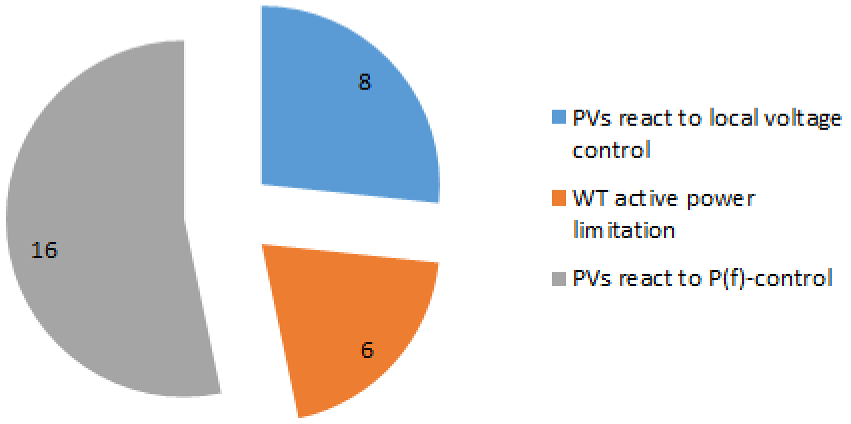


Figure 65. Type distribution of active power limitation.

The next common interaction type was the excess of reactive power window limits which was measured at HV/MV breaker. Among 72 simulation cases there were 21 cases in which the limits were exceeded. Of those 21 cases nineteen were Fingrid's and only two ENTSO-E's cases. Clearly, ENTSO-E's reactive power limits are more permissible than Fingrid's.

Figure 66 presents the total appearance of interactions by used reactive power limits (reactive power window).

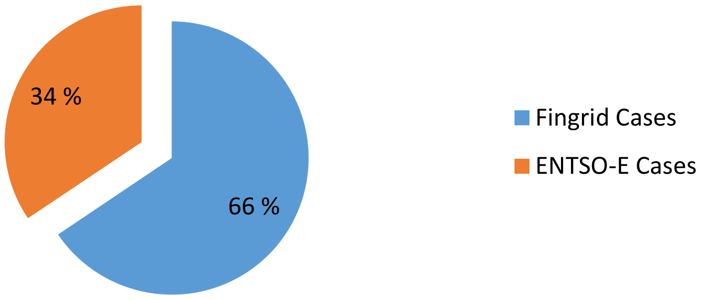


Figure 66. The percentage of interactions by used reactive power limits.

Clearly, there were more interactions among Fingrid's cases. The main reason for this was the more restrictive reactive power limits of Fingrid. Figure 67 presents the total appearance of interactions by used bus voltage (target voltage at HV/MV substation).

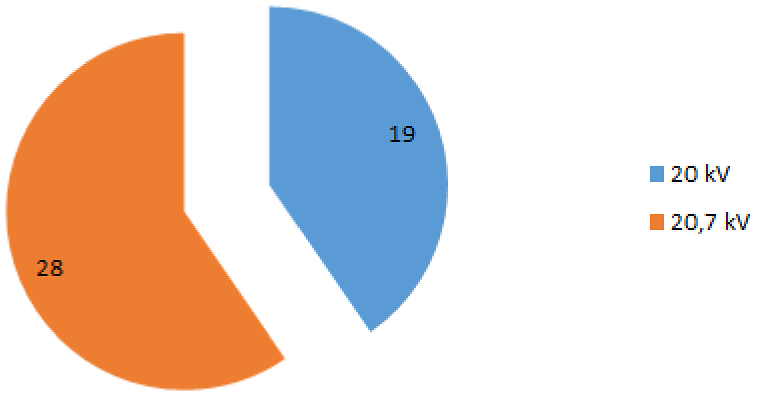


Figure 67. The amount of cases with interactions by used target voltage.

The next two interaction types were equally common. The wind turbine's active power limitation is considered to be the final measure in the control topology of these simulations. Active power limitation occurred in six cases total of which half were Fingrid's cases and half ENTSO-E's cases. The amount of limitation among Fingrid's cases varied between 880-900 kW. Among ENTSO-E's cases the amount of limitation was between 383-434 kW. The less the limitation was the less production capacity was lost. The most notable observations for above limitation-cases were that all of them were cases with the higher target voltage (20,7 kV) at HV/MV substation and the loading on feeders was 'very low load'.

The LV voltage limits were exceeded also in six cases, in four ENTSO-E's cases and in two Fingrid's cases. All these cases were cases with the higher target voltage (20,7 kV) at HV/MV substation. Three of them were actually the same cases that were 'very low load' –cases with active power limitation. The rest three cases were 'very high load' –cases.

The MV voltage limits were exceeded in four cases. All these cases were Fingrid's cases with the higher target voltage (20,7 kV) at HV/MV substation and a 'very high load' on feeders i.e. Fingrid Case 3.

When comparing the 47 cases with interactions by target voltage it can be noted that 28 of these cases were higher voltage-cases. The occurrence of interactions was clearly higher when the target voltage was 20,7 kV. For example, all the voltage limit excesses (LV and MV) took place when the target voltage was 20,7 kV.

When taking a look at individual cases and the incidence of interactions the best way is to look at figure 68 which presents the occurrence of interactions per case type.

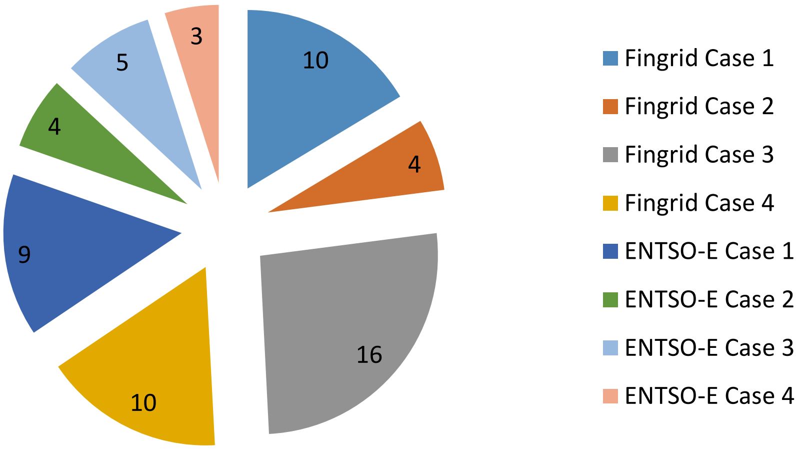


Figure 68. The amount of interactions per case.

Again, it is good to remember that each of the nine simulation sets contained eight simulations that are listed in above figure. The total amount of interactions was 61. It can be noticed that Fingrid Case 3 (20,7 kV, very high load) had the highest incidence of interactions. Also, the next two highest incidence cases were also Fingrid's cases, Fingrid Case 1 (20,7 kV, very low load) and Fingrid Case 4 (20 kV, very high load).

There were no OLTC tap changes in these simulations which is desirable because of the possible wearing of the OLTC. The fewer tap changes there occur, the less maintenance cost has to be expended.

8.1 Potential to ancillary services

When examining the list of ancillary services (p. 19-20) and comparing it to these simulations and overall interactions it is quite effortless to notice that inverter-connected DERs have a great potential for ancillary services. They can provide many of the ancillary services that are traditionally provided by rotating generators and voltage regulators. Of course a centralized control is needed for the coordination of the available resources. Also it has to be remembered that some of the resources are needed for local control of DERs before committing them for the use of ancillary services.

Combining the available resources by aggregators would be beneficial from the business standpoint because bigger entities are easier to market and control. Some type of “realtime database” would be needed for overall coordination of available resources (size, distance, scheduling, suitability to different types of markets etc.). Further development could include smart metering and invoicing.

The difference between photovoltaics and wind turbines from the perspective of ancillary services is basically the fact that the wind turbines utilize an electric machine to produce electricity.

8.2 Further research needs

Some interesting research ideas came into mind when working with this project. Due to the variable nature of wind and solar energy the utilization of energy storage systems could provide more stability to electricity systems. The idea would be to charge up the ESSs during high generation and consume the stored energy during low generation. The utilization of ESSs also increases the potential to shorter response times and the system's ability to handle bigger fluctuations.

Electric vehicles may provide possibilities for the ancillary services in the future. Usually EVs are plugged in and loaded during nighttime which could offer a stabile reserve of power i.e. for intermittent energy production. Of course, the customer has to be compensated for the use of the resources and some type of time limitation should be introduced for the use of the customer's capacity to ensure that the EV's battery wouldn't be drained in the next morning.

Both above thoughts could provide interesting scenarios for new simulation studies. The utilization of energy storage systems (or battery energy storage systems) for the use of ancillary services should definitely be studied further.

LIST OF REFERENCES

Björklund, Janne (2010). Kohti uusiutuvaa ja hajautettua energiantuotantoa, Suomen luonnonsuojeluliitto, *Energiailta 30.9.2010.* Mynämäki.

Commission Regulation (EU) 2016/1388. *Network Code on Demand Connection*. [Online] 2016. Retrieved: 29.1.2018. Available at: https://publications.europa.eu/en/publication-detail/-/publication/514fd1e3-650b-11e6-9b08-01aa75ed71a1/language-en/format-PDF/source-44168342

Crappe, Michel (ed.) (2008). Janssens, N., Trecat, J., Crappe, M., Delincé, J-M., Robert, A., Hajsaid, N., Georges, D., Snyder, A.F., van Cutsem, T., Ruiz-Vega, D., Pavella, M., Stubbe, M., Deuse, J., Dupuis, S. *Electric power systems*. 2nd Ed. ISTE Ltd., London.

ERA-Net, DeCAS project, DeCAS-project www-pages. [Online] 2017b. Retrieved: 24.1.2018. Available at: http://www.decas-project.eu/

ERA-Net, DeCAS project, DeCAS-project www-pages. [Online] 2017c. Retrieved: 4.4.2018. Available at: http://www.decas-project.eu/Innovation-Cells/

ERA-Net, ERA-Net Smart Grids plus, Eranet’s www-pages. [Online] 2017a. Retrieved 24.1.2018. Available at: http://www.eranet-smartgridsplus.eu/

European Union, EUs energy www-pages [Online] 2018. Retrieved: 31.1.2018. Available at : https://europa.eu/european-union/topics/energy_en

F. Khan, M., Ali, Y., Sood, V. K., Bhuiyan, F., Insull, P., Ahmad, F. (2017). Simulation of microgrid system with distributed generation, *2017 IEEE Electrical Power and Energy Conference (EPEC)*, Saskatoon, SK, Canada.

Fingrid Oyj, Fingrid’s www-pages. [Online] 2018. Retrieved: 29.1.2018. Available at: https://www.fingrid.fi/kantaverkko/suomen-sahkojarjestelma/fingridin-sahkonsiirtoverkko/

Fingrid Oyj. Fingrid’s www-pages. Application manual, *Loissähkön toimitus ja loistehoreservin ylläpito* [Online] 2017. Retrieved: 12.3.2018. Available at: https://www.fingrid.fi/globalassets/dokumentit/fi/palvelut/kayttovarma-sahkonsiirto/loissahkon-toimituksen-ja-loistehoreservin-yllapito.pdf

IET (2006). *Distributed generation,* Institution of engineering and technology’s factfile, Stevenage, United Kingdom.

Korpinen, Leena (1998). *Sähkövoimatekniikkaopus: 9. Muuntajat ja sähkölaitteet.* [Online] Retrieved: 4.1.2018. Available at: http://www.leenakorpinen.fi/archive/svt_opus/9muuntajat_ja_sahkolaitteet.pdf

Laaksonen, Hannu & P. Hovila. (2016). ERA-Net Smart Grids plus*, DeCAS – Active Network Management (ANM) and Islanding Detection Development Possibilities in Sundom Smart Grid.* ABB – Medium Voltage products, Vaasa.

Laaksonen, Hannu (2017) An e-mail conversation about the utilization of inverters’ voltage control, 5.12.2017, Vaasa.

Laaksonen, Hannu (2018a) An e-mail conversation about reactive power control in the simulation model, 14.4.2018, Vaasa.

Laaksonen, Hannu (2018b) An e-mail conversation about the controls in the PSCAD simulation model, 9.8.2018, Vaasa.

Microgrid knowledge, *Eaton adds name to growing list offering microgrid controllers*, Microgrid knowledge www-pages [Online] 2015. Retrieved 15.2.2018 Available at: https://microgridknowledge.com/eaton-adds-name-to-growing-list-offering-microgrid-controllers/

Monot, A. Wahler, M., Valtari, Rita-Kasari, J. M., and Nikko, J. (2016). Real-time research lab in the Sundom smart grid pilot, *CIRED Workshop 2016*, Helsinki.

Office of electricity delivery & energy reliability, Energy.gov www-pages [Online] 2018. Retrieved: 29.1.2018. Available at: https://energy.gov/oe/activities/technology-development/grid-modernization-and-smart-grid/demand-response

Pahkala, T., Uimonen, H., Väre, V. (2017). Matkalla kohti joustavaa ja asiakaskeskeistä sähköjärjestelmää – Älyverkkotyöryhmän väliraportti, *Työ- ja elinkeinoministeriön julkaisuja, TEM raportteja 38/2017,* Ministry of Economic Affairs and Employment, Helsinki.

Pesola, A., Hoviniemi, H., Vehviläinen, I., and Vanhanen, (2010). By Gaia Consulting for Motiva, Ministry of employment and the economy of Finland, TEM. *Selvitys hajautetusta ja paikallisesta energiantuotannosta erilaisilla asuinalueilla,* Helsinki, Finland.

Siemens, *The difference between cosine phi and power factor*, Product support www-pages [Online] 2013. Retrieved 14.2.2018 Available at: https://support.industry.siemens.com/cs/document/51402748/7km-difference-between-cosine-phi-and-the-power-factor?dti=0&lc=en-WW

Silvonen, Kimmo (2004). *Sähkötekniikka ja elektroniikka*. 2nd Ed. Otatieto, Hakapaino Oy, Helsinki.

Sirviö, K., Laaksonen, H., Kauhaniemi, K. (2017). Innovation Cell Sundom Smart Grid – Active network management scheme for reactive power control, *DeCAS Project 2017,* Vaasa.

US Government. *Ancillary Services*, Greening the grid www-pages [Online] 2017. Retrieved: 28.1.2018. Available at:http://greeningthegrid.org/integration-in-depth/ancillary-services

van Gerwen, Rob (2006). *Introduction to distributed generation and renewables*, Power quality and utilization quide, Leonardo energy - European copper institute, Brussels, Belgium.

Xiaoyan, Yu & L. M., Tolbert (2006). Ancillary services provided from DER with power electronics interface, *2006 IEEE Power Engineering Society General Meeting*, Montreal, Quebec.

APPENDIX 1. Simulation results

Table 14. Base Cases

CASE	MV network interactions	MV and LV network interactions	LV network interactions	MV network voltage limits exceeded (YES / NO)	LV network voltage limits exceeded (YES / NO)	Number of OLTC operations at HV/MV substation	Main utility active power exchange (kW) t_1 t_2 t_3	Main utility reactive power exchange (kVar) t_1 t_2 t_3	Reactive Power window limits exceeded? (YES / NO)
	Does some event or control action at MV level lead to other control need at MV level? Which one and how much in kWs or kVArs?	Does some event or control action at MV or LV level lead to control need at the other level (e.g. LV demand response to under-frequency)? Which one and how much in kWs or kVArs?	Does some event or control action at LV level lead to other control need at LV level (e.g. LV demand response to under-frequency)? Which one and how much in kWs or kVArs?						
Case 1 (Fingrid)	No	No	No	No	No	0	800	-680	Yes
Case 2 (Fingrid)	No	No	No	No	No	0	735	-638	Yes
Case 3 (Fingrid)	No	No	No	No	No	0	8300	2500	Yes
Case 4 (Fingrid)	No	No	No	No	No	0	7780	2350	Yes
Case 1 (ENTSO-E)	No	No	No	No	No	0	800	-680	Yes
Case 2 (ENTSO-E)	No	No	No	No	No	0	735	-638	Yes
Case 3 (ENTSO-E)	No	No	No	No	No	0	8300	2500	No
Case 4 (ENTSO-E)	No	No	No	No	No	0	7780	2350	No

Table 15. Cases Wind-A

CASE	**Reactive and Active Power Control needs of MV network connected DER units**	**MV network interactions**	**MV and LV network interactions**	**LV network interactions**
	Required Reactive Power Control from WT (J08) to fulfill 'Reactive Power Window' Requirement (kVAr) t_1 t_2 t_3	**Does some event or control action at MV level lead to other control need at MV level? Which one and how much in kWs or kVArs?**	**Does some event or control action at MV or LV level lead to control need at the other level (e.g. LV demand response to under-frequency)? Which one and how much in kWs or kVArs?**	**Does some event or control action at LV level lead to other control need at LV level (e.g. LV demand response to under-frequency)? Which one and how much in kWs or kVArs?**
Case 1 (Fingrid)	-468 -537 -651	No	No	No
Case 2 (Fingrid)	-432 -506 -627	No	No	No
Case 3 (Fingrid)	1045 983 880	No	No	No
Case 4 (Fingrid)	1041 976 860	No	No	No
Case 1 (ENTSO-E)	-770 -843 -960	No	No	No
Case 2 (ENTSO-E)	-737 -813 -937	No	No	No
Case 3 (ENTSO-E)	-39 -104 -213	No	No	No
Case 4 (ENTSO-E)	-37 -107 -222	No	No	No

$t_1 = 20$ s, $t_2 = 40$ s, $t_3 = 80$ s

Table 16. Cases Wind-A

CASE	**MV network voltage limits exceeded (YES / NO)**	**LV network voltage limits exceeded (YES / NO)**	**Number of OLTC operations at HV/MV substation**	**Main utility active power exchange (kW) t_1 t_2 t_3**	**Main utility reactive power exchange (kvar) t_1 t_2 t_3**	**WT (J06) PCC Voltage (p.u.) t_1 t_2 t_3**	**WT (J08) active power (kW) t_1 t_2 t_3**	**Reactive Power window limits exceeded? (YES / NO)**
Case 1 (Fingrid)	No	No	0	-695 -1670 -2735	-207 -136 -20	1,03333 1,03334 1,03262	1485 2460 3520	No
Case 2 (Fingrid)	No	No	0	-753 -1727 -2780	-205 -130 -8	1.00255 1,00231 1,00174	1485 2460 3520	No
Case 3 (Fingrid)	Yes	No	0	6950 5990 4925	1510 1572 1673	1,04763 1,04805 1,04814	1481 2460 3524	Yes
Case 4 (Fingrid)	No	No	0	6450 5470 4180	1352 1420 1468	1,01632 1,01643 1,00148	1480 2457 3518	Yes
Case 1 (ENTSO-E)	No	No	0	-700 -1660 -2736	97 170 285	1,03095 1,03081 1,03028	1483 2460 3521	No
Case 2 (ENTSO-E)	No	No	0	-755 -1726 -2790	100 180 305	1,00008 0,99987 0,99925	1482 2457 3516	No
Case 3 (ENTSO-E)	No	No	0	6825 5850 4788	2550 2620 2730	1,03964 1,03998 1,04000	1487 2464 3527	No
Case 4 (ENTSO-E)	No	No	0	6320 5345 4280	2395 2465 2580	1,00808 1,00836 1,00829	1486 2462 3523	No

t_1 = 20 s, t_2 = 40 s, t_3 = 80 s ; Upper voltage limit (p.u.) = 1,0475

Input sequence for J08 wind turbine (WIND):

Time (s)	Active power (MW)	Ramp (MW/s)
0	0,5	-
10	1,5	0,83
30	2,5	0,47
45	3,6	1,00

Table 17. Cases Wind-B

CASE	Reactive and Active Power Control needs of MV network connected DER units				MV network interactions	MV and LV network interactions	LV network interactions	MV network voltage limits exceeded (YES / NO)	LV network voltage limits exceeded (YES / NO)	Number of OLTC operations at HV/MV substation
	Required Reactive Power Control from WT (J08) to fulfill 'Reactive Power Window' Requirement (kVAr) t_1 t_2 t_3	Required Reactive Power Control from WT (J06) to fulfill 'Reactive Power Window' Requirement (kVAr) t_1 t_2 t_3	Required Reactive Power Control from WT (J06) to maintain local MV voltage in allowed limits (kVAr) t_1 t_2 t_3 *	Required Active Power Limitation from WT (J06) to maintain local voltage in allowed limits (kW) t_1 t_2 t_3 *	Does some event or control action at MV level lead to other control need at MV level? Which one and how much in kWs or kVArs?	Does some event or control action at MV or LV level lead to control need at the other level (e.g. LV demand response to under-frequency)? Which one and how much in kWs or kVArs?	Does some event or control action at LV level lead to other control need at LV level (e.g. LV demand response to under-frequency)? Which one and how much in kWs or kVArs?			
Case 1 (Fingrid)	-362 269 258	NA	-30 -825 -419	0 0 900	No	No	No	No	No	0
Case 2 (Fingrid)	-283 -354 -474	NA	0 0 0	0 0 0	No	No	No	No	No	0
Case 3 (Fingrid)	1045 982 877	NA	0 -139 -802	0 0 0	No	No	No	Yes	Yes	0
Case 4 (Fingrid)	1041 976 860	NA	0 0 0	0 0 0	No	No	No	No	No	0
Case 1 (ENTSO-E)	-717 -445 -266	NA	0 -511 -750	0 0 383	No	No	No	No	No	0
Case 2 (ENTSO-E)	-670 -745 -868	NA	0 0 0	0 0 0	No	No	No	No	No	0
Case 3 (ENTSO-E)	-39 -104 -214	NA	0 -299 0	0 0 0	No	No	No	No	No	0
Case 4 (ENTSO-E)	-42 -110 -226	NA	0 0 0	0 0 0	No	No	No	No	No	0

t_1 = 20 s, t_2 = 35 s, t_3 = 80 s ; NA = Not Assigned ; Upper voltage limit (p.u.) = 1,0475

* the amount of control (change in output) from three time periods (0-t_1, t_1-t_2, t_2-t_3).

Table 18. Cases Wind B

CASE	Main utility active power exchange (kW) t_1 t_2 t_3	Main utility reactive power exchange (kW) t_1 t_2 t_3	WT (J06) PCC Voltage (p.u.) t_1 t_2 t_3	WT (J08) active power (kW) t_1 t_2 t_3	WT (J06) active power (kW) t_1 t_2 t_3	Reactive Power window limits exceeded? (YES / NO)
Case 1 (Fingrid)	-2157 -4235 -5307	-275 360 356	1,03444 1,03050 1,03048	1486 2460 3526	1487 2532 2652	No
Case 2 (Fingrid)	-2216 -4130 -6190	-302 -140 125	1,00384 1,00314 1,00140	1485 2461 3521	1486 2463 3526	No
Case 3 (Fingrid)	5512 3590 1435	1550 1763 2672	1,04863 1,04847 1,04282	1481 2460 3524	1487 2465 3523	Yes
Case 4 (Fingrid)	5000 3090 783	1402 1550 1723	1,01714 1,01741 1,00159	1480 2457 3518	1486 2463 3523	Yes
Case 1 (ENTSO-E)	-2162 -4082 -5780	82 958 952	1,03168 1,02758 1,02592	1483 2460 3525	1487 2463 3142	No
Case 2 (ENTSO-E)	-2218 -4132 -6192	89 255 525	1,00076 1,00002 0,99822	1483 2458 3517	1486 2463 3526	No
Case 3 (ENTSO-E)	5370 3460 1360	2595 2741 3167	1,04058 1,04093 1,03897	1487 2464 3527	1486 2464 3527	No
Case 4 (ENTSO-E)	4865 2957 887	2420 2575 2826	1,00912 1,00933 1,00862	1486 2462 3523	1486 2462 3524	No

$t_1 = 20$ s, $t_2 = 35$ s, $t_3 = 80$ s ; Upper voltage limit (p.u.) = 1,0475

Input sequences of J08 (WIND) and J06 (WIND2) wind turbines:

Time (s)		Active power (MW)		Ramp (MW/s)	
WIND	WIND2	WIND	WIND2	WIND	WIND2
0	0	0,5	0,5	-	-
10	15	1,5	1,5	0,83	0,83
30	25	2,5	2,5	0,47	0,47
45	40	3,6	3,6	1,00	1,00

Table 19. Cases Wind-C

CASE	Reactive and Active Power Control needs of MV network connected DER units				MV network interactions	MV and LV network interactions	LV network interactions	MV network voltage limits exceeded (YES / NO)	LV network voltage limits exceeded (YES / NO)	Number of OLTC operations at HV/MV substation
	Required Reactive Power Control from WT (J08) to fulfill 'Reactive Power Window' Requirement (kVAr) t_1 t_2 t_3	Required Reactive Power Control from WT (J06) to fulfill 'Reactive Power Window' Requirement (kVAr) t_1 t_2 t_3	Required Reactive Power Control from WT (J06) to maintain local MV voltage in allowed limits (kVAr) t_1 t_2 t_3 *	Required Active Power Limitation from WT (J06) to maintain local voltage in allowed limits (kW) t_1 t_2 t_3 *	Does some event or control action at MV level lead to other control need at MV level? Which one and how much in kWs or kVArs?	Does some event or control action at MV or LV level lead to control need at the other level (e.g. LV demand response to under-frequency)? Which one and how much in kWs or kVArs?	Does some event or control action at LV level lead to other control need at LV level (e.g. LV demand response to under-frequency)? Which one and how much in kWs or kVArs?			
Case 1 (Fingrid)	NA	-359 -898 -804	0 -539 94	0 0 880	No	No	No	No	Yes	0
Case 2 (Fingrid)	NA	-284 -355 -467	0 0 0	0 0 0	No	No	No	No	No	0
Case 3 (Fingrid)	NA	1044 984 885	30 62 98	0 0 0	No	No	No	Yes	Yes	0
Case 4 (Fingrid)	NA	1041 977 868	0 0 0	0 0 0	No	No	No	No	No	0
Case 1 (ENTSO-E)	NA	-719 -914 -1286	0 -195 -373	0 0 434	No	No	No	No	Yes	0
Case 2 (ENTSO-E)	NA	-673 -751 -871	0 0 0	0 0 0	No	No	No	No	No	0
Case 3 (ENTSO-E)	NA	-40 -105 -404	0 0 -299	0 0 0	No	No	No	No	Yes	0
Case 4 (ENTSO-E)	NA	-15 -83 -193	0 0 0	0 0 0	No	No	No	No	No	0

t_1 = 20 s, t_2 = 35 s, t_3 = 80 s ; NA = Not assigned ; Upper voltage limit (p.u.) = 1,0475

* the amount of control (change in output) from three time periods (0-t_1, t_1-t_2, t_2-t_3).

Table 20. Cases Wind-C

CASE	**Main utility active power exchange (kW)** **t_1** **t_2** **t_3**	**Main utility reactive power exchange (kvar)** **t_1** **t_2** **t_3**	**WT (J06) PCC Voltage (p.u.)** **t_1** **t_2** **t_3**	**WT (J08) active power (kW)** **t_1** **t_2** **t_3**	**WT (J06) active power (kW)** **t_1** **t_2** **t_3**	**Reactive Power window limits exceeded? (YES / NO)**
Case 1 (Fingrid)	-2160 -4075 -5310	-276 360 380	1,03445 1,03016 1,03029	1487 2464 3530	1486 2460 2645	Yes
Case 2 (Fingrid)	-2215 -4130 -6190	-300 -135 133	1,00382 1,00310 1,00134	1486 2462 3522	1486 2462 3525	No
Case 3 (Fingrid)	5515 3592 1514	1695 1890 2119	1,04750 1,04749 1,04710	1487 2464 3528	1481 2460 3526	Yes
Case 4 (Fingrid)	5015 3107 800	1407 1555 1735	1,01708 1,01737 1,00158	1486 2463 3522	1480 2458 3520	Yes
Case 1 (ENTSO-E)	-2160 -4075 -5730	90 376 890	1,03136 1,03004 1,02640	1486 2464 3525	1484 2460 3090	No
Case 2 (ENTSO-E)	-2216 -4130 -6187	95 267 546	1,00071 0,99991 0,99806	1486 2461 3521	1483 2460 3521	No
Case 3 (ENTSO-E)	5375 3462 1362	2595 2740 3168	1,04058 1,04093 1,03897	1487 2464 3527	1486 2464 3527	No
Case 4 (ENTSO-E)	4868 2957 890	2420 2575 2825	1,00912 1,00933 1,00862	1486 2462 3523	1486 2462 3524	No

t_1 = 20 s, t_2 = 35 s, t_3 = 80 s ; (X) = Distorted signal ; Upper voltage limit (p.u.) = 1,0475

Input sequences of J08 (WIND) and J06 (WIND2) wind turbines:

Time (s)		Active power (MW)		Ramp (MW/s)	
WIND	WIND2	WIND	WIND2	WIND	WIND2
0	0	0,5	0,5	-	-
10	15	1,5	1,5	0,83	0,83
30	25	2,5	2,5	0,47	0,47
45	40	3,6	3,6	1,00	1,00

Table 21. Cases Wind-D

CASE	**Reactive and Active Power Control needs of MV network connected DER units**				**MV network interactions**	**MV and LV network interactions**	**LV network interactions**	**MV network voltage limits exceeded (YES / NO)**	**LV network voltage limits exceeded (YES / NO)**	**Number of OLTC operations at HV/MV substation**
	Required Reactive Power Control from WT (J08) to fulfill ‘Reactive Power Window’ Requirement (kVAr) t_1 t_2 t_3	**Required Reactive Power Control from WT (J06) to fulfill ‘Reactive Power Window’ Requirement (kVAr)** t_1 t_2 t_3	**Required Reactive Power Control from WT (J06) to maintain local MV voltage in allowed limits (kVAr)** t_1 t_2 t_3 *	**Required Active Power Limitation from WT (J06) to maintain local voltage in allowed limits (kW)** t_1 t_2 t_3 *	**Does some event or control action at MV level lead to other control need at MV level? Which one and how much in kWs or kVArs?**	**Does some event or control action at MV or LV level lead to control need at the other level (e.g. LV demand response to under-frequency)? Which one and how much in kWs or kVArs?**	**Does some event or control action at LV level lead to other control need at LV level (e.g. LV demand response to under-frequency)? Which one and how much in kWs or kVArs?**			
Case 1 (Fingrid)	-197 -98 240	-197 -898 -1227	0 -701 -329	0 0 882	No	No	No	No	Yes	0
Case 2 (Fingrid)	-162 -233 -351	-162 -231 -342	0 0 0	0 0 0	No	No	No	No	No	0
Case 3 (Fingrid)	375 983 880	1045 319 -35	31 726 284	0 0 0	No	No	No	Yes	Yes	0
Case 4 (Fingrid)	817 828 817	818 838 844	0 0 0	0 0 0	No	No	No	No	No	0
Case 1 (ENTSO-E)	-374 -443 -287	-376 -729 -1274	0 -353 -545	0 0 393	No	No	No	No	Yes	0
Case 2 (ENTSO-E)	-355 -429 -549	-358 -430 -545	0 0 0	0 0 0	No	No	No	No	No	0
Case 3 (ENTSO-E)	-39 -105 -214	-40 -105 -404	0 0 -294	0 0 0	No	No	No	No	Yes	0
Case 4 (ENTSO-E)	-41 -111 -226	-15 -83 -193	0 0 0	0 0 0	No	No	No	No	No	0

$t_1 = 20$ s, $t_2 = 35$ s, $t_3 = 80$ s

* the amount of control (change in output) from three time periods (0-t_1, t_1-t_2, t_2-t_3).

Table 22. Cases Wind-D

CASE	Main utility active power exchange (kW) t_1 t_2 t_3	Main utility reactive power exchange (kvar) t_1 t_2 t_3	WT (J06) PCC Voltage (p.u.) t_1 t_2 t_3	WT (J08) active power (kW) t_1 t_2 t_3	WT (J06) active power (kW) t_1 t_2 t_3	Reactive Power window limits exceeded? (YES / NO)
Case 1 (Fingrid)	-2160 -4075 -5303	-274 358 357	1,03443 1,03018 1,03047	1486 2464 3526	1487 2460 2643	Yes
Case 2 (Fingrid)	-2215 -4130 -6192	-300 -137 128	1,00384 1,00312 1,00137	1486 2461 3521	1486 2463 3526	No
Case 3 (Fingrid)	5585 3655 1540	1156 1284 1756	1,05161 1,05213 1,04989	1486 2460 3525	1481 2465 3530	Yes
Case 4 (Fingrid)	5094 3204 920	794 783 751	1,02186 1,02337 1,00933	1482 2459 3519	1482 2460 3522	No
Case 1 (ENTSO-E)	-2162 -4080 -5770	86 534 955	1,03165 1,02881 1,02590	1486 2462 3525	1486 2462 3132	No
Case 2 (ENTSO-E)	-2220 -4132 -6192	92 261 535	1,00074 0,99996 0,99814	1485 2460 3520	1485 2462 3524	No
Case 3 (ENTSO-E)	5375 3460 1362	2595 2740 3167	1,04058 1,04093 1,03897	1485 2464 3527	1486 2464 3527	No
Case 4 (ENTSO-E)	4868 2957 887	2420 2575 2825	1,00912 1,00933 1,00862	1486 2462 3523	1486 2462 3524	No

$t_1 = 20$ s, $t_2 = 35$ s, $t_3 = 80$ s

Input sequences of J08 (WIND) and J06 (WIND2) wind turbines:

Time (s)		Active power (MW)		Ramp (MW/s)	
WIND	WIND2	WIND	WIND2	WIND	WIND2
0	0	0,5	0,5	-	-
10	15	1,5	1,5	0,83	0,83
30	25	2,5	2,5	0,47	0,47
45	40	3,6	3,6	1,00	1,00

Table 23. Cases PV-A

CASE	Reactive and Active Power Control needs of MV network connected DER units	MV network interactions	MV and LV network interactions	LV network interactions	Reactive and Active Power Control needs of LV network connected DER units			
	Required Reactive Power Control from WT (J08) to fulfill 'Reactive Power Window' Requirement (kVAr) t_1 t_2 t_3	Does some event or control action at MV level lead to other control need at MV level? Which one and how much in kWs or kVArs?	Does some event or control action at MV or LV level lead to control need at the other level (e.g. LV demand response to under-frequency)? Which one and how much in kWs or kVArs?	Does some event or control action at LV level lead to other control need at LV level (e.g. LV demand response to under-frequency)? Which one and how much in kWs or kVArs? *	Required Reactive Power Control from PV (which one) to fulfill 'Islanding Detection Enabling' Requirement (kVAr)	Required Reactive Power Control from PV (which one) to maintain local LV voltage in allowed limits (kVAr) *	Required Active Power Limitation from PV (which one) to maintain local LV voltage in allowed limits (kW)	Required Active Power Limitation from PV (which one) to whole power system frequency during over-frequencies (between 50.1 – 50.3 Hz) (kW)
Case 1 (Fingrid)	-51 -118 -372	No	No	PVs 2, 3, 4, 6, 7, 8 (-12…12 kvar)	NA	0	0	NA
Case 2 (Fingrid)	-40 -110 -318	No	No	PVs 2, 3 (-12…12 kvar)	NA	PVs 4, 6, 7, 8 (-12…12)	0	NA
Case 3 (Fingrid)	1045 983 880	No	No	No	NA	0	0	NA
Case 4 (Fingrid)	1041 976 860	No	No	No	NA	0	0	NA
Case 1 (ENTSO-E)	-493 -562 -813	No	No	PVs 2, 3, 4, 6, 7, 8 (-12…12 kvar)	NA	0	0	NA
Case 2 (ENTSO-E)	-446 -520 -756	No	No	PVs 2, 3 (-12…12 kvar)	NA	PVs 4, 6, 7, 8 (-12…12)	0	NA
Case 3 (ENTSO-E)	-38 -104 -212	No	No	No	NA	0	0	NA
Case 4 (ENTSO-E)	-42 -112 -227	No	No	No	NA	0	0	NA

t_1 = 20 s, t_2 = 40 s, t_3 = 100 s ; NA = Not Assigned

* LV network interactions: The reactive power of the PV-units react to under frequency period. The change in output is presented in this column.

Table 24. Cases PV-A

CASE	Main utility active power exchange (kW) t_1 t_2 t_3	Main utility reactive power exchange (kW) t_1 t_2 t_3	WT (J08) active power (kW) t_1 t_2 t_3	MV network voltage limits exceeded (YES / NO)	LV network voltage limits exceeded (YES / NO)	Number of OLTC operations at HV/MV substation	Reactive Power window limits exceeded? (YES / NO)
Case 1 (Fingrid)	-2375 -3350 -4412	-405 -338 -80	1487 2464 3526	No	No	**0**	No
Case 2 (Fingrid)	-2430 -3402 -4452	-369 -298 -85	1486 2462 3522	No	No	0	No
Case 3 (Fingrid)	5280 4308 3245	1651 1716 1820	1481 2460 3524	Yes	No	0	Yes
Case 4 (Fingrid)	4778 3800 2500	1512 1580 1632	1480 2457 3518	No	No	0	Yes
Case 1 (ENTSO-E)	-2380 -3353 -4415	40 112 367	1485 2462 3522	No	No	0	No
Case 2 (ENTSO-E)	-2431 -3405 -4465	41 118 359	1484 2460 3518	No	No	0	No
Case 3 (ENTSO-E)	5145 4172 3110	2700 2766 2875	1487 2464 3527	No	No	0	No
Case 4 (ENTSO-E)	4635 3665 2605	2560 2632 2748	1486 2462 3523	No	No	0	No

$t_1 = 20$ s, $t_2 = 40$ s, $t_3 = 100$ s

Input sequence for J08 wind turbine (WIND):

Time (s)	Active power (MW)	Ramp (MW/s)
0	0,5	-
10	1,5	0,83
30	2,5	0,47
45	3,6	1,00

Table 25. Cases PV-B

CASE	**Reactive and Active Power Control needs of MV network connected DER units**	**MV network interactions**	**MV and LV network interactions**	**LV network interactions**	**Reactive and Active Power Control needs of LV network connected DER units**			
	Required Reactive Power Control from WT (J08) to fulfill 'Reactive Power Window' Requirement (kVAr) **t_1** **t_2** **t_3**	**Does some event or control action at MV level lead to other control need at MV level? Which one and how much in kWs or kVArs?**	**Does some event or control action at MV or LV level lead to control need at the other level (e.g. LV demand response to under-frequency)? Which one and how much in kWs or kVArs?**	**Does some event or control action at LV level lead to other control need at LV level (e.g. LV demand response to under-frequency)? Which one and how much in kWs or kVArs? ***	**Required Reactive Power Control from PV (which one) to fulfill 'Islanding Detection Enabling' Requirement (kVAr)** **PV 2, PV4**	**Required Reactive Power Control from PV (which one) to maintain local LV voltage in allowed limits (kVAr)**	**Required Active Power Limitation from PV (which one) to maintain local LV voltage in allowed limits (kW)**	**Required Active Power Limitation from PV (which one) to whole power system frequency during over-frequencies (between 50.1 – 50.3 Hz) (kW)**
Case 1 (Fingrid)	-39 -106 -24	No	No	PV4 (-18 kvar) PV6 (-14 kvar) PV7 (-7 kvar) PV8 (-12 kvar)	-100, -82 -100, -82 -100, -100	0	PV3 (103)	NA
Case 2 (Fingrid)	-40 -110 -204	No	No	PV2 (-8 kvar) PV4 (-16 kvar) PV6 (-14 kvar) PV7 (-10 kvar) PV8 (-17 kvar)	-92, -22 -92, -22 -100, -38	0	PV3 (30)	NA
Case 3 (Fingrid)	1044 982 879	No	No	No	-100, -42 -100, -43 -100, -43	0	PV2 (35) PV3 (133)	NA
Case 4 (Fingrid)	1041 975 866	No	No	No	-100, -0.24 -100, -0.24 -100, -0.24	0	PV3 (59)	NA
Case 1 (ENTSO-E)	-472 -542 -626	No	No	PV4 (-17 kvar) PV6 (-14 kvar) PV7 (-8 kvar) PV8 (-16 kvar)	-100, -75 -100, -75 -100, -92	0	PV3 (97)	NA
Case 2 (ENTSO-E)	-427 -502 -623	No	No	PV2 (-12 kvar) PV4 (-16 kvar) PV6 (-14 kvar) PV7 (-11 kvar) PV8 (-17 kvar)	-85, -16 -85, -16 -98, -32	0	PV3 (29)	NA
Case 3 (ENTSO-E)	-38 -104 -213	No	No	No	-100, -27 -100, -27 -100, -27	0	PV3 (115)	NA
Case 4 (ENTSO-E)	-42 -112 -227	No	No	No	-97, -0.24 -97, -0.24 -98, -0.24	0	PV3 (40)	NA

$t_1 = 20$ s, $t_2 = 40$ s, $t_3 = 100$ s

* LV network interactions: The reactive power of the PV-units react to under frequency period. One measurement is taken just before 70 s. and one after 85 s. when the signals have been leveled. For example, the output of PV4 is about -82 kvar before and -100 kvar after the under frequency so the change in output is -18 kvar.

Table 26. Cases PV-B

CASE	Main utility active power exchange (kW) t_1 t_2 t_3	Main utility reactive power exchange (kW) t_1 t_2 t_3	WT (J08) active power (kW) t_1 t_2 t_3	MV network voltage limits exceeded (YES / NO)	LV network voltage limits exceeded (YES / NO)	Number of OLTC operations at HV/MV substation	Reactive Power window limits exceeded? (YES / NO)
Case 1 (Fingrid)	-2284 -3250 -4316	161 229 202	1486 2464 3526	No	No	0	No
Case 2 (Fingrid)	-2395 -3370 -4434	-40 30 200	1486 2462 3522	No	No	0	No
Case 3 (Fingrid)	5380 4410 3346	1927 1992 2098	1481 2459 3524	No	No	0	Yes
Case 4 (Fingrid)	4800 3830 2768	1710 1776 1887	1480 2457 3520	No	No	0	Yes
Case 1 (ENTSO-E)	-2295 -3270 -4330	571 643 790	1485 2462 3523	No	No	0	No
Case 2 (ENTSO-E)	-2402 -3378 -4440	321 396 600	1484 2460 3519	No	No	0	No
Case 3 (ENTSO-E)	5210 4238 3175	2924 2992 3102	1487 2464 3527	No	No	0	No
Case 4 (ENTSO-E)	4657 3686 2624	2723 2795 2912	1486 2462 3523	No	No	0	No

$t_1 = 20$ s, $t_2 = 40$ s, $t_3 = 100$ s

Input sequence for J08 wind turbine (WIND):

Time (s)	Active power (MW)	Ramp (MW/s)
0	0,5	-
10	1,5	0,83
30	2,5	0,47
45	3,6	1,00

Table 27. Cases PV-C

CASE	**Reactive and Active Power Control needs of MV network connected DER units**	**MV network interactions**	**MV and LV network interactions**	**LV network interactions**	**Reactive and Active Power Control needs of LV network connected DER units**			
	Required Reactive Power Control from WT (J08) to fulfill 'Reactive Power Window' Requirement (kVAr) t_1 t_2 t_3	**Does some event or control action at MV level lead to other control need at MV level? Which one and how much in kWs or kVArs?**	**Does some event or control action at MV or LV level lead to control need at the other level (e.g. LV demand response to under-frequency)? Which one and how much in kWs or kVArs?**	**Does some event or control action at LV level lead to other control need at LV level (e.g. LV demand response to under-frequency)? Which one and how much in kWs or kVArs?**	**Required Reactive Power Control from PV (which one) to fulfill 'Islanding Detection Enabling' Requirement (kVAr)** **PV2 PV4**	**Required Reactive Power Control from PV (which one) to maintain local LV voltage in allowed limits (kVAr) ***	**Required Active Power Limitation from PV (which one) to maintain local LV voltage in allowed limits (kW)**	**Required Active Power Limitation from PV (which one) to whole power system frequency during over-frequencies (between 50.1 – 50.3 Hz) (kW)**
Case 1 (Fingrid)	-39 -106 -156	No	No	No	-100, -82 -100, -82 -100, -82	PV7 (7) PV8 (3)	PV3 (100)	PVs 2, 4, 6, 7, 8 (150) PV3 (50)
Case 2 (Fingrid)	-40 -110 -227	No	No	No	-92, -22 -92, -22 -93, -21	PV2 (-1) PV4 (1) PV6 (2) PV7 (5) PV8 (2)	PV3 (35)	PVs 2, 4, 6, 7, 8 (150) PV3 (115)
Case 3 (Fingrid)	1044 982 879	No	No	No	-100, -42 -100, -43 -100, -43	PV7 (1)	PV2 (34) PV3 (133)	PVs 4, 6 ,7 ,8 (150) PV2 (116) PV3 (17)
Case 4 (Fingrid)	1041 975 866	No	No	No	-100, -0.24 -100, -0.24 -100, 17	PV4 (17) PV6 (40) PV7 (30) PV8 (40)	PV3 (59)	PVs 2, 4, 6, 7, 8 (150) PV3 (91)
Case 1 (ENTSO-E)	-472 -542 -657	No	No	No	-100, -75 -100, -75 -100, -75	PV6 (1) PV7 (11) PV8 (4)	PV3 (97)	PVs 2, 4, 6, 7, 8 (150) PV3 (53)
Case 2 (ENTSO-E)	-427 -502 -623	No	No	No	-85, -16 -85, -16 -90, -15	PV2 (-5) PV4 (1) PV6 (2) PV7 (5) PV8 (2)	PV3 (29)	PVs 2, 4, 6, 7, 8 (150) PV3 (121)
Case 3 (ENTSO-E)	-38 -104 -213	No	No	No	-100, -27 -100, -27 -100, -27	PV7 (1)	PV3 (115)	PVs 2, 4, 6, 7, 8 (150) PV 3 (35)
Case 4 (ENTSO-E)	-42 -112 -227	No	No	No	-97, -0.24 -97, -0.24 -100, 33	PV2 (-2) PV4 (33) PV6 (40) PV7 (40) PV8 (40)	PV3 (40)	PVs 2, 4, 6, 7, 8 (150) PV3 (110)

$t_1 = 20$ s, $t_2 = 40$ s, $t_3 = 100$ s

* The change in PVs' reactive power output caused by the over frequency period

Table 28. Cases PV- C

CASE	Main utility active power exchange (kW) t_1 t_2 t_3	Main utility reactive power exchange (kW) t_1 t_2 t_3	WT (J08) active power (kW) t_1 t_2 t_3	MV network voltage limits exceeded (YES / NO)	LV network voltage limits exceeded (YES / NO)	Number of OLTC operations at HV/MV substation	Reactive Power window limits exceeded? (YES / NO)
Case 1 (Fingrid)	-2283 -3260 -4320	160 230 268	1486 2464 3526	No	No	0	No
Case 2 (Fingrid)	-2395 -3370 -4430	-40 30 140	1486 2462 3522	No	No	0	No
Case 3 (Fingrid)	5380 4410 3346	1927 1993 2097	1481 2459 3524	No	No	0	Yes
Case 4 (Fingrid)	4802 3830 2794	1710 1776 1759	1480 2457 3520	No	No	0	Yes
Case 1 (ENTSO-E)	-2295 -3271 -4332	572 644 745	1485 2462 3523	No	No	0	No
Case 2 (ENTSO-E)	-2400 -3378 -4438	320 396 515	1484 2460 3519	No	No	0	No
Case 3 (ENTSO-E)	5210 4237 3175	2924 2993 3102	1487 2464 3527	No	No	0	No
Case 4 (ENTSO-E)	4658 3685 2656	2722 2795 2762	1486 2462 3523	No	No	0	No

$t_1 = 20$ s, $t_2 = 40$ s, $t_3 = 100$ s.

Input sequence for J08 wind turbine (WIND):

Time (s)	Active power (MW)	Ramp (MW/s)
0	0,5	-
10	1,5	0,83
30	2,5	0,47
45	3,6	1,00

Table 29. Cases PV-D

CASE	Reactive and Active Power Control needs of MV network connected DER units	MV network interactions	MV and LV network interactions	LV network interactions	Reactive and Active Power Control needs of LV network connected DER units			
	Required Reactive Power Control from WT (J08) to fulfill 'Reactive Power Window' Requirement (kVAr) t_1 t_2 t_3	Does some event or control action at MV level lead to other control need at MV level? Which one and how much in kWs or kVArs?	Does some event or control action at MV or LV level lead to control need at the other level (e.g. LV demand response to under-frequency)? Which one and how much in kWs or kVArs?	Does some event or control action at LV level lead to other control need at LV level (e.g. LV demand response to under-frequency)? Which one and how much in kWs or kVArs?	Required Reactive Power Control from PV (which one) to fulfill 'Islanding Detection Enabling' Requirement (kVAr) PV2 PV4	Required Reactive Power Control from PV (which one) to maintain local LV voltage in allowed limits (kVAr) *	Required Active Power Limitation from PV (which one) to maintain local LV voltage in allowed limits (kW)	Required Active Power Limitation from PV (which one) to whole power system frequency during over-frequencies (between 50.1 – 50.3 Hz) (kW)
Case 1 (Fingrid)	-312 -381 -403	No	No	No	-100, -84 -100, -84 -100, -84	PV7 (8) PV8 (3)	PV3 (140)	PVs 2, 4, 6, 7, 8 (150) PV3 (32)
Case 2 (Fingrid)	-247 -319 -438	No	No	No	-100, -25 -100, -25 -97, -23	PV2 (2) PV4 (2) PV6 (2) PV7 (4) PV8 (2)	PV3 (50)	PVs 2, 4, 6, 7, 8 (150) PV3 (100)
Case 3 (Fingrid)	-39 -104 -212	No	No	No	-100, -65 -100, -66 -100, -66	PV7 (2) PV8 (1)	PV2 (23) PV3 (140)	PVs 4, 6, 7, 8 (150) PV2 (127) PV3 (10)
Case 4 (Fingrid)	-40 -109 -223	No	No	No	-100, -5 -100, -5 -100, -5	PV7 (10) PV8 (13)	PV3 (66)	PVs 2, 4, 6, 7, 8 (150) PV3 (84)
Case 1 (ENTSO-E)	-757 -829 -947	No	No	No	-100, -77 -100, -77 -100, -77	PV6 (2) PV7 (9) PV8 (5)	PV3 (112)	PVs 2, 4, 6, 7, 8 (150) PV3 (38)
Case 2 (ENTSO-E)	-684 -760 -883	No	No	No	-92, -18 -92, -18 -94, -16	PV4 (2) PV6 (2) PV7 (4) PV8 (2)	PV3 (43)	PVs 2, 4, 6, 7, 8 (150) PV3 (107)
Case 3 (ENTSO-E)	-39 -104 -212	No	No	No	-100, -65 -100, -66 -100, -66	PV7 (3) PV8 (1)	PV2 (27) PV3 (140)	PVs 4, 6, 7, 8 (150) PV2 (123) PV3 (10)
Case 4 (ENTSO-E)	-40 -109 -223	No	No	No	-100, -4 -100, -5 -100, -5	PV6 (13) PV7 (12) PV8 (13)	PV3 (67)	PVs 2, 4, 6, 7, 8 (150) PV3 (83)

$t_1 = 20$ s, $t_2 = 40$ s, $t_3 = 100$ s.

* The change in PVs' reactive power output caused by the over frequency period

Table 30. Cases PV-D

CASE	**Main utility active power exchange (kW)** **t_1** **t_2** **t_3**	**Main utility reactive power exchange (kW)** **t_1** **t_2** **t_3**	**WT (J08) active power (kW)** **t_1** **t_2** **t_3**	**MV network voltage limits exceeded (YES / NO)**	**LV network voltage limits exceeded (YES / NO)**	**Number of OLTC operations at HV/MV substation**	**Reactive Power window limits exceeded? (YES / NO)**
Case 1 (Fingrid)	-2208 -3185 -4245	189 258 268	1486 2463 3525	No	No	0	No
Case 2 (Fingrid)	-2322 -3300 -4358	-65 8 118	1485 2461 3521	No	No	0	No
Case 3 (Fingrid)	6695 5730 4670	110 177 283	1487 2464 3528	No	No	0	No
Case 4 (Fingrid)	6076 5106 4056	-45 23 100	1486 2462 3523	No	No	0	No
Case 1 (ENTSO-E)	-2219 -3195 -4257	612 687 790	1483 2459 3521	No	No	0	No
Case 2 (ENTSO-E)	-2332 -3308 -4366	342 421 539	1483 2458 3517	No	No	0	No
Case 3 (ENTSO-E)	6700 5728 4670	111 177 284	1487 2464 3528	No	No	0	No
Case 4 (ENTSO-E)	6077 5107 4056	-46 23 100	1486 2462 3523	No	No	0	No

$t_1 = 20$ s, $t_2 = 40$ s, $t_3 = 100$ s

Input sequence for J08 wind turbine (WIND):

Time (s)	Active power (MW)	Ramp (MW/s)
0	0,5	-
10	1,5	0,83
30	2,5	0,47
45	3,6	1,00