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RESEARCH ARTICLE

Advanced Distributed Energy Resources and On-Load Tap-Changer Control Principles for Enhanced Flexibility Services Provision

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ABSTRACT Due to large-scale integration of variable renewable generation and accelerating electrification of transportation and heating sectors as well as industrial processes, increased amount of flexibility is needed from different voltage levels to fulfill simultaneously the flexibility needs of local distribution system operators (DSOs) and system-wide transmission system operator (TSO). This paper develops further the coordinated and frequency level-dependent distributed energy resources (DERs) control and adaptive on-load-tap-changers (OLTCs) management scheme which enables prioritized flexibility services provision for the DSOs and TSO. The key idea of the scheme is that the coordination of flexibility utilisation between DSOs and TSOs is done depending on the severity of the situation from the whole power system's viewpoint regarding frequency deviation level. During smaller frequency deviations DSOs' needs are prioritized and during larger frequency deviations priority is on TSO's needs to support momentarily the stability of the whole power system. The overall target of the studied management scheme is also to increase DERs', especially photovoltaics' (PVs') and electric vehicles' (EVs'), hosting capacity in the DSOs' networks and increase DERs availability for the flexibility services provision to the TSO during smaller frequency deviations. In this paper, enhanced OLTC control principles are presented including novel interconnection transformer OLTC control scheme for larger medium-voltage (MV) network-connected DER units. This MV DER OLTC control logic can enable, for example, same DER active power response with 7.7% smaller current or 8.5% higher DER unit active power response with the same current value. In addition, this paper studies the effect of different OLTC control inputs, DER reactive power control settings, LV feeder length and large-scale integration of EVs on low-voltage (LV) network with multiple PSCAD simulations. At the end, further improvement possibilities of the studied management scheme are also briefly described.

INDEX TERMS Distributed energy resources, flexibility services, frequency control, voltage control, active network management.

I. INTRODUCTION

A. BACKGROUND

In the future, coordinated control of DERs and OLTCs could be used to fulfill increasing flexibility and resiliency needs of the DSOs and TSOs. Flexibility services from the DERs can support the power system frequency (f) and local voltage (U) or congestion management at the corresponding voltage level. The effective use of different active (P) and reactive power (Q) control or voltage level control -based flexibility services could be achieved by advanced and coordinated control of DERs and OLTCs. Fig. 1 shows the different DER and OLTC control possibilities for the TSOs and DSOs. In general, from the DSO perspective priority during

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normal power system operation (i.e. during smaller frequency deviations) should be on solving local problems locally by distribution network-connected flexibilities like DERs and OLTCs. Possible conflict of interest between DSOs and TSO in the use of the flexibility services from these resources should be avoided by enhanced TSO-DSO coordinated control principles, state-forecasting and -monitoring. In addition, different DER units' P and Q control modes, settings and coordination with OLTC settings and other active network management (ANM) functionalities should be increasingly considered already in the operation planning phase [1], [2], [3], [4], [5], [6], [7], [8].

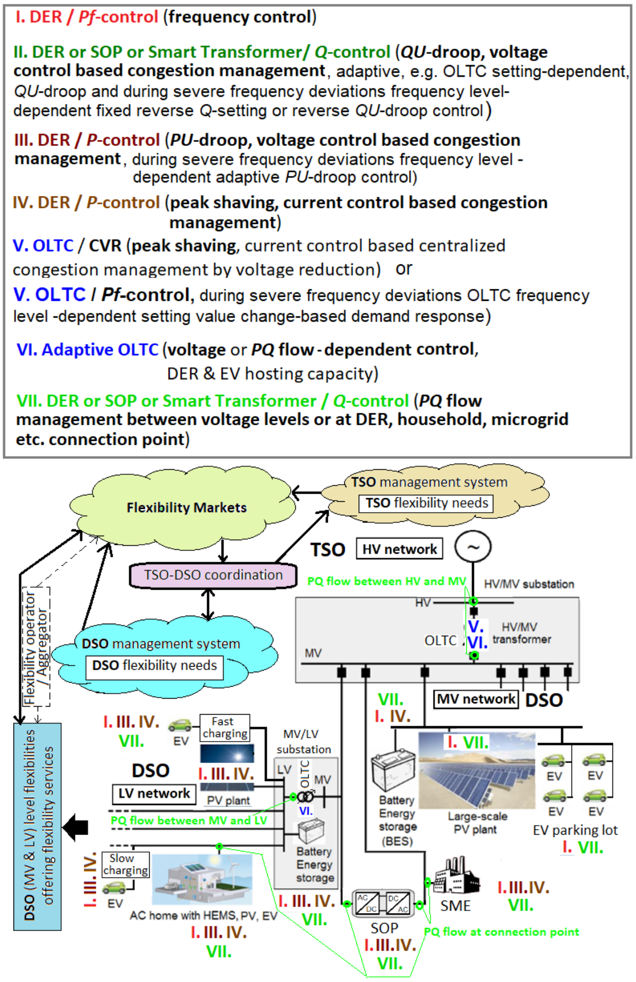


FIGURE 1. DERs' and OLTCs' control possibilities to increase flexibilities availability for the flexibility services provision and DER hosting capacity enhancement [8].

This paper develops further the coordinated, adaptive and frequency level-dependent DERs' and OLTCs' control and management scheme from [8] as well as the previous studies [9], [10], [11], [12], [13], [14] which enables prioritized flexibility services provision for the DSOs and TSO. The main idea is that the coordination between DSOs and TSOs regarding flexibility utilisation is based on the severity of the frequency deviation (see Fig. 2). During smaller frequency deviations (level 1 and 2, Fig. 2) priority is on the DSOs' needs and during larger frequency deviations (level 3 and 4, Fig. 2) TSO's needs are prioritized. The general aim of the holistic TSO-DSO coordinated DERs and OLTCs control and management scheme is to increase DERs' hosting capacity in the DSOs' network as well as increase the availability of DERs for flexibility services provision to the TSO during smaller frequency deviations. Fig. 2 summarizes the DER (Fig. 2a) and OLTC (Fig. 2b) related flexibility services of the proposed scheme. In the proposed scheme, DERs' (Fig. 2a) reactive power-voltage (QU), active power-voltage (PU) and active power-frequency (Pf) droop control and OLTCs' (Fig. 2b) management principles are adapted depending on the frequency deviation severity (level) so that in case of larger frequency deviations (level 3 or 4) priority is on the whole power system support and TSO needs. Adaptation of control principles or settings is done based on local frequency measurements and therefore there are no communication related time delays in the adaptation.

As already stated in [8], [9], [10], [11], [12], [13], and [14], the connection point of each DER in the distribution network (i.e. location of DER) needs to be considered when feasible P and Q control methods, settings and principles of different DER units (Figs. 1 and 2a) are determined and chosen as part of the proposed scheme. For example:

- Utilisation of reactive power capabilities of the DSO network-connected DERs', which are located close to the HV/MV substation, for the Q-flow control to support TSO's (high-voltage) HV network reactive power needs is more feasible than the utilisation of reactive power resources located far away from HV network connection point, i.e. deep in MV or LV network.
- Utilisation of DERs' reactive power deep in the MV or LV (DSO) network for the provision of local flexibility services, e.g. for voltage control, is more feasible than their utilisation to provide services for the HV network and TSO needs (Q-flow control).
- Active Q-flow management (Fig. 2a) to ensure the detection of islanding with traditional passive methods [9], [10], [11] as part of the combined islanding detection schemes has not been utilized in the simulations of this paper, but it is part of the overall concept so that DER units close to HV/MV or MV/LV substation (at the frequency levels 1-2) are utilized for the Q-flow management through communication.
- In [14], the studied control schemes and settings of the MV DERs (e.g. QU- and PU-control) in the middle of MV feeder were different than with the DERs connected directly at HV/MV substation like in this paper as well as previously in [8].

Flexibilities efficient utilisation for the DSO and TSO needs requires also compatible tariff, pricing and/or flexibility market structures. In [13], an example about DSO network-connected DERs participation on the provision of TSO frequency control services (Fig. 1) through different markets by considering the location and type of DER as well as possible DSO network congestions has been presented.

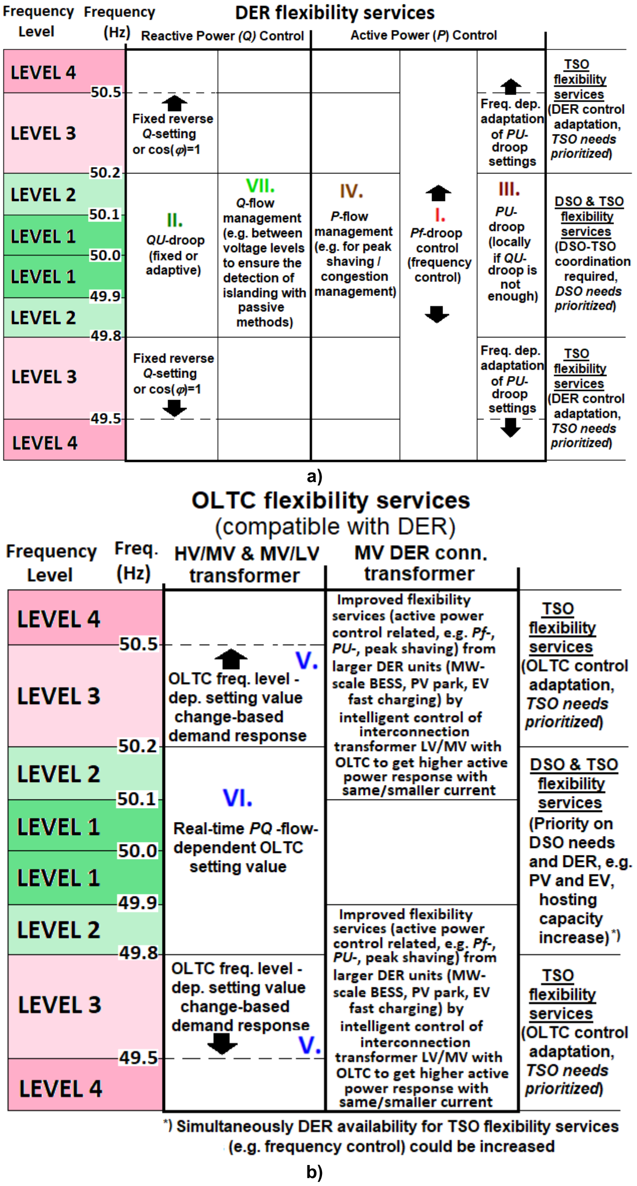


FIGURE 2. a) DERs' and b) OLTCs' flexibility services in the proposed TSO-DSO coordinated and frequency level-dependent control and management scheme (see Fig. 1).

B. OBJECTIVES AND ORGANIZATION

In this paper, enhanced OLTC control principles are presented including, for example

- Novel MV/LV interconnection transformer OLTC's control scheme for larger MV network-connected DER units.
  - It can enable improved flexibility services provision (active power control related, e.g. *Pf*-, *PU*-, peak shaving) from the larger DER units (like MW-scale battery energy storage system (BESS), PV park, EV fast charging) and has an effect on sizing of inverters (can reduce it) and operation with e.g. second-life or aged BESSs (can improve it).
  - Regarding OLTC flexibility services of MV DER MV/LV interconnection transformer in Fig. 2b), it should be noted that higher active power P response with same or smaller current is dependent on the actual control scheme implementation of the DER and it can be, for example, higher P response with same current or same P response with smaller current. In this paper, used control logic enabled, for example, same MV BESS P response during level 3 under-frequency (Fig. 2) with 7.7% smaller current and simultaneously MV PV was able to feed 8.5% more active power P to the network with the same current based on its interconnection OLTC's control logic.
- Description of HV/MV OLTC frequency-dependent control blocking logic when frequency deviation from nominal is more than ± 0.2 Hz and MV network P load is less than 0.2 MW. Respectively, with MV/LV OLTC frequency-dependent control blocking logic is used if LV network P load is less than 0 MW (directly at MV or LV bus connected DERs' active powers are not considered in the blocking logic).
- MV/LV transformer's OLTC's (at the secondary substation in distribution network) active power load - dependent adaptive setting at frequency levels 3-4.

In addition, this paper studies the effect of different OLTC control inputs, DER reactive power control settings, LV feeder length and large-scale integration of EVs on the LV network with multiple PSCAD simulations as follows:

- *PQ*-flow input for HV/MV OLTC can be either a) *PQ*-flow through e.g. HV/MV transformer or b) sum of P and Q flows from MV feeders (excluding DER units which are directly connected at the HV/MV substation).
- Effect of steeper LV network connected PV *QU*-droop without deadzone on voltage fluctuations and reactive power feeding/absorbing of LV and MV network connected DER.
- Effect of LV feeder length and charging of EVs in LV network
  - LV feeder length 600 m instead of 200 m (like in [8] and [14])
  - EV charging in LV network instead of PV generation (like in [8] and [14]).

At the end, further improvement possibilities of the proposed control and management scheme are briefly described.

In the following, Section II shortly presents the paper topics related state-of-the-art by a brief literature review. Then, Section III presents the simulation models and study cases. After that, the simulation results are presented in Section IV. Section V describes the further development possibilities and conclusions are stated in Section VI.

II. STATE-OF-THE-ART

In general, flexibility utilisation for the distribution networks' real-time and short-term operational planning requires accurate and advanced forecasting. Network state-forecasting enables the detection of network congestions and limitation in hosting capacity of the network. However, accurate state-forecasting requires also accurate load, generation, flexibility need and availability, topology etc. knowledge as inputs. Multi-timescale and multi-source advanced forecasts could enable short-term operational planning from 15 min to day-ahead effectively and could be realized in the future e.g. through dynamic tariffs (or distribution use of system charges) and/or flexibility marketplaces. The future real-time and short-term operation requires also increased TSO-DSO coordination, new operation planning tools and methods as well as supporting digital architecture enabling use of digital twins.

In this Section II, the proposed coordinated and frequency level-dependent DERs' and OLTCs' control and management scheme related state-of-the-art literature is briefly reviewed. In the following, the brief literature review is divided into following subsections:

a) Advanced forecasts and TSO-DSO coordination for improved flexibility utilisation,

b) Voltage control and congestion management to improve DER hosting capacity and

c) Market structures & platforms and regulation for enhanced flexibility utilisation.

A. ADVANCED FORECASTS AND TSO-DSO COORDINATION FOR IMPROVED FLEXIBILITY UTILISATION

Accurate real-time and short-term forecasts about MV and LV network loads [88], [89], local needs and availability of active and reactive power [19] flexibilities at different parts of the network is of importance for improved flexibility utilization in the operation of future distribution and transmission networks [12], [13], [20]. Traditional forecasting methods may not be sufficient to deal with different uncertainties e.g. related to aggregated flexibility forecasting of smart homes [21] or energy communities [22]. Therefore, for example, AI-based [22] or probabilistic [23] forecasts might be increasingly needed for future flexibility needs and availability prediction.

Increasing research interest has recently been also on aggregated DSO flexibility forecasting at TSO-DSO interconnection point (e.g. at the HV/MV substation). Related to this there is a need for determination of allowed operating envelope or feasible operating region at the TSO-DSO interconnection point which means practically operation limits for the active P and reactive Q power flows between DSO and TSO networks in order to prevent e.g. unwanted mutual effects if DSO network connected flexibilities are used for flexibility services provision to the TSO needs [3], [24], [25], [26], [27], [28], [29], [30], [31], [32], [90], [97].

Regarding system operators' flexibility needs forecasting, increasing need will be in future inverter-based, low-inertia power systems on inertia forecasting [33], [91], reactive power forecasting [34], [35], power flow forecasting [92], as well as on determination of the impact of day-ahead renewable forecasts on DER hosting capacity estimation [36]. Operating envelopes can be also determined for the LV customers' connection points or MV/LV interconnection points at the secondary substations by using smart meter data and neural networks [37].

Aggregated DSO flexibility forecasting at the TSO-DSO interconnection point and allowed P and Q operating envelope [38], [39] or feasible operating region determination at the HV/MV, MV/LV and customer interconnection points are important parts of the future flexibilities coordinated and more active [40], [41] utilisation by the DSOs and TSOs. New TSO-DSO control and coordination approaches as well as collaborative planning principles for real- and short-time (e.g. day-ahead) operation based on flexibility utilisation are increasingly needed [4], [42], [43], [44], [45], [46], [47]. Also principles for optimal siting and sizing of flexible energy resources like BESSs [48], [93] are of importance in the future.

B. VOLTAGE AND CONGESTION MANAGEMENT TO IMPROVE DER HOSTING CAPACITY

Distribution network-connected DERs traditional and dynamic hosting capacity definitions and enhancement techniques has been well presented in the literature, for instance, in [5], [6], [7], and [49]. Traditionally DER hosting capacity defines how much DER (e.g. PVs and EVs) can be integrated to different parts of the distribution network without voltage and line/component thermal/current limit violations. In addition, the DER hosting capacity can be locally restricted by excessive level of current and/or voltage harmonics or due to unwanted effects on existing distribution network protection schemes and practices. However, in this paper DER hosting capacity is viewed mainly from voltage and congestion management point of view with a focus on different DER control and OLTC management schemes, like [15], [16], [17], [18], [50], [51], [52], [53], [54], [55], [56], and [57] including also different EV charging schemes that could be utilized for the hosting capacity enhancement.

Increasing interest has been in the DSO network-connected DERs utilisation for the TSO's frequency control services provision like in [58], [59], [60], [61], and [62]. This requires improved TSO-DSO coordination and real-time monitoring as well as state prediction in order to avoid unwanted voltage and thermal limit violations in the distribution networks. Also, for example, in [15], [16], [17], and [18] different type of coordination between OLTC and DER inverter QU-droop settings have been previously studied. However, the OLTCs and DERs control settings coordination and dependency on simultaneous frequency level, like in this paper, has not been considered in any of the previous studies. In [63], the importance of using real data e.g. for the modelling of EV charging in hosting capacity studies using real time-series has been emphasized. In [64], realization of proactive congestion management was found to be challenging.

Lot of research focus has been also in the development of LV networks' DER hosting capacity methods. For example, in [57] the most efficient DER reactive power control scheme from LV network hosting capacity viewpoint was found to be the $\tan(\varphi) = -0{,}35$ control mode which is now a requirement for all new DERs connected to Enedis grid in France. In [65], possibilities to improve the PV hosting capacity was piloted in Switzerland by using MV/LV OLTCs and low voltage regulators. However, PV inverter *QU*-droops and *PQ*-flow based MV/LV OLTC -control were not considered. Paper [94] studied the utilization of in-line voltage regulator (IVR) in LV network with OLTC on MV/LV substation and paper [66] focused on increasing PV hosting capacity by use of MV/LV OLTC as well as measurements from smart meters. However, also in these cases (like in [65]) *PQ*-flow based MV/LV OLTC control and coordination with upper level HV/LV OLTC [67] control was not considered which could further increase the hosting capacity. In [95], two different MV/LV OLTC control principles were tested in which the idea was to use smart meters' data for the OLTC setting value adjustment. It was stated in [95] that due to the time delays in the used smart meter data it was not possible to compensate voltage changes that occurred after rapid changes in PV generation output in consequence of the cloud movements. Similar challenge to mitigate rapid voltage fluctuations in the distribution networks [96] exists if e.g. 10 s operation time delays are utilized on DER inverter *QU*-droops. Therefore, in [10] it was stated that *QU*-droops should be used without any time delays also because the time delays can potentially introduce local Q, P and voltage transients and increase the possibility of oscillations in Q and U during steady-state operation.

C. MARKET STRUCTURES & PLATFORMS AND REGULATION FOR ENHANCED FLEXIBILITY UTILISATION

The efficient flexibility services provision to the DSOs and TSOs requires flexibility utilisation enabling regulation, pricing and tariff structures as well as flexibility markets and flexibility platforms [13]. The level of flexibility utilisation and related markets' development in Europe has a lot of variety [68]. Only Great Britain, the Netherlands and France have commercial DSO markets for the flexibility utilisation and from regulation viewpoint market is not open for the flexibility aggregators in many countries [68]. In general, multiple different procurement mechanisms can be applied to the flexibility services provision [69] and their governance can be realised in different ways from local to centralised. Procurement mechanisms can consist of [69]: a) market-based procurement mechanisms (bilateral contracts, flexibility markets) and b) non-market-based procurement mechanisms (rules and network codes -based procurement, dynamic network tariffs, connection agreements). Flexibility platforms in can be split into three type of platforms [70]: 1) market-based platforms: intermediary and marketplace platforms, 2) administrative flexibility scheme coordinators and 3) internal platforms. Flexibility platforms could support DER integration, TSO-DSO coordination and market design as well as help the integration of flexibilities into operational planning. In [71], it was stated also that the implementation of domestic demand response and citizen participation to local energy markets is hindered, for example, by insufficient energy and a network tariff structure, complexity of prosumers' remuneration, technical responsibilities for aggregators, separate power exchange and flexibility market, lack of standardization on smart metering and DSOs regulations motivating investment in only wired solutions. Regulation and flexibility platforms standardization and harmonization, development of interoperability and universal flexibility trading and aggregation rules and systems are needed to speed up the utilisation of distribution network-connected flexibilities for services provision to the DSOs and TSOs in a coordinated manner.

Different local and coordinated flexibility markets, incentives and tariff structures for flexibility utilization has been proposed and piloted during the recent years. For example, in [2] separated but coordinated TSO and DSO flexibility markets were proposed and in [72] a framework for the DSO-TSO market-based coordination in a feasible and transparent way was proposed. [73] compared the efficiency of common (joint) and multilevel (sequential) DSO-TSO flexibility markets. In [74], the most recent local flexibility market (LFM) initiatives in Finland, Norway and Sweden were reviewed and it was concluded that clear market rules and roles for market participants as well as clearly defined flexibility products are required for the successful realisation of LFMs. In [75], flexibility platform development at E.ON Hungary was described stating the need for supporting regulatory framework. In [76], [77], [78], different power and energy-based tariffs as well as distribution use-of-system tariff structures were studied with a focus on improved flexibility provision. In addition, [79], [80], [81], and [82] researched and presented congestion management and related congestion and capacity markets and market-based solutions.

In overall, related to the focus of this paper i.e. TSO-DSO coordinated and frequency level-dependent DERs control and adaptive OLTCs management scheme which enables prioritized flexibility services provision for the DSOs and TSO, it is of key importance that the flexibility procurement schemes e.g. market-based are fully compatible with the planned operation and control principles.

III. SIMULATION MODELS AND STUDY CASES

Fig. 3 shows the HV/MV/LV network PSCAD model that is used for the simulation studies. The model includes active DER units connected in the MV network (1 MW PV, 2 MW BESS, 1 MW hydrogen electrolyzer / fast EV charging station) as well as in the LV network (0.45 MW PV, 0.2 MW BESS). In addition, there are OLTCs at HV/MV and MV/LV substations as shown in Fig. 3. MV network-connected DER units also have in their connection transformers own OLTCs (see also Fig. 7). In order to reduce the required simulation time, DER average models without detailed inverter models with power electronic switches have been used also in this paper like previously in [83], [84], [85], and [86]. Fig. 3

presents the studied frequency level-dependent adaptive *QU*-, *PU*-, and *Pf*-control methods of the DER units as well as the adaptive OLTC control methods. However, the MV network-connected DER OLTCs are not visible in the Fig. 3. In Fig. 4, the simulated frequency behaviour and the frequency level changes during the 250 s simulation time in the different study cases of this paper (Table 1) are shown.

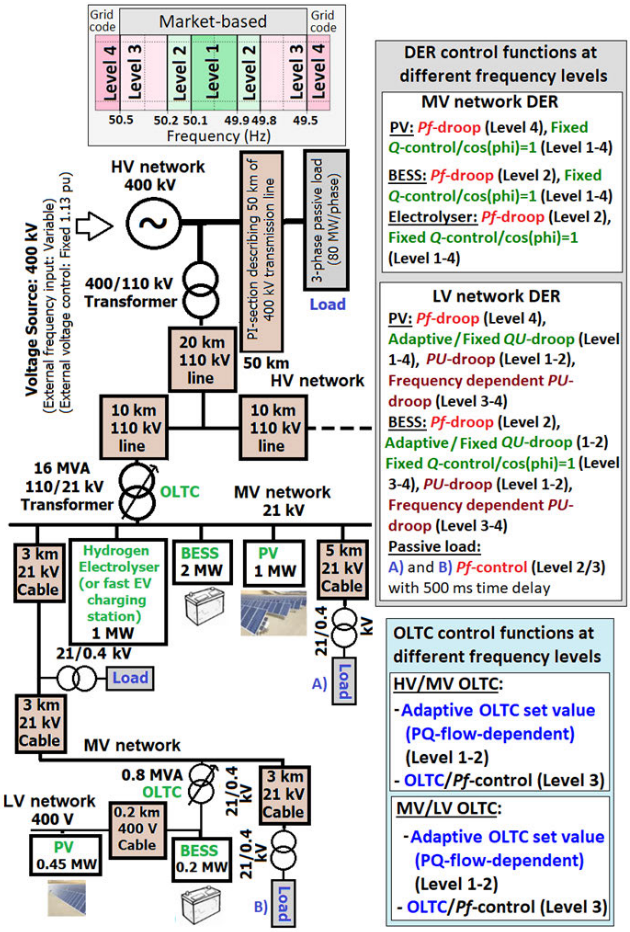
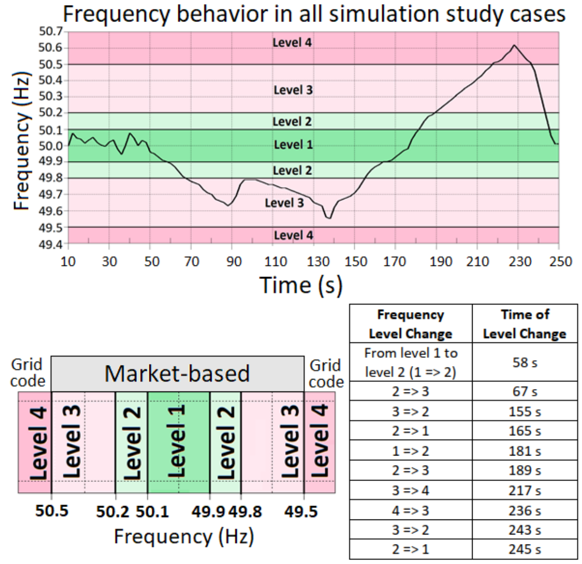


FIGURE 3. Studied HV/MV/LV network model with active DER units in urban MV network and DER units' control methods at MV and LV networks as well as OLTCs and their control principles at HV/MV and MV/LV substations (see Figs. 4-8 and Table 1) [8].

Traditionally, HV/MV transformer OLTCs are operated based on fixed voltage setting values and MV/LV transformers have either off- or on-line tap-changers. However, the traditional approach is rather limiting from DER hosting capacity and TSO-DSO flexibility support viewpoint. Therefore, this paper proposes and studies *PQ*-flow and frequency level-dependent operation logics (Fig. 5 and 6). Fig. 5a) shows HV/MV substation transformer OLTC's adaptive *PQ* flow -based settings for frequency levels 1-2 and Fig. 5c) respectively for MV/LV transformer. In Fig. 5b), demand response -based HV/MV OLTC operation logic and settings at frequency level 3 are presented and in Fig. 5d) similarly for MV/LV OLTC.



Frequency Level Change	Time of Level Change
From level 1 to level 2 (1 => 2)	58 s
2 => 3	67 s
3 => 2	155 s
2 => 1	165 s
1 => 2	181 s
2 => 3	189 s
3 => 4	217 s
4 => 3	236 s
3 => 2	243 s
2 => 1	245 s

FIGURE 4. Frequency behavior and frequency level changes in the simulations with all different study cases (see Fig. 3) [14].

TABLE 1. Main study cases with different DER & OLTC control functions at frequency levels 1-2 (See Figs. 2, 4 and 5 for more information e.g. *Pf* - and *PU*-Droops of DER units at different frequency levels).

Case*)	DER *QU*-control (LV DER)	Adaptation of *QU*-droop (LV DER)***)	DER *QU*-control (LV DER) at level 3-4	OLTC control (at level 1-2) / Time delay
CASE A	*QU*-droop (fixed, level 1-2)	Frequency level	Fixed cos(φ)=1	Fixed 20.5 kV (HV/MV)/5 s & 0.41 kV (MV/LV)/10 s
CASE B	*QU*-droop (adaptive, level 1-2) **)	MV/LV OLTC set value & Freq. level		*PQ* flow-based (HV/MV)/5 s & MV/LV)/10 s
CASE C	*QU*-droop (fixed, level 1-2)	Frequency level		
CASE D	*QU*-droop (fixed, level 1-2)		Fixed reverse *Q*-setting	

*) Demand response frequency control settings (with 500 ms time delay after +/- 0.2 Hz frequency deviation i.e. disconnection/connection of passive load at level 2/3, see Fig. 3), **) With adaptation delays similar to MV/LV OLTC operation time delays, ***) Based on

Fig. 6 presents HV/MV OLTC's frequency-dependent control blocking logic when frequency deviation from nominal is more than 0.2 Hz and MV network active power *P* load is less than 0.2 MW (see also Fig. 5b) and respectively for MV/LV OLTC if LV network active power *P* load is less than 0 MW (see Fig. 5d). It should be noted that directly at MV bus (or LV bus) connected DERs' active powers are not considered in the blocking logic (Figs. 5b, 5d and 6).

Fig. 7 shows novel interconnection transformer OLTC's control logic for directly MV network connected DER units (i.e. MV PV, MV BESS, MV EV fast charger/Hydrogen electrolyzer in Fig. 3). Typically, MV DER units do not have OLTCs on their interconnection transformers. However,

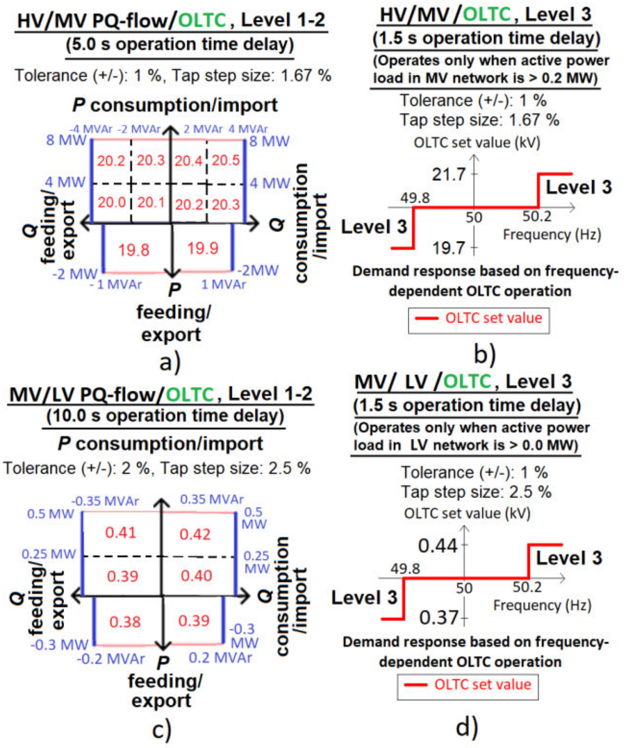


FIGURE 5. a) HV/MV substation transformer's adaptive PQ flow -based OLTC setting at levels 1-2, b) demand response -based HV/MV OLTC operation logic and settings at level 3, c) MV/LV substation transformer's adaptive PQ flow -based OLTC setting at levels 1-2 and d) demand response -based MV/LV OLTC operation logic and settings at level 3. (see Fig. 3 and Table 1) [8], [14].

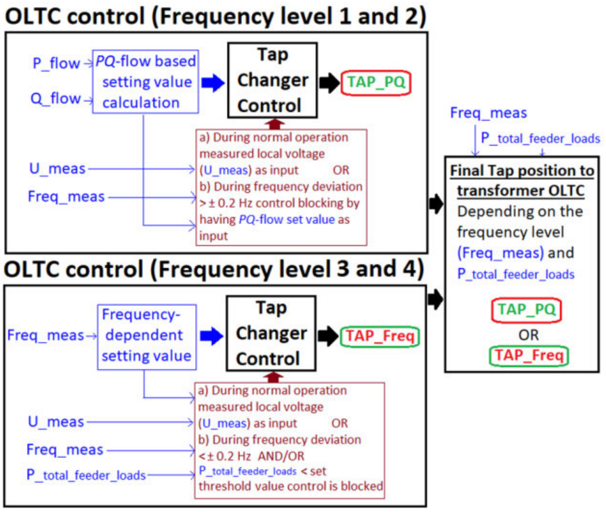


FIGURE 6. HV/MV and MV/LV OLTC's frequency-dependent control blocking (see Figs. 5b) and 5d).

Fig. 7 control logic could enable improved active power control-based flexibility services (e.g. *Pf*-, *PU*-, peak shaving) provision by these MV DER units. OLTC's control logic (Fig. 7) could potentially also reduce inverter sizing and improve the active power support from second-life or aged BESSs.

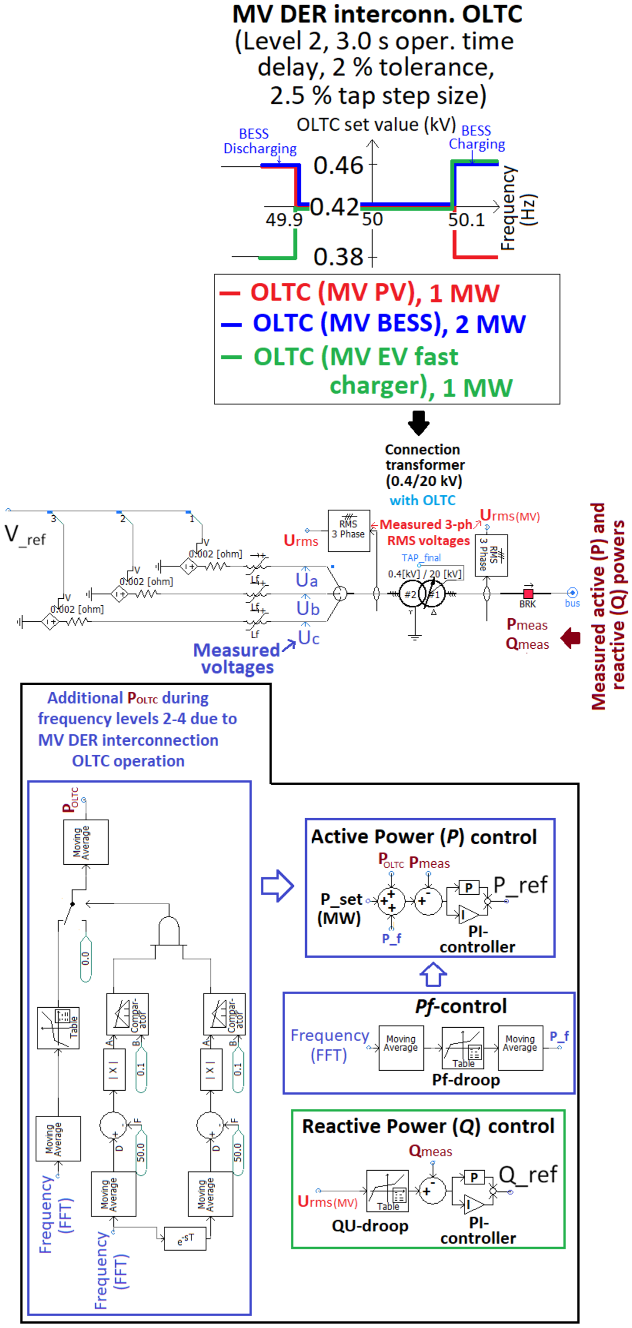


FIGURE 7. Novel interconnection transformer OLTC control logic and modified P control for larger MV network connected DER units (MV PV, MV BESS, MV EV fast charger/Hydrogen electrolyzer, see Fig. 3).

Regarding OLTC flexibility services described in Fig. 2b, it can be noted that MV DER MV/LV interconnection transformer can potentially provide higher active power *P* response with same/smaller current due to its OLTC's novel control logic. This can be achieved by controlling MV DER unit's side voltage level by interconnection transformer OLTC and by modifying the *P* control scheme of MV DER accordingly. However, the realized active power response and effect is dependent also on the actual compatible control scheme implementation in the DER inverter and it can be, for example, higher P response with the same current or same P response with smaller current (could be e.g. applicable to aged and second-life batteries). For instance, with the MV PV (Fig. 3) the novel PV interconnection transformer OLTC control logic (Fig. 7) was implemented so that with the same current better P response during level 2-4 under- or over-frequency deviations was achieved. Actual control algorithm implementation in this paper with the used PV simulation model was done so that during level 2-4 under-frequency +75 kW additional P_{OLTC} (Fig. 7) input was added to the active power control scheme and it enabled together with compatible OLTC control logic (Fig. 7) +8.5% higher P response (see Fig. 18a) in Section IV-A.2). Respectively, during level 2-4 over-frequency −85 kW additional P_{OLTC} (Fig. 7) input together with OLTC control (Fig. 7) enabled 10% reduction in PV active power (i.e. better frequency support (Fig. 18a) in Section IV-A.2). On the other hand, this control logic should be coordinated with MV DER *Pf*-droop setttings to ensure that certain active power capacity is left for rapid frequency support by *Pf*-droop control after OLTC's operation (Fig. 7). In this paper's simulations novel DER interconnection OLTC's control scheme on MV DER units was implemented so that it enabled, for example, same DER active power response with 7.7% smaller current or 8.5% higher DER active power response with the same current (see Section IV-A.2). Fig. 8 presents DER *Pf*-, *PU*- and *QU*-droops at different frequency levels in detail.

The different study cases (Table 1) are chosen to compare the traditional fixed DER unit *QU*-droop and OLTC settings with the proposed adaptive frequency- and *PQ* flow-dependent OLTC settings (Fig. 5) as well as to find out potential mutual unwanted effects of the controls. It can be also highlighted that in CASES A, C and D the adaptation of LV DER *QU*-droop settings at frequency levels 1-2 would not require communication from MV/LV OLTC, because the locally measured voltage at DER connection point is used for the settings adaptation. In [87], it was also concluded that with larger flexible loads, local frequency measurement-based frequency control would be better as well as with smaller loads if the communication network is weak (high latency, unreliable etc.). Therefore, promising enhanced schemes for the local frequency measurement proposed in [86] could be used also in the demand response, frequency-dependent OLTC operation and under-frequency-load-shedding (UFLS) to improve their response speed and power system frequency stability support.

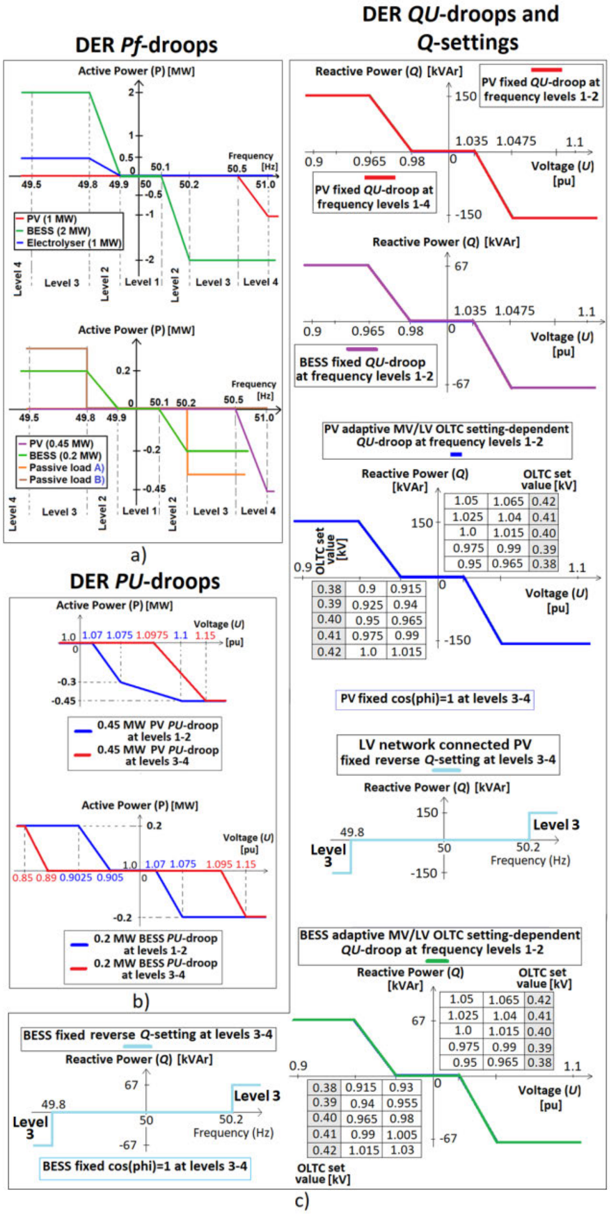


FIGURE 8. a) MV and LV DER Pf-droops, b) LV DER and MV BESS PU- and c) QU-droops or Q-settings, (modified from [8] and [14], see also Figs. 3-7 & Table 1).

IV. SIMULATION RESULTS

In the following subsections IV-A and IV-A1, the main simulation results from the different study cases are presented. First, in subsection IV-A results from the main simulation CASES A-D (Table 1) are shown. Subsection IV-A1 presents also as an example the provided P and Q flexibility at different frequency levels 1-4 in CASE C. After that, subsection IV.A2 shows the control behavior of MV DER units OLTCs' in CASE C. At last, in subsection IV-A1 simulation results from the CASE C subcases C1-C4 are presented. In all cases, the total simulation time was $t = 250$ s and frequency behaved between $t =$ 10-250 s as shown in the Fig. 4.

A. CASES A-D

In this subsection IV-A, main simulation results from the study CASES A-D (Table 1) are presented in Figs. 9-14.

Fig. 9 shows voltages in the different cases (Table 1) at the HV/MV, MV/LV substation and at the end of LV feeder with LV PV and LV BESS. From Fig. 9 it can be seen that in CASE C and D voltage level is lowest in LV network during frequency levels 1-2. This is very useful from the viewpoint of PV hosting capacity. In addition, during

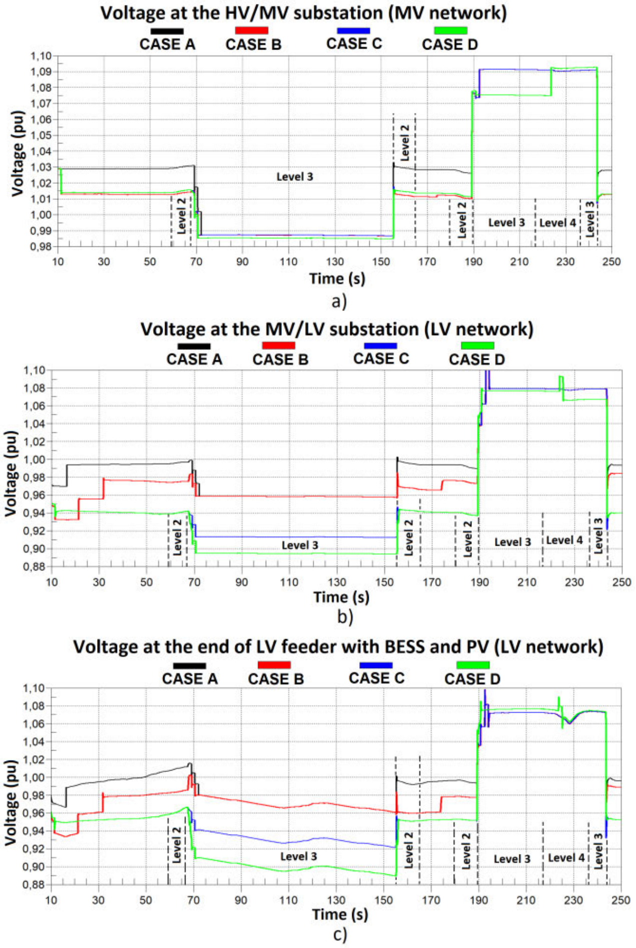


FIGURE 9. Voltages in study CASES A-D at the a) HV/MV substation, b) MV/LV substation and c) end of LV feeder with PV and BESS (see Figs. 3-8 & Table 1).

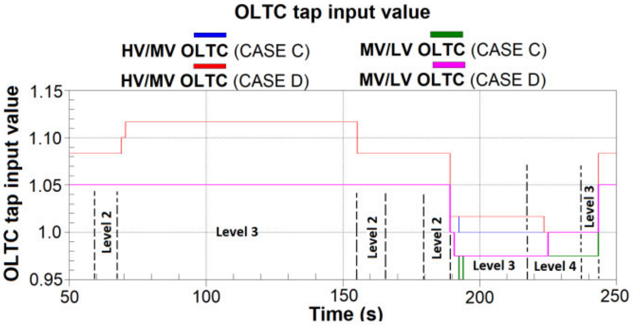


FIGURE 10. HV/MV and MV/LV OLTCs' tap input values behavior in study CASES C and D (see Figs. 3-8 & Table 1).

frequency levels 3-4 under- and over-frequencies lowest and highest voltages in CASES C and D can potentially support the system frequency by voltage-dependent demand response more than in CASES A and B. Due to reversed active power P flow (Fig.12a) during level 3 under-frequency event (at $t = 67 - 155$ s), frequency-dependent MV/LV OLTC operation (Figs. 5d and 10) is blocked. However, it can be seen from Figs. 9b) and 9c) that during level 3 under-frequency event (at $t = 67 - 155$ s) voltages in the LV network go momentarily below 0.9 pu in CASE D. Therefore, if fixed reverse Q-control is utilized (CASE D, Table 1) some real-time state-monitoring about lowest voltages (e.g. by combined information from smart meters at the MV/LV edge) should be available in order to control the OLTCs or their settings accordingly to avoid violating the low-voltage limit 0.9 pu even momentarily. It can be seen from Fig. 9a that during level 3 over-frequency at $t = 190 - 230$ s voltages behave differently in CASES C and D. This is due to the different tapping of OLTCs (Fig. 10) during frequency-dependent operation at level 3 (there is 1% tolerance for the OLTC operation in these simulations). This momentary lower voltage at HV/MV substation at $t = 190 - 220$s in CASE D reduces also the simultaneous P support from HV/MV substation (Fig. 11a) to HV network.

Fig. 11 shows P and Q flows at the HV/MV substation in CASES A-D (Table 1) and respectively Fig. 12 P and Q flows at the MV/LV substation. From Fig. 13 LV network-connected DER units' reactive power Q behavior in different CASES A-D (Table 1) can be seen. In Fig. 14, the active power P behavior of MV and LV network connected DERs in CASE D and for LV 0.45 MW PV also in CASE C is shown.

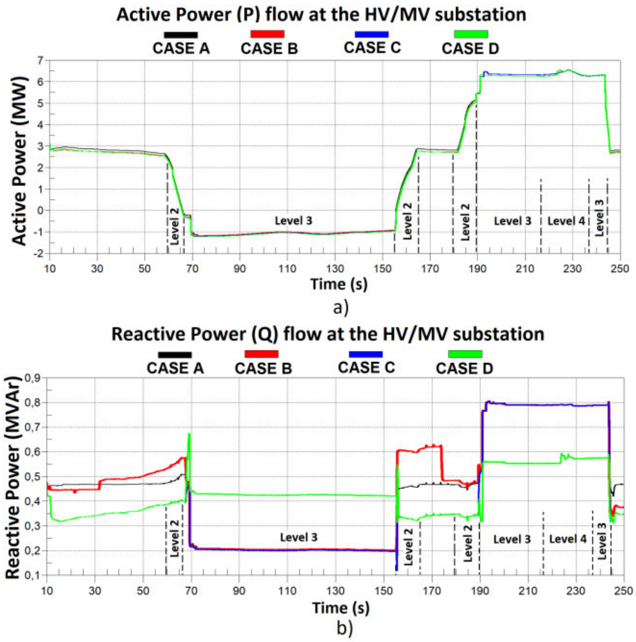


FIGURE 11. a) Active and b) reactive power flow at the HV/MV substation in study CASES A-D (see Figs. 3-8 & Table 1).

It can be seen from Fig.14b that 0.45 MW PV active power output in LV networks is reduced due to local over-voltages in CASE D at $t = 190 - 220$ s (during level 3 over-frequency). This is due to the fixed reverse Q-control of LV network connected 0.45 MW PV (Fig.13b) and 0.2 MW BESS (Fig.13a) at level 3 frequency deviations (at t = 190-220 s) in CASE D (Table 1). Reactive power Q feeding of LV DER (Fig. 13) leads to PV active power curtailment at the LV network in

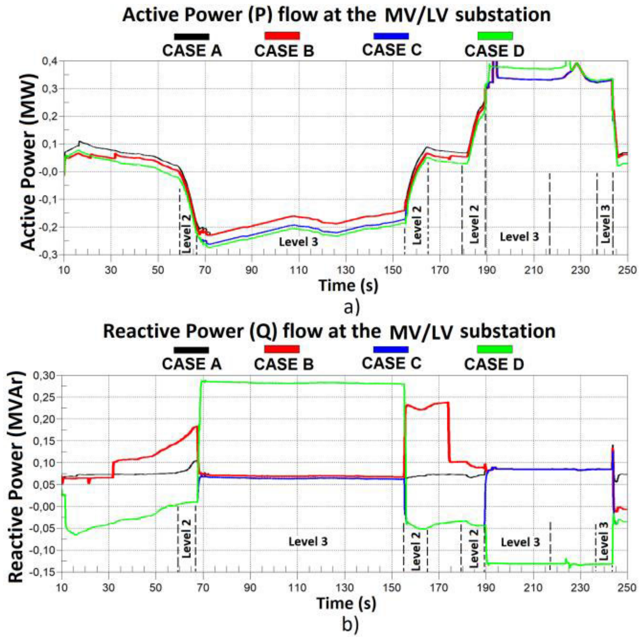


FIGURE 12. a) Active and b) reactive power flow at the MV/LV substation in study CASES A-D (see Figs. 3-8 & Table 1).

CASE D (i.e. reduced PV hosting capacity during level 3 over-frequency).

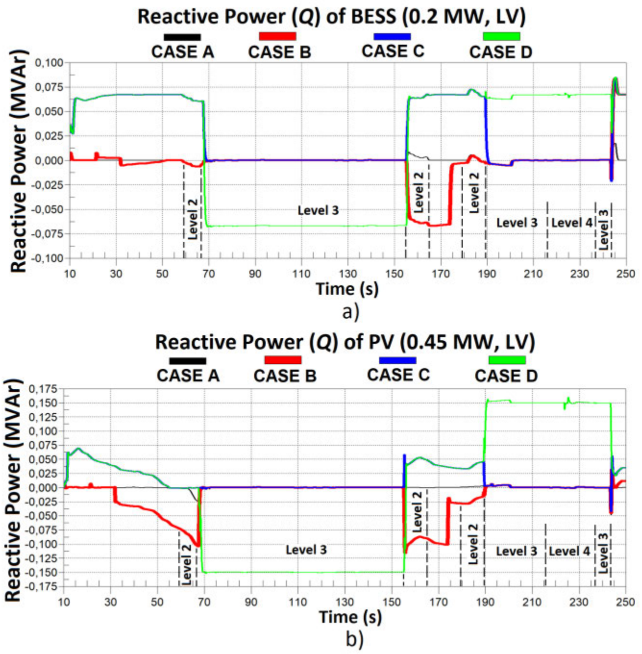


FIGURE 13. a) 0.2 MW BESS and b) 0.45 MW PV reactive power Q behavior in study CASES A-D (see Figs. 3-8 & Table 1).

In overall, based on [8] and the simulation results of this subsection IV-A it can be concluded that, with the used settings, the CASE C seems to be most feasible from the studied cases (Table 1) with PQ-flow based control of OLTCs, fixed DER QU-droop control at level 1-2 frequencies and fixed $\cos(\phi) = 1$ setting at level 3 and 4 frequencies seems to be the most feasible OLTC and DER control scheme.

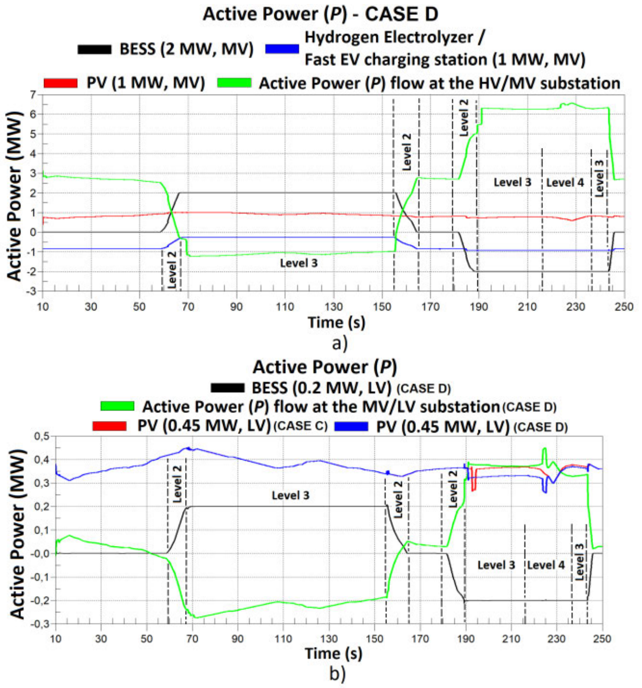


FIGURE 14. Active power behavior of a) MV and b) LV network connected DERs in CASE D and for LV 0.45 MW PV also in CASE C (see Figs. 3-8 & Table 1).

1) PROVIDED FLEXIBILITY AT DIFFERENT FREQUENCY LEVELS (CASE C)

Fig. 15 shows an example about provided P flexibility and change in P -flows through the HV/MV and MV/LV substations from CASE C (Table 1) when compared to BASE CASE C without any P and Q -control functionalities on DER units and with fixed OLTC settings at all frequency levels (no OLTC on MV DER and on MV/LV substation). From Fig. 15 one can see approximately the amount of provided active power P flexibility at different frequency levels 1-4 in CASE C (Table 1).

Fig. 16 provides LV network voltage levels from CASE C (Table 1) when compared to BASE CASE C. It can be seen from Fig. 16 that due to the proposed DER and OLTC control schemes in CASE C (Table 1) the LV network DER hosting capacity from voltage level viewpoint during the frequency levels 1-2 has increased substantially when compared to the BASE CASE C. It can be also seen (Fig. 16) that the allowable voltage limits (e.g. 0.9-1.1 pu) can be still respected in CASE C while providing P flexibility (Fig. 15) during levels 1-4 frequency deviations (Fig. 4).

In addition, in the future the flexibility forecasts at different flexibility zones e.g. at HV/MV and MV/LV substation level could be more clearly categorized and defined for the TSO-DSO coordinated management, for example, by

a) considering the frequency level i.e. frequency deviation severity, so that

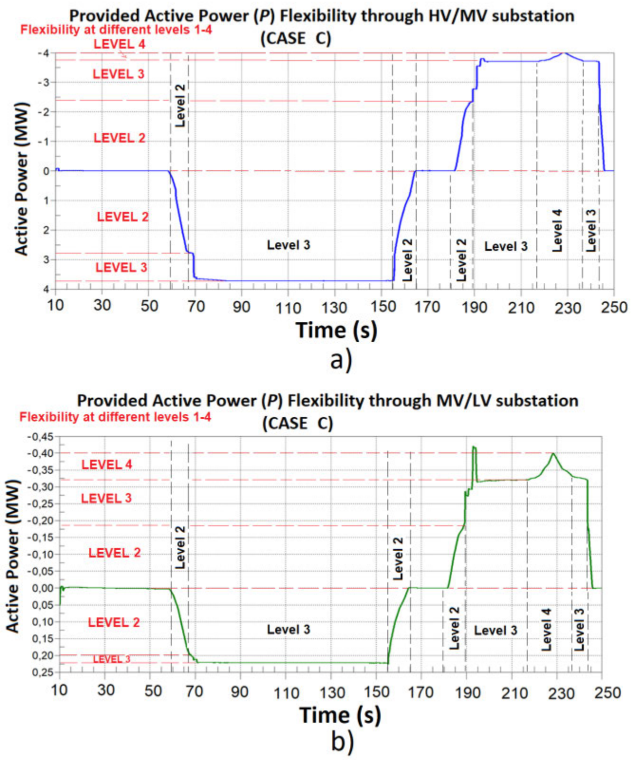


FIGURE 15. Provided *P* flexibility through a) HV/MV and b) MV/LV substation in CASE C at different frequency levels (see Figs. 3-8 & Table 1).

- for steady-state frequency fluctuations at level 1-2 there would be different flexibility availability at HV/MV substation ($\text{flex}_{\text{MV}\_1-2}$) and
- for more severe frequency fluctuations at level 3-4 increased flexibility availability at HV/MV substation ($\text{flex}_{\text{MV}\_3-4}$)

b) considering also the location (e.g. flexibilities connected directly at the HV/MV substation). Additionally, main flexibility related constraints could be defined so that category A means that the main constraint is related to HV/MV transformer rating and category B could mean flexibilities which have also other constraints (line/current/thermal rating, voltage) for their utilization due to congestions in the distribution network), so that

- for steady-state frequency fluctuations at level 1-2 there would be flexibility availability at HV/MV substation in different categories like $\text{flex}_{\text{MV}\_1-2\_\text{A}}$ and $\text{flex}_{\text{MV}\_1-2\_\text{B}}$ and for more severe frequency fluctuations at level 3-4 respectively in different categories $\text{flex}_{\text{MV}\_3-4\_\text{A}}$ and $\text{flex}_{\text{MV}\_3-4\_\text{B}}$

Additionally, c) availability uncertainty and d) control response speed could also be considered as part of advanced flexibility forecasts.

2) MV DER UNIT INTERCONNECTION TRANSFORMER OLTCS' CONTROL (CASE C)

Previously, in Section III the control logic (Fig. 7) of MV/LV interconnection transformer OLTCs' for directly MV

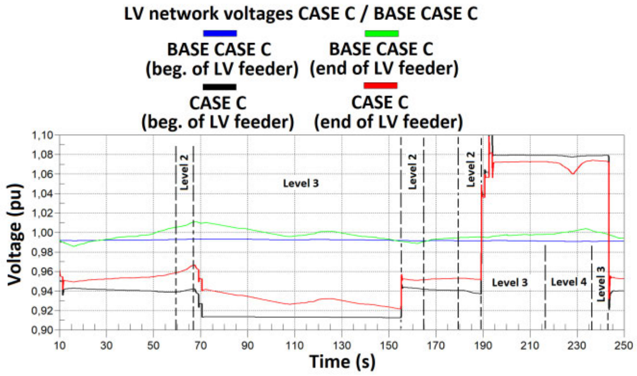


FIGURE 16. LV network voltages at different frequency levels in CASE C and BASE CASE C (see Figs. 3-8 & Table 1).

network-connected DER units (i.e. MV PV, MV BESS, MV EV fast charger/Hydrogen electrolyzer in Fig. 3) was presented. In this subsection IV-A2, related simulation results from CASE C (Table 1) are shown.

Fig. 17 shows the MV DER's OLTCs' tap input values and connection point transformers' LV side voltages behavior in the study CASE C (Table 1) based on the principles presented in Fig. 7.

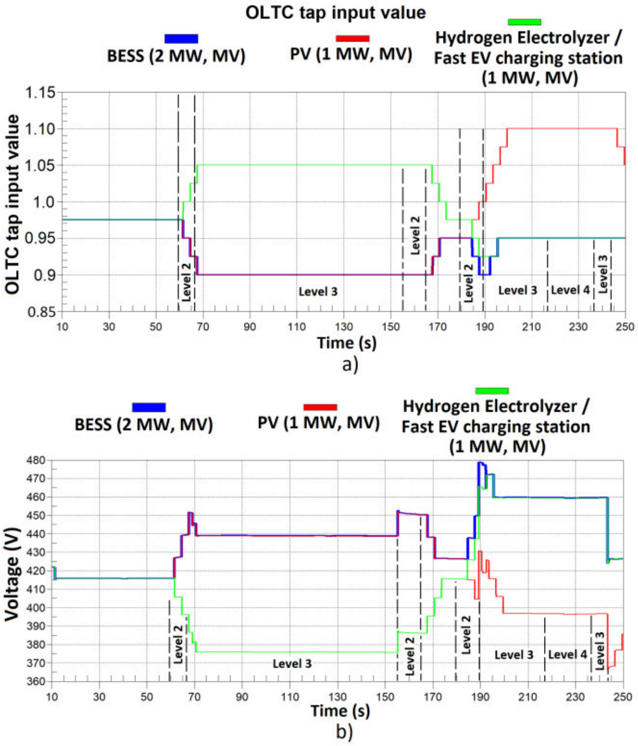


FIGURE 17. MV DER's OLTCs' a) tap input values and b) connection point transformers' LV side voltages behavior in study CASE C (see Figs. 3-8 & Table 1).

Fig. 18a) shows the active power of MV DER units' in CASE C and Fig. 18b) the current (phase A, RMS) of MV DERs' with and without DER interconnection transformer OLTC in CASE C (see also Fig. 17). It can be seen from

Fig. 18a) that same active power *P* of MV BESS can be fed to the network with 7.7% smaller current (Fig. 18b) due to its MV/LV interconnection transformer control logic (Fig. 7) during level 3 under-frequency. In addition, Fig. 18 a) shows that during level 3 under-frequency MV PV can feed 8.5% more active power *P* to the network with the same current (Fig. 18b) due to its MV/LV transformer OLTC's control logic presented in Fig. 7.

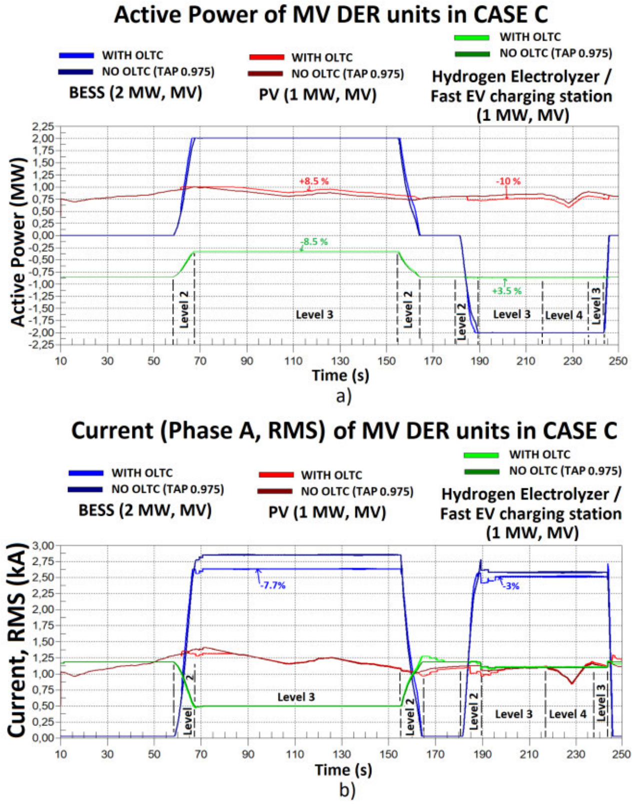


FIGURE 18. MV DERs' a) active powers' and b) phase A RMS-currents' in study CASE C with interconnection OLTCs' and without OLTCs' (see Figs. 3-8 & Table 1).

B. SUBCASES OF CASE C

In this subsection IV-B simulation results from CASE C (Table 1) subcases C1-C4 (Table 2) are presented.

TABLE 2. Studied (Table 1) Sub-cases C1-C4 and their differences to CASE C.

Cases	Differences to CASE C
CASE C	-
CASE C1	Different active and reactive power (*P* and *Q*) inputs at HV/MV OLTC control (i.e. sum of *P* and *Q* flows from MV feeders are used and directly at HV/MV substation MV bus connected MV DER units' *P* and *Q* values are excluded)
CASE C2	Steeper *QU*-droop without dead zone on LV network PV
CASE C3	Longer LV feeders (600 m instead of 200 m)
CASE C4	EV parking lot in LV network instead of PV

Purpose of these subcases C1-C4 (Table 2) is to compare the cases with different OLTC control inputs, DER reactive power control settings, LV feeder lengths as well as large-scale integration and simultaneous charging of EVs (instead of PVs) on LV network. Table 2 shows the differences of the subcases when compared to CASE C (Table 1). Fig. 19 shows the modified LV network PV unit's *QU*-droop without dead-zone (CASE C2 in Table 2, see also Fig. 8) as well as LV network EV parking lot's *QU*-, *Pf*- and *PU*-droops (CASE C4 in Table 2).

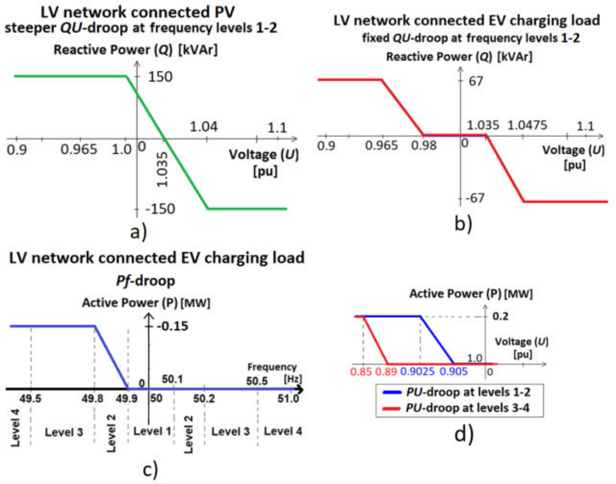


FIGURE 19. a) LV network PV unit's QU-droop without deadzone (CASE C2) and LV DER and LV network EV parking lot's b) QU-, c) Pf- as well as d) PU-droops (CASE C4, see also Figs. 3-8 & Table 1-2).

Fig. 20 shows voltages in the different subcases (Table 2) at the HV/MV and MV/LV substation, at the end of LV feeder with LV PV and LV BESS as well as at the LV PV/EV connection point. It can be seen from Fig. 20 that during level 3 under-frequency in CASE C4 (Table 2) the voltages at the end of LV feeder are very low (0.85 pu). Therefore, in order to support local voltage level (i.e. prevent under-voltages) it could be feasible to modify the MV/LV OLTC demand response-based operation setting, LV EV(/PV) fixed reverse *Q*-settings as well as more sensitive EV *PU*-droop settings at frequency levels 3-4 as shown in Fig. 21. It can be seen also that there is a small (0.025 pu) difference between voltage levels at the end of LV feeder (Fig. 20 c) and at the connection point of LV PV/EV (Fig. 20 d). The local operation of DER *QU*- and *PU*- functionality is in this paper's studies based on the connection point voltages (Fig. 20 d). Simulation results in Figs. 20 c) and d) show also that the steeper *QU*-droop of LV PV in CASE 2 (Table 2, Fig. 19a) during frequency levels 1-2 leads to higher voltage level at the end of LV feeder due to higher *Q* output of the LV PV (Fig. 23 b). In CASE C3 (Table 2), interestingly the voltage levels are generally higher at the end of LV feeder (Figs. 20 c) and d) than in other cases (except at the end of the simulation during level 3-4 over-frequencies, Fig. 4) due to MV/LV OLTC operation.

Fig. 22 presents the active and reactive power flows at the MV/LV substation in CASE C and C1-C4 as well as EV's active power in CASE C4 (Tables 1-2). Fig. 23 shows the LV

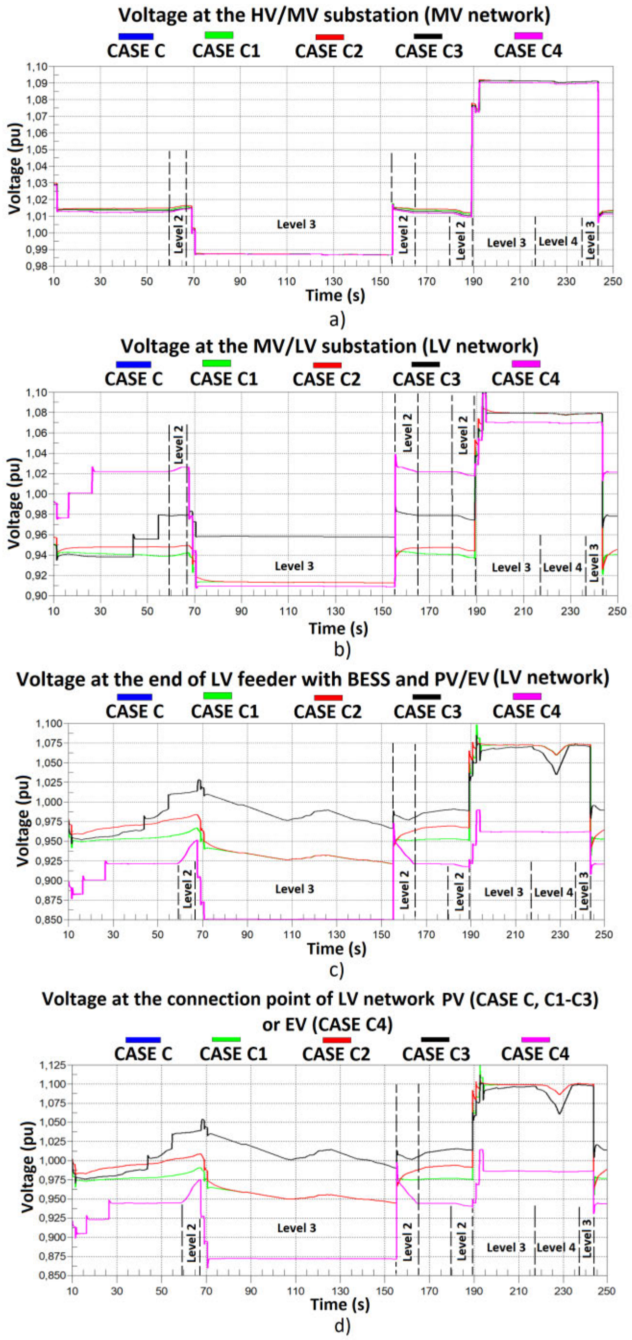


FIGURE 20. Voltages in different cases at the a) HV/MV substation, b) MV/LV substation and c) end of LV feeder with PV/EV and BESS as well as at the connection point of LV network connected PV/EV in CASE C & C1-C4 (see Figs. 3-8 and 19 & Table 1-2).

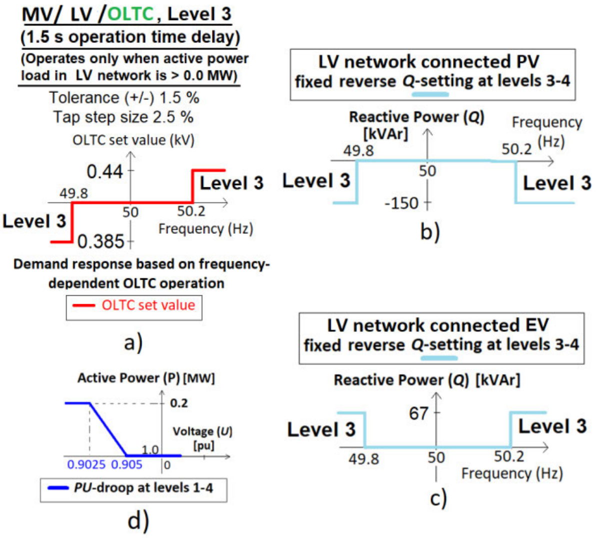


FIGURE 21. Modified a) MV/LV OLTC demand response-based operation setting, b) LV EV and c) LV PV fixed reverse Q-settings as well as d) EV more sensitive PU-droop settings at frequency levels 3-4 in CASE C & C1-C4 (see Figs. 3-8 & Tables 1-2).

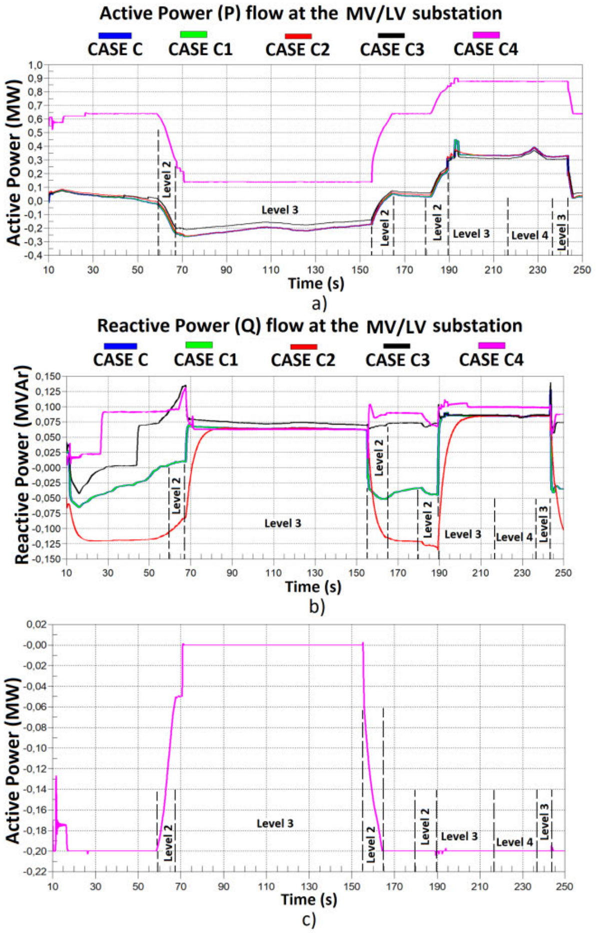


FIGURE 22. a) Active and b) reactive power flow at the MV/LV substation in CASE C & C1-C4 as well as c) EV's active power in CASE C4 (see Figs. 3-8 & Table 1- 2).

network-connected 0.2 MW BESS's and 0.45 MW PV's or EV parking lot's reactive power Q behavior in CASE C and C1-C4 (Tables 1-2).

Fig. 22b) presents how the steeper LV network PV's QU-droop setting (Fig. 19a) increases both the reactive power fed by the PV (Fig. 23b) as well as reactive power fed from the MV/LV substation to the MV network in CASE C2 (Table 2) at frequency levels 1-2. Fig. 22 c) shows how LV network connected EVs' charging is reduced during level 2 and 3 under-frequencies in CASE 4 (Table 2). Fig. 23 a) presents the reactive power output of 0.2 MW BESS in

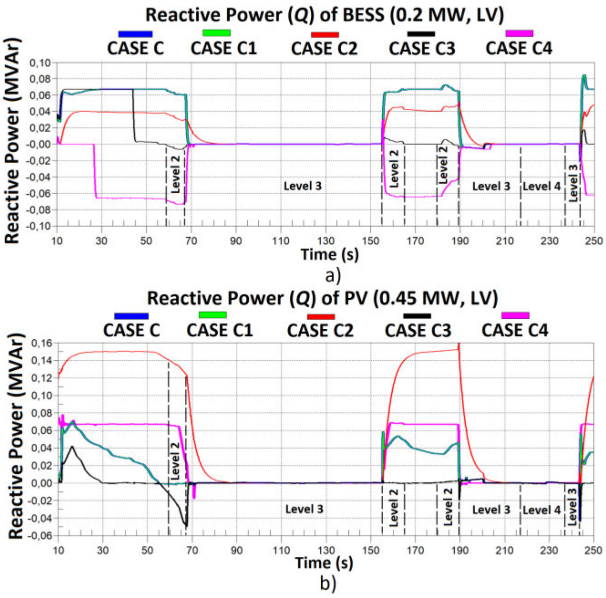


FIGURE 23. a) 0.2 MW BESS and b) 0.45 MW PV or EV parking lot reactive power Q behavior in CASE C & C1-C4 (see Figs. 3-8 & Table 1- 2).

CASES C1-C4 and it can be seen that the reactive power output of LV BESS is in the opposite direction in CASE 4 during level 1-2 frequency deviations. This is due to the higher voltage levels at the LV BESS's connection point in CASE 4 (see also Fig. 20b) and the higher voltage level in turn is due to the *PQ*- -dependent MV/LV OLTC's operation during level 1-2 frequency deviations (Fig. 5c) in order to increase EV (charging related) hosting capacity in the LV network. So from DER hosting capacity increase viewpoint, the *PQ*-dependent OLTC's operation logic operates as planned.

V. FURTHER DEVELOPMENT POSSIBILITIES

Due to the large-scale integration of intermittent renewable generation (like wind and PV) and transport electrification, rapid power flow changes will increase in the future power systems at different voltage levels both in TSO and DSO networks. This increases the need for more dynamic operational planning and power flows active management between voltage levels as already described in the Section II of this paper. In this paper, the focus has been on the principles and overall scheme further development to increase simultaneously the DER hosting capacity of the DSO network by DERs and OLTCs related flexibility services as well as provision of frequency support to the TSO depending on the frequency deviation severity/level (Fig. 2). However, this approach could be even further developed to consider also the forecasted and close to real-time HV network line congestions (e.g. related to voltage stability or thermal/current limits of HV network lines) and needed *P* and *Q* flexibility from DSO networks side or from the other HV network-connected resources (e.g. large-scale BESSs or hydrogen electrolyzers). In the future, this could be potentially realized at the frequency deviation levels 1-2 by forecast-based hourly day-ahead and corrective dynamic one hour-ahead *PQ*-flow (between TSO and DSO networks) -dependent Transmission Network Use of Service (TNUoS) or Transmission Use of System (TUoS) prices at the HV/MV substations (Fig. 24a). Respectively, at the MV feeders, MV/LV substations (Fig. 24b), LV feeders and at LV customer connection points during frequency levels 1-2, similar forecast-based hourly day-ahead and one hour-ahead *PQ*-flow (between MV and LV networks) -dependent Distribution Use of Service or System (DUoS) prices (Fig. 24b) could be implemented to manage the DSO network congestions.

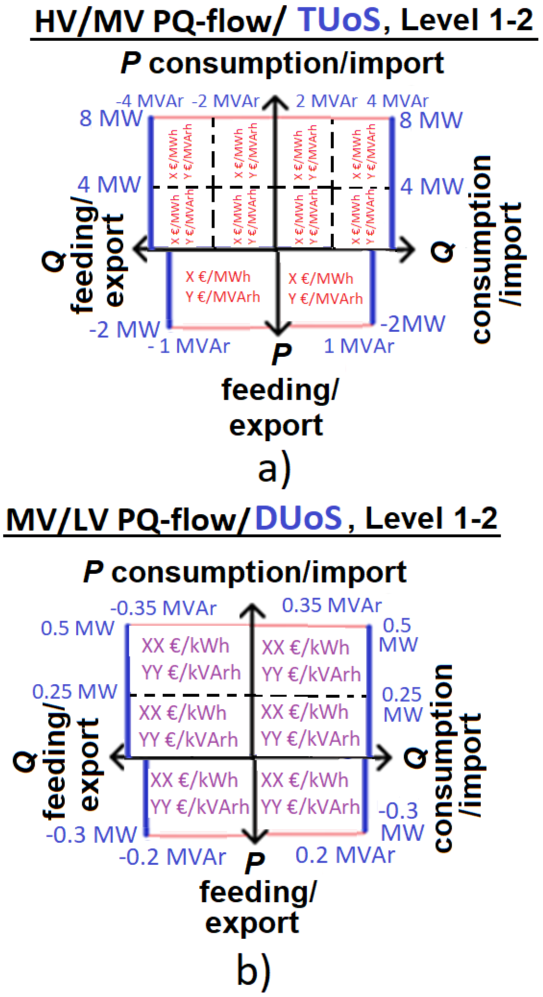


FIGURE 24. Principle of forecast-based hourly day-ahead or corrective dynamic one hour ahead *PQ* -flow-dependent a) TUoS prices at the HV/MV substation and b) DUoS prices at the MV/LV substation.

This kind of dynamic TUoS as DUoS pricing scheme could be integrated to ANM functionalities at the HV/MV or MV/LV cloud-/edge-levels. Simultaneously, it would benefit from accurate state monitoring and forecasting. In addition, OLTC settings real-time tuning based on accurate state-estimation at the edge-level could be used in the future to ensure that voltage limits are not violated during level 1-2 frequency deviations (when operating close to the limits of *PQ*-flow-based setting window at the HV/MV and/or MV/LV substations) or during level 3-4 frequency deviations (OLTC setting fine tuning during levels 3-4). This would require real-time knowledge about minimum and maximum voltages from LV network smart meters at the edge level (for MV/LV and HV/MV substation OLTCs).

VI. CONCLUSION

This paper presents further developments of the novel coordinated and frequency level-dependent DERs' and OLTCs' management scheme which could enable prioritized flexibility services provision for the DSOs and TSO. The essential idea is that the coordination between DSOs and TSO regarding flexibility utilisation from the DSO network-connected resources is based on the severity of the frequency deviation. During smaller level 1-2 frequency deviations priority is on the needs of the DSO and during larger level 3-4 frequency deviations TSO's needs are prioritized. The general aim of the holistic TSO-DSO coordinated and frequency level-dependent DERs' and OLTCs' management scheme is to increase the DERs' hosting capacity in the DSO networks as well as to increase the availability of DERs for the TSO flexibility services provision during smaller level 1-2 frequency deviations.

This paper studies, for example, the effect of different OLTC control inputs, DER reactive power control settings, LV feeder length and large-scale integration of electric vehicles (EVs) on LV network. The following conclusions are made based on the simulations:

- Adaptation of MV and LV DER *QU*-droop settings during frequency levels 1-2 based on simultaneous MV/LV or HV/MV OLTC's setting value is not recommended from the TSO frequency support viewpoint as well as from the LV network PV hosting capacity viewpoint. Instead fixed *QU*-droop settings at levels 1-2 and $\cos(\phi) = 1$ or fixed reverse *Q*-settings at levels 3-4 with some proposed modifications (Fig. 21) are recommended. Fixed DER *QU*- droop or reverse *Q*-settings are based on local DER connection point measurements and don't require any communication for the adaptation of the settings. Therefore, local stable, accurate and fast frequency measurement is very crucial for frequency-dependent adaptation of the functions. Frequency measurement proposed in [86] could, for example, be potentially used for the BESSs, EV chargers, load demand response and frequency-dependent OLTCs in order to improve their flexibility provision response speed and TSO's frequency stability support.
- It is shown by the simulations that *PQ* -flow-dependent control of HV/MV and MV/LV OLTCs' can increase the DSO network's hosting capacity most during level 1-2 frequency deviations (for example, in LV network either during high amount of PV generation or alternatively during charging of multiple EVs).

In this paper, enhanced OLTC control principles are also presented including novel MV/LV interconnection transformer OLTC's control logic for MV network-connected DER units. The PSCAD simulations show that the proposed novel control logic enabled, for example, same MV BESS active power response with 7.7% smaller current and MV PV was able to feed 8.5% more active power to the network with the same current due to its OLTC's novel control logic. In addition, the paper presents HV/MV and MV/LV OLTCs' frequency-dependent control blocking logic to be used when required conditions for this functionality utilization are not met.

At the end, even further improvement possibilities of the proposed coordinated control and management scheme are also briefly described like, for example, principle of forecast-based *PQ*-flow-dependent TUoS pricing at the HV/MV substation and DUoS pricing at the MV/LV substation.

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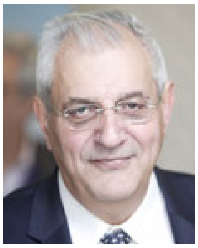

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