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# FREQUENCY-DEPENDENT CONTROL OF DERS AND OLTCS IN THE FUTURE DISTRIBUTION NETWORKS

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## Abstract

In the future, large amount of flexibility is needed from different voltage levels to fulfill the flexibility needs of the transmission and distribution system operators (TSOs and DSOs) in increasingly renewables-based power systems. This paper develops further the TSO-DSO coordinated, frequency-dependent distributed energy resources' (DERs') and on-load-tap-changers' (OLTCS') control scheme for the future electricity distribution networks to enable prioritized flexibility services provision for the TSOs and DSOs by proposing dynamic adaptive and frequency-dependent current/thermal limits utilization for distribution network lines, cables and transformers as part of the overall scheme. In addition, the paper focuses on comparison of  $\tan(\phi)=-0.35$  as reactive power ( $Q$ ) control method for solar photovoltaics (PVs),  $\tan(\phi)=-0.35$  (discharging) / 0.4 (charging) for battery energy storages and  $\tan(\phi)=0.4$  for electric vehicle (EV) chargers instead of previously proposed frequency-dependent  $Q$ -control principles for DERs. Also the effect of more rapid PV active power ( $P$ ) fluctuations as well as further modified active power-frequency droop ( $Pf$ -droop) settings in MV BESS's multi-use cases with PV and EV are studied by PSCAD simulations.

## 1 Introduction

Distribution network-connected DERs' active  $P$  and reactive power  $Q$  control together with existing assets, like OLTCS, offer great potential to fulfill the future  $P$ - and  $Q$ - control-related flexibility service needs of the TSOs and DSOs. DERs' flexibility services can support the power system's frequency ( $f$ ) and local voltage ( $U$ ) level or congestion management at the corresponding voltage level. Potential conflict of interest between DSOs and TSOs in the use of the flexibility from distribution network-connected DERs should be avoided by improved TSO-DSO coordination, state-forecasting and state-monitoring together with new collaborative DSO and TSO operation and planning principles based on active use of the available flexibilities. Therefore, different DER units'  $P$ - and  $Q$ -control modes, settings and coordinated OLTC settings and control principles should be increasingly considered already in the planning phase. [1], [2]

This paper develops further the TSO-DSO coordinated, frequency-dependent DERs' and OLTCS' control scheme [3]-[5] for the future electricity distribution networks to enable prioritized flexibility services provision for the TSOs and DSOs. Flexibility use prioritization is based on the severity of the frequency deviation. During smaller frequency deviations priority is on the DSO needs and during larger frequency deviations TSO needs are prioritized. In general, target is also to increase distribution networks' DER hosting capacity and increase simultaneously also the TSO flexibility services provision by the distribution network-connected DERs during smaller frequency deviations. In the proposed scheme, DERs' reactive power-voltage ( $QU$ ), active power-voltage ( $PU$ ),  $Pf$ -droops and OLTCS' management principles are adapted depending on the frequency deviation severity / level (frequency levels 1-4 are shown in Fig. 1) so that in case of larger frequency deviation (level 3 or 4) support for the whole power system and TSO needs is prioritized. In the proposed scheme, during smaller frequency deviations (level 1 or 2) HV/MV and MV/LV OLTCS are controlled based on the real-time  $P$  and  $Q$  flows between different voltage levels to increase

DER hosting capacity in the DSO's network as well as increase the availability of the distribution network-connected DERs for the TSO flexibility services provision at frequency levels 1-2. [3]-[5]

In this paper, comparison is made between the utilization of  $\tan(\phi)=-0.35$  as  $Q$ -control method for PVs (French Enedis requirement, [6]),  $\tan(\phi)=-0.35$  (discharging) / 0.4 (charging) for battery energy storages and  $\tan(\phi)=0.4$  for EV chargers instead of previously proposed frequency-dependent  $Q$ -control principles for DERs. Also the effect of more rapid PVs' active power  $P$  fluctuations as well as further modified  $Pf$ -droops in MV BESS's multi-use cases with PV and EV are studied by PSCAD simulations. In addition, this paper suggests enhancements to the frequency-dependent DERs and OLTCS control scheme by proposing dynamic adaptive and frequency-dependent current/thermal limits utilization for distribution network lines, cables and transformers i.e. frequency-dependent dynamic line/transformer rating (FDLTR) as part of the overall scheme.

## 2 Study System and Cases

Fig. 1 shows the studied simplified HV/MV/LV network with rural MV network model including cables, overhead (OH) lines, OLTCS at HV/MV and MV/LV substations as well as MV DER units connected in the middle of the MV feeder. DERs' average models, similar to the models used and presented with more details in [7]-[11], have also been used in this paper. Three different MV DER units (1 MW PV, 2 MW BESS, 1 MW EV charging station) and three LV DER units (0.45 MW PV, 0.2 MW BESS, 0.2 MW EV charging) are used in the simulations but not at the same time (number of active DERs depends on the case, see Tables 1-3). In addition, Fig. 1 shows the used frequency level-dependent, adaptive  $QU$ -/ $Q$ -,  $PU$ -, and  $Pf$ -control methods of the DER units, the adaptive OLTC control methods as well as the simulated frequency behavior and the frequency level changes during the 250 s simulations in all the study cases (see Tables 1-3).

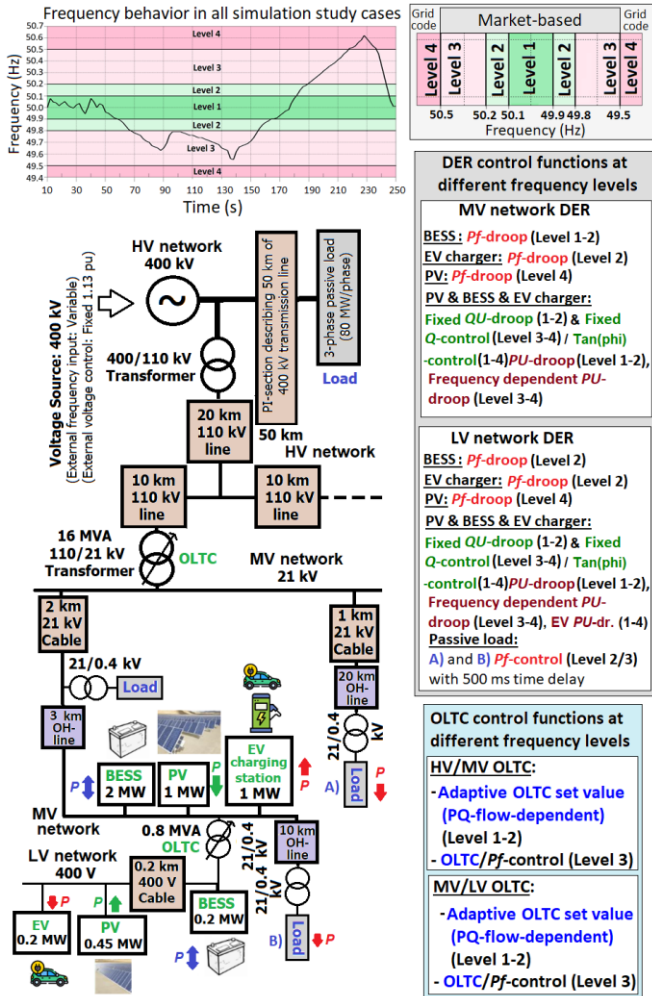


Fig. 1. Studied HV/MV/LV network model with active DER units in rural MV network (with cable and overhead, OH, lines) and DER units' control methods at MV and LV networks, OLTCs and their control principles at HV/MV and MV/LV substations (see Figs. 2 and 3) as well as frequency behavior and frequency level changes in the simulations with all different study cases).

Fig. 2a) presents HV/MV substation transformer's adaptive *PQ* flow -based OLTC settings for frequency levels 1-2 and Fig. 2b) demand response -based HV/MV OLTC operation logic and settings for frequency level 3. In Fig. 2c), correspondingly MV/LV substation transformer's adaptive *PQ* flow -based OLTC settings at the frequency levels 1-2 and in Fig. 2d) at the frequency level 3 are shown. Fig. 3 shows the principle of proposed further development of the TSO-DSO coordinated, frequency-dependent distributed DERs' and OLTCs' control scheme by adding FDLTR (frequency-dependent dynamic line/transformer rating) i.e. dynamic adaptive and frequency-dependent current/thermal (or power) limits for transformers and feeders (OH and cable lines) in it. In FDLTR method (Fig. 3), current/thermal or apparent (*S*)/active (*P*) power limits

- I) at frequency level 1-2 are also adaptive/dynamic taking into account the season (winter, summer), actual current measurements, ambient temperature and line/transformer

- II) during frequency levels 3-4 with more severe frequency deviations higher maximum current level for distribution network components (transformers and lines) can be momentarily allowed.

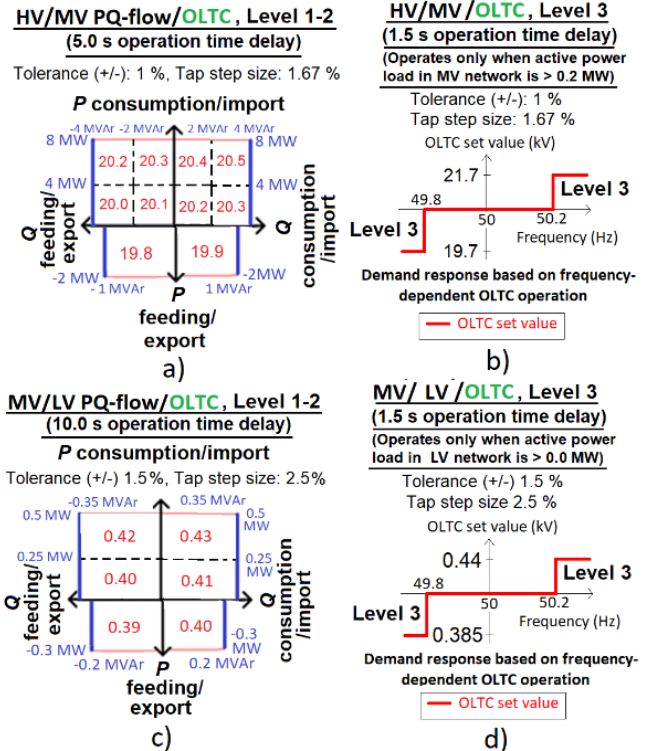


Fig. 2. a) HV/MV substation transformer's adaptive *PQ* flow -based OLTC setting at levels 1-2, b) demand response -based HV/MV OLTC operation logic and settings at level 3, c) MV/LV substation transformer's adaptive *PQ* flow -based OLTC setting at levels 1-2 and d) demand response -based MV/LV OLTC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

**Dynamic adaptive and frequency-dependent current (/thermal) and power limits for transformers and feeders (OH lines & cables)**

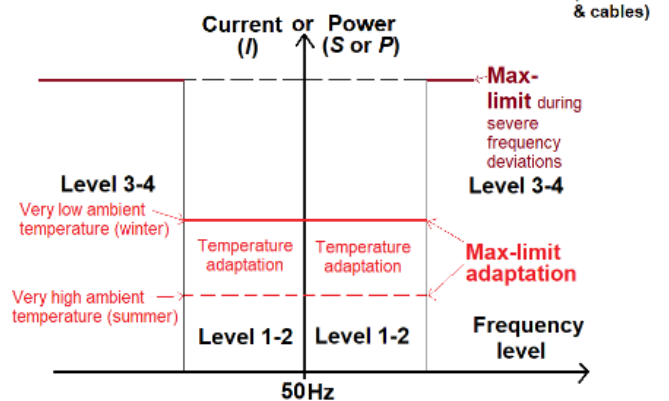


Fig. 3. Principle of FDLTR (frequency-dependent dynamic line/transformer rating) i.e. dynamic adaptive and frequency-dependent current/thermal (or power) limits for transformers and feeders (OH and cable lines).

In Fig. 4, MV and LV DER units'  $P_f$ ,  $P_U$ ,  $Q_U$ -droops and  $Q$ -settings at different frequency levels are presented.

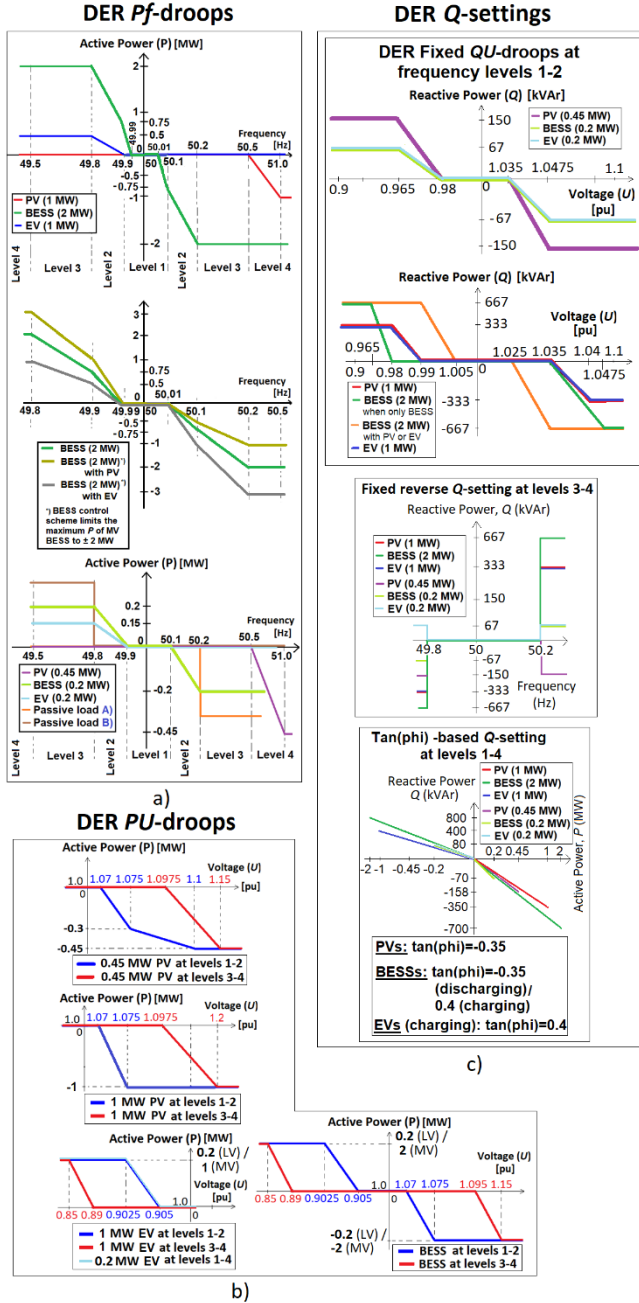


Fig. 4. a) MV and LV DERs'  $P_f$ -droops, b) LV DERs' and MV BESS's  $P_U$ - and c)  $Q_U$ -droops or  $Q$ -settings when MV BESS is located in the middle of MV feeder, see also Figs. 1 and 2).

In Table 1, basic information of the studied simulation cases is presented. Table 2 shows the main study cases CASE 1 and CASE 2 which are used to compare the effect of different DER  $Q$  -control schemes focusing on  $\tan(\phi)$ -based control in CASE 2. After that, Table 3 presents the subcases with MV PV unit (CASE 1 PV\_A, CASE 1 PV\_B and CASE 2 PV) or with MV EV charging unit (CASE 1 EV and CASE 2 EV) and their differences to the main study cases CASE 1 and 2.

Table 1. Basic information of the study cases (see Figs. 1-4 & Tables 2 and 3 for more information).

Case <sup>a)</sup>	Type of MV network	MV DERs' connection point	OLTC control (at level 1-2) / Time delay
All Cases	Rural	Middle of MV feeder	$PQ$ flow-based (HV/MV)/5 s & MV/LV/10 s

<sup>a)</sup> 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. 1)

Table 2. Main study cases to compare the effect of different DER reactive power ( $Q$ ) -control schemes (see Figs. 1-4 & Tables 1 and 3 for more information).

Case	MV and LV DERs'	DERs' $Q$ -control at level 1-2	DERs' $Q$ -control at level 3-4	Adaptation principle of DERs' $Q$ -control
CASE 1	MV: BESS (2 MW) LV: BESS (0.2 MW), PV (0.45 MW)	Fixed $Q_U$ -droop	Fixed reverse $Q$ -setting	Frequency level change (2↔3)
CASE 2		PVs: $\tan(\phi)=-0.35$ BESSs: $\tan(\phi)=-0.35$ (discharging) / 0.4 (charging) EVs (charging): $\tan(\phi)=0.4$		-

Table 3. Studied subcases with MV PV unit (CASE 1 PV\_A, CASE 1 PV\_B and CASE 2 PV) or with MV EV charging unit (CASE 1 EV and CASE 2 EV) and their differences to the main study cases CASE 1 and 2 (Figs. 1-4 & Tables 1-2).

Cases	Differences to CASE 1 and CASE 2
CASE 1 PV_A CASE 1 PV_B <sup>a)</sup> CASE 2 PV_A CASE 2 PV_B <sup>a)</sup>	<ul style="list-style-type: none"> <li>- PV unit (1 MW) in the middle of MV feeder at the same connection point with MV BESS</li> <li>- MV BESS with more sensitive <math>Q_U</math>-droop (at frequency level 1-2) than PV</li> <li>- MV BESS <math>P</math>-control compensates MV PV active power fluctuations and provides unsymmetrical frequency support (Fig. 4, different MV BESS <math>P_f</math>-droop than without PV or with EV)</li> </ul>
CASE 1 EV CASE 2 EV	<ul style="list-style-type: none"> <li>- In LV network 0.2 MW EV charging load (instead of 0.45 MW PV)</li> <li>- Fast EV charging unit (1 MW) in the middle of MV feeder at the same connection point with MV BESS</li> <li>- MV BESS with more sensitive <math>Q_U</math>-droop (at frequency level 1-2) than EV</li> <li>- MV BESS <math>P</math>-control compensates MV EV active power consumption and provides unsymmetrical frequency support (Fig. 4, different MV BESS <math>P_f</math>-droop than without EV or with PV)</li> </ul>

<sup>a)</sup> More rapid PV output power fluctuations

### 3 Simulation Results

In this Section, the main simulation results from the different study cases (Tables 1-3) are presented. The total simulation time  $t$  in all cases was 250 s and frequency behavior between  $t=10$ -250 s is shown in Fig. 1. The PSCAD simulation results from Tables 1-3 cases are shown in Figs. 5-7. In Fig. 5,  $P$  and  $Q$  flows through the HV/MV and MV/LV substations are presented. Fig. 6 shows the voltages at the HV/MV and MV/LV substations as well as at the end of LV feeder with PV and BESS. In Fig. 7, phase A RMS-currents in different cases (Tables 1-3) through HV/MV and MV/LV transformers as well as at the beginning of MV and LV feeders with PV/EV and BESS are presented.

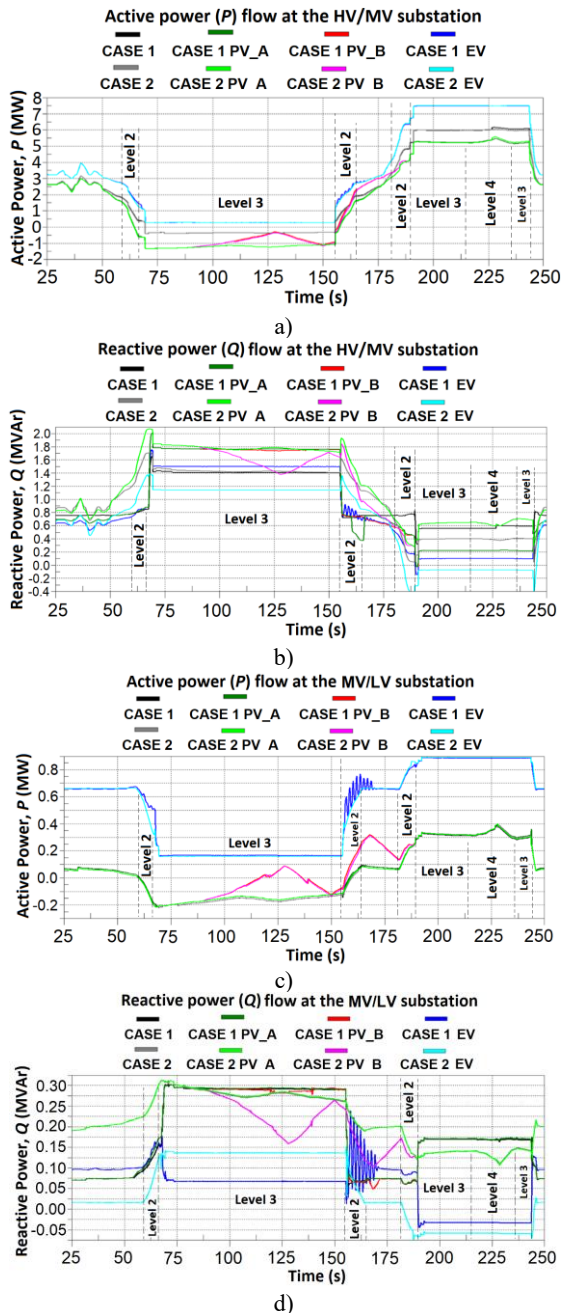


Fig. 5. a) Active, b) reactive power flow at the HV/MV substation, c) active and d) reactive power flow at the MV/LV substation in the different cases (see Figs. 1-2 & Tables 1-3).

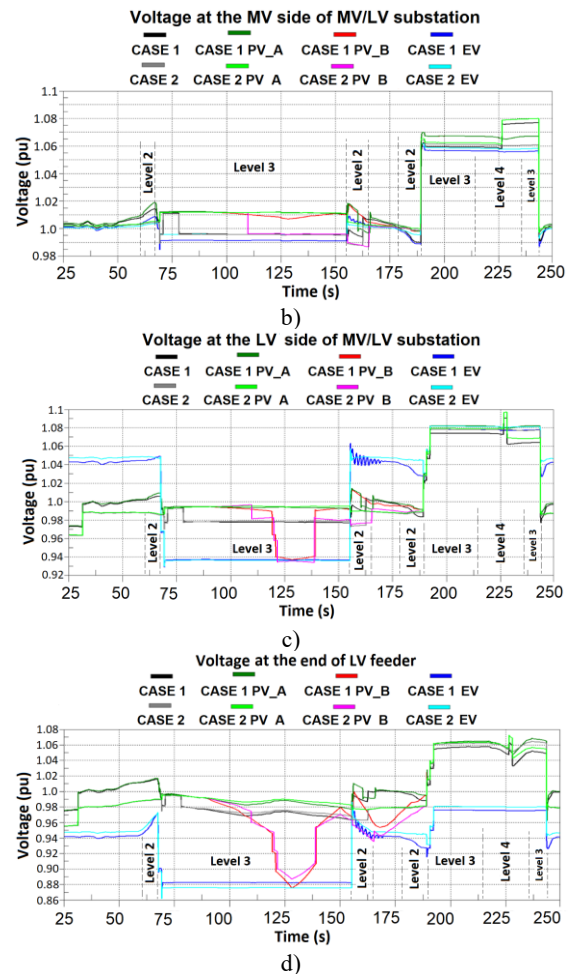
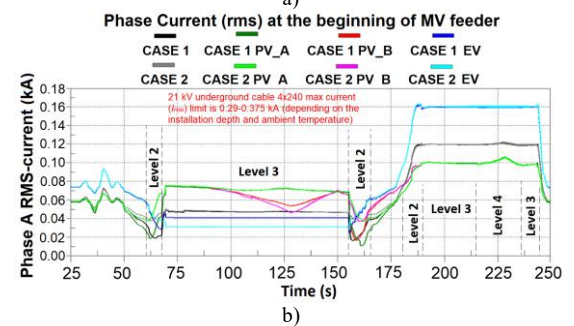
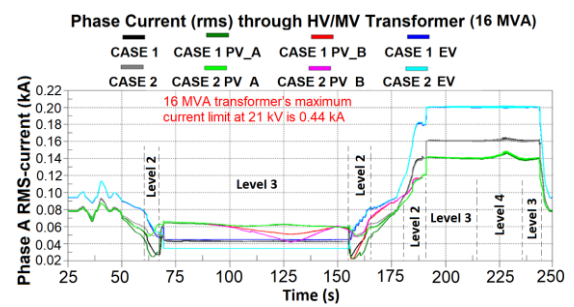
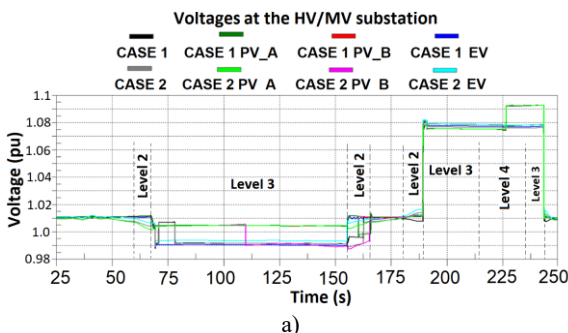


Fig. 6. Voltages in different cases at the a) HV/MV substation, b) MV side of MV/LV substation with PV/EV and BESS in the LV network, c) LV side of MV/LV substation and d) end of LV feeder with PV/EV and BESS (see Figs. 1-2 & Tables 1-3).



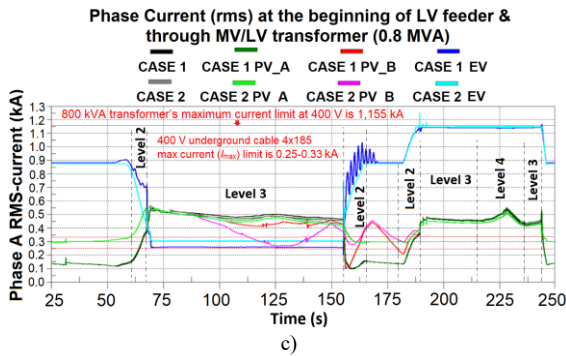


Fig. 7. Phase A RMS-currents in different cases at the a) HV/MV transformer, b) Beginning of MV feeder with PV/EV and BESS in the LV network, c) Beginning of LV feeder & MV/LV transformer with PV/EV and BESS (see Figs. 1-3 & Tables 1-3).

Based on the simulation results of Figs. 5-7, one can see that the largest differences are between the cases CASE 1/2 PV\_A/B and CASE 1/2 EV (Tables 2 and 3) due to the different amount of load (EV) or generation (PV, instead of EV). In cases CASE 1/2 PV\_B with more rapid PV  $P$  fluctuations also some deviations in the provided  $P$  support (Fig. 5) when compared to cases CASE 1/2 PV\_A can be seen. In addition, it can be concluded from the simulation results (Figs. 5-7), that during more severe level 3 under-frequency situation,  $\tan(\phi)$ -based DER reactive power  $Q$ -control principle did not enable use of the allowed voltage range (Fig. 6) in the same way as the previously proposed frequency-dependent  $Q$ -control principles for DERs. Therefore, also the simultaneous  $P$ -based frequency support (Fig. 5) for the TSO network was smaller. However, due to the tapping of HV/MV and MV/LV transformer OLTCs with frequency-dependent settings, the situation may also change during severe over-frequency situations as seen in the simulations. On the other hand,  $\tan(\phi)=-0.35$  -based PV's reactive power  $Q$ -control principle led, for example, to higher current flows through MV/LV transformer (Fig. 7) during smaller level 1-2 frequencies as well as to lower MV/LV transformer current flows during more severe level 3-4 frequency deviations. Fig. 7 shows that 16 MVA HV/MV and 0.8 MVA MV/LV transformer's maximum current limits were not exceeded in the simulations. In addition, 21 kV 4x240 underground cable's max current ( $I_{max}$ ) limit (0.29-0.375 kA depending on the installation depth and ambient temperature) was not exceeded at the beginning of MV feeder (Fig. 7), but 400 V LV feeder 4x185 underground cable's max current ( $I_{max}$ ) limit (0.25-0.33 kA) was exceeded due to used simplified LV network topology with only one LV feeder (Fig. 1). However, at frequency levels 1-2 LV feeder's max current limit could be adaptive (Fig. 3) by taking also ambient temperature etc. into account as well as frequency level -dependent (Fig. 3). But how much lines' and transformers' max current ( $I_{max}$ ) or power limit (Fig. 3) could be exceeded during severe level 3-4 frequency deviations and how long? This should be further determined and studied i.e. could the limits be in most of the cases, for example, so that  $I_{max\_limit\_level\_3-4}=2*I_{max\_limit\_level\_1-2}$  for 10-15 s and  $I_{max\_limit\_level\_3-4}=1.5*I_{max\_limit\_level\_1-2}$  for 45-60 s taking into account the thermal constants of the network components as well as other relevant issues.

## 4 Conclusions

This paper further developed the TSO-DSO coordinated, frequency-dependent DERs' and OLTCs' control scheme by proposing dynamic adaptive and frequency-dependent current/thermal limits utilization for distribution network lines, cables and transformers as well as compared the utilization of  $\tan(\phi)=-0.35$   $Q$ -control method to the previously proposed DERs' frequency-dependent  $Q$ -control principles. Also the effect of more rapid PV  $P$  fluctuations as well as further modified  $Pf$ -droop settings in MV BESS's multi-use cases with PV and EV were studied by PSCAD simulations. The main conclusions from the simulations have been stated at the end of Section 3 Simulation Results.

## 5 Acknowledgements

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