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COORDINATED CONTROL SCHEMES FOR IMPROVED DER HOSTING CAPACITY AND FLEXIBILITY PROVISION

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Abstract

In the future, efficient utilization of all potential flexible energy resources from different voltage levels is needed to fulfill simultaneously the flexibility needs of local distribution system operator (DSO) and system-wide transmission system operator (TSO) in a coordinated way. This paper studies coordinated and frequency level-dependent distributed energy resources' (DERs') control and adaptive on-load-tap-changer (OLTC) management scheme to enable prioritized flexibility services provision for the DSOs and TSO. The main idea is that the coordination of flexibilities utilization between distribution and transmission system operators is done depending on the frequency deviation severity. During smaller frequency deviations priority is on DSO needs and during larger frequency deviations priority is on TSO needs in order to support the frequency stability of the whole power system. However, the overall target is to increase DERs' hosting capacity in the DSO network and increase their availability for the TSO flexibility services provision during the smaller frequency deviations. In this paper, the effect of different DERs' reactive power control schemes, their location and type of distribution feeders are studied with multiple PSCAD simulations.

1 Introduction

In the future, DER control and management in coordination with OLTCs could be increasingly used to fulfill the TSO and DSO flexibility needs. Flexibility services provided by DER can be used to support the power system frequency (*f*) and local voltage (*U*) or congestion management at the corresponding voltage levels. The effective use of different active (*P*) and reactive power (*Q*) control or voltage level control -based flexibility services could be achieved by coordinated utilisation of DERs and OLTCs. Effective active network management (ANM) and DER control for different local (DSO) and system-wide (TSO) flexibility services provision requires also new collaborative DSO and TSO operation and planning principles based on active use of flexibilities. Potential conflict of interest between DSOs and TSO in utilisation of the flexibility services from distribution network connected resources should be avoided by enhanced TSO-DSO coordination, state-forecasting and state-monitoring. For instance, different DER units' *P* and *Q* control modes, settings and coordination with OLTC settings and other ANM functionalities should be increasingly considered already in the planning phase. [1]-[8]

This paper studies further previously proposed [8] novel adaptive, coordinated and frequency level-dependent DER inverter and adaptive OLTC management scheme in order to enable prioritized flexibility services provision for the TSOs and DSOs. In the proposed scheme, DER *QU*, active power-voltage (*PU*) and active power-frequency (*Pf*) -droops and OLTC management principles are adapted depending on the frequency deviation severity i.e. level so that in case of larger frequency deviation (level 3 or 4) support for the whole power system and TSO needs is prioritized (see frequency levels from Fig. 1 and 2). In the proposed scheme, during smaller frequency deviations (level 1 or 2) HV/MV and MV/LV OLTCs are controlled based on real-time *P* and *Q* flows between different voltage levels. The target is to increase DER hosting capacity in the DSO network as well as increase the availability of the distribution network connected DER for the TSO flexibility services provision at levels 1-2.

Previous studies in [8] focused on urban MV and LV network in which MV network connected DER units were directly connected to the HV/MV substation MV busbar. However, in this paper the effect of MV DERs (BESS, BESS+PV or BESS+EV charging) location in the middle of MV feeder as well as the effect of type of MV feeders (urban/cable or rural/overhead line) is studied further with PSCAD simulations. Based on the previous studies [8]-[13], the location i.e. the connection point of the MV DER unit also has an effect on the feasible *P* and *Q* control methods. Therefore, the studied control schemes and settings of the MV DER (e.g. *QU*- and *PU*-control) in the middle of MV feeder are different than with the DER connected directly at HV/MV substation. In addition, different frequency level-dependent DER fixed or adaptive *QU*-control schemes will be compared when simultaneously the control of HV/MV and MV/LV OLTCs is *PQ*-flow based.

This paper studies also the effect of modified and coordinated *QU*- and *Pf*-droop settings and *P* capacity sharing of MV BESS in multi-use schemes with PV and EV dependent on the frequency deviation level (1-4). This means, for example, that during smaller frequency deviations (level 1-2, Fig. 1 and 2) part of the BESS *P* capacity is used locally to manage PV or fast EV charging effects (DSO needs) and remaining part of the BESS *P* capacity is used to system-wide frequency support (TSO needs) by modified *Pf*-droop. In addition, during larger frequency deviations (level 3-4) TSO flexibility needs are prioritized and DERs' as well as OLTCs' settings are adapted accordingly.

2. Study System

The simulation studies are done with simplified HV/MV/LV network PSCAD model including active DER units in the MV network (1 MW PV, 2 MW BESS, 1 MW EV charging station) and in the LV network (0.45 MW PV, 0.2 MW BESS) as well as OLTCs at HV/MV and MV/LV substations as shown in Fig. 1.

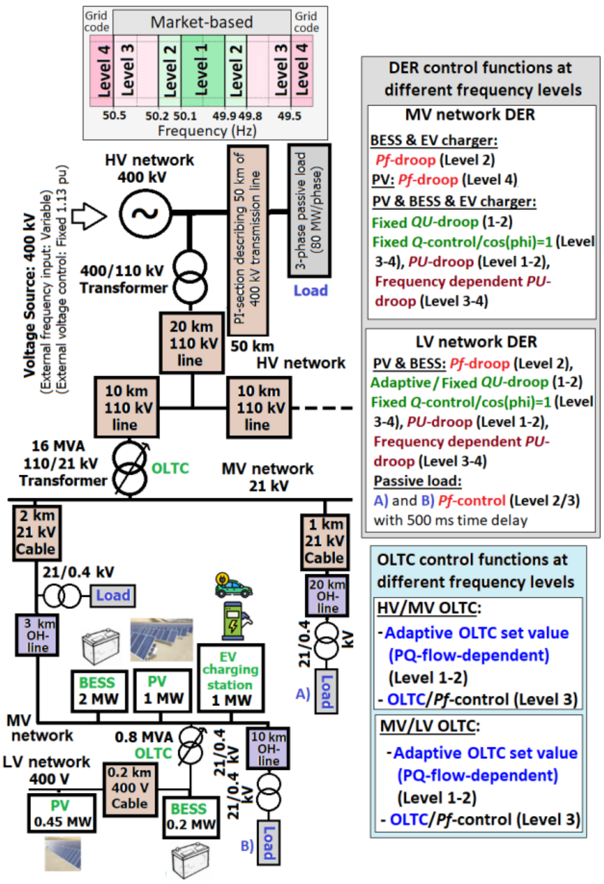


Fig. 1. Studied HV/MV/LV network model with active DER units in rural MV network (with overhead, OH, lines) and DER units' control methods at MV and LV networks as well as OLTCs and their control principles at HV/MV and MV/LV substations (see Fig. 2-4, urban MV network-based study system is described in detail in [8]).

Fig. 1 shows the rural MV network model with overhead (OH) lines and MV DER units' connection in the middle of the MV feeder. Urban MV network-based study system can be found from [8]. DER average models, similar to the models in [14]-[17], are also used in this paper. Fig. 1 presents the used frequency level-dependent, adaptive *QU*-, *PU*-, and *Pf*-control methods of the DER units as well as the adaptive OLTC control methods. Fig. 2 shows the simulated frequency behavior and the frequency level changes during the 250 s simulation in the different study cases. In Fig. 3a), HV/MV substation transformer's adaptive *PQ* flow -based OLTC settings for frequency levels 1-2 are shown. Fig. 3b) presents demand response -based HV/MV OLTC operation logic and settings for frequency level 3. Correspondingly, Fig. 3c) shows MV/LV substation transformer's adaptive *PQ* flow -based OLTC settings for the frequency levels 1-2 and Fig. 3d) for the frequency level 3.

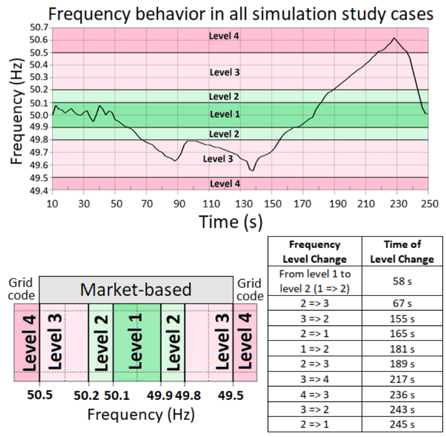


Fig. 2. Frequency behavior and frequency level changes in the simulations with all different study cases (see Fig. 1).

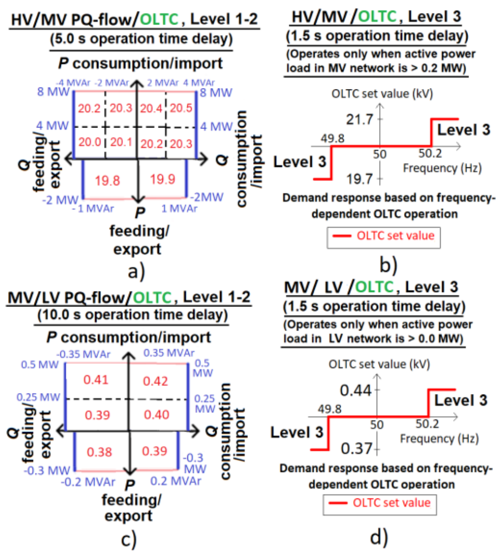


Fig. 3. a) HV/MV substation transformer's adaptive *PQ* flow -based OLTC setting at levels 1-2, b) demand response -based HV/MV OLTC operation logic and settings at level 3, c) MV/LV substation transformer's adaptive *PQ* flow -based OLTC setting at levels 1-2 and d) demand response -based MV/LV OLTC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

Fig. 4 presents DER *Pf*-, *PU*- and *QU*-droops at different frequency levels in detail.

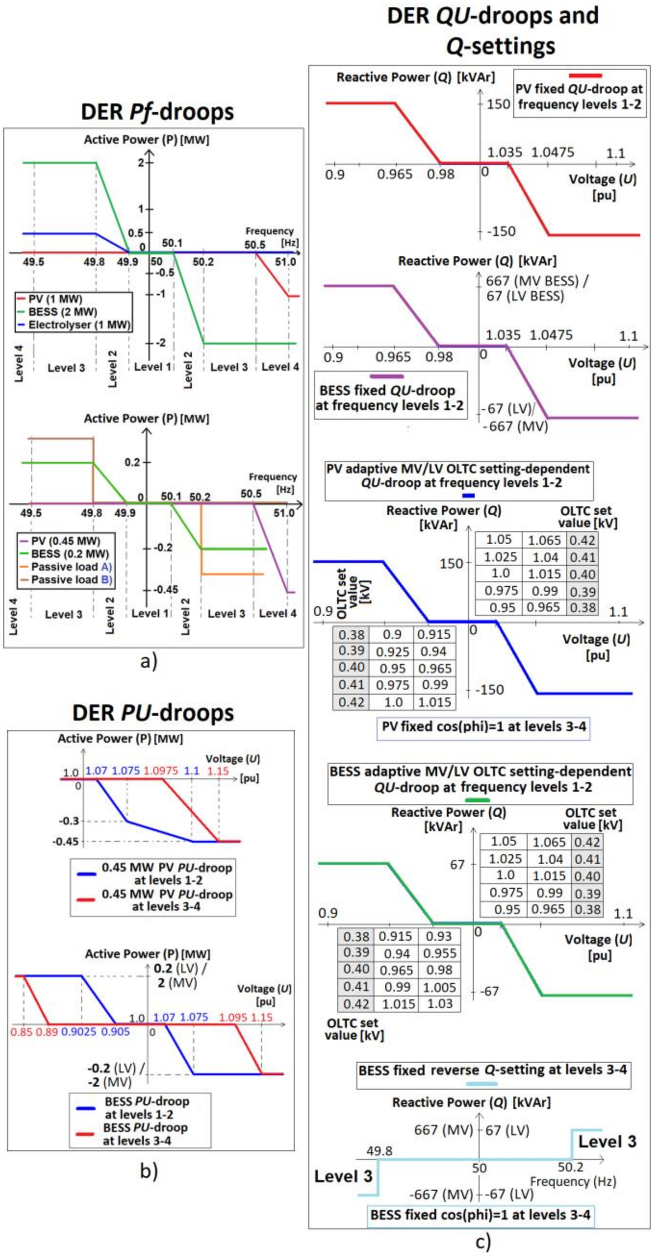


Fig. 4. a) MV and LV DER *Pf*-droops, b) LV DER and MV BESS *PU*- and c) *QU*-droops or *Q*-settings when MV BESS is located in the middle of MV feeder, see also Fig. 1-3).

3 Simulations

In the following subsections 3.1-3.3 of this Section 3, the main simulation results from the different study cases are presented. First, in Section 3.1 results from the simulations about the effect of MV DER location and type of MV network (urban/cables or rural/OH lines) are shown. After that, Section 3.2 presents the results from the simulations related to the effect of different DER reactive power control schemes in urban or rural MV network. At last, Section 3.3. shows the simulations about the multi-use of rural MV network-connected BESS with PV or EV. The total simulation time in all cases was *t*=250 s and frequency behavior between *t*=10-250 s was as shown in Fig. 2.

3.1 Effect of MV DER Location and Type of MV network

The main simulation study cases of this Section 3.1 are presented in Table 1. It should be noted that the HV/MV OLTC frequency-dependent control is blocked when frequency deviation from nominal 50 Hz is more than ± 0.2 Hz and MV network *P* load is less than 0.2 MW (Fig. 3b) Respectively, MV/LV OLTC frequency-dependent control is blocked if LV network *P* load less than 0 MW (Fig. 3d). In addition, directly at MV or LV bus connected DERs' active powers are not considered in the blocking logic when calculating the total MV or LV *P* load (Fig. 3b and 3d).

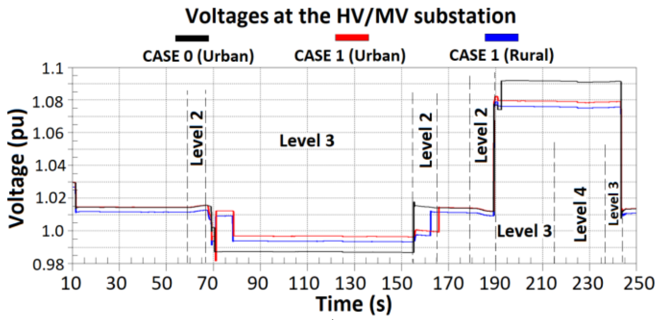
Table 1. Cases to study the effect of MV DER location and type of MV network (see Fig. 2, 4 and 5 for more information e.g. *Pf*- and *PU*-droops of DER units at the different frequency levels).

Case*),**),***)	**Type of MV network**	**MV DER (BESS) connection point**	**DER *QU*-control (LV DER) at level 3-4**	**OLTC control (at level 1-2) / Time delay**
CASE 0 (Urban)	Urban	HV/MV substation	Fixed cos(*φ*)=1	*PQ* flow-based (HV/MV)/5 s & MV/LV)/10 s
CASE 1 (Urban)	Urban	Middle of MV feeder		
CASE 1 (Rural)	Rural			

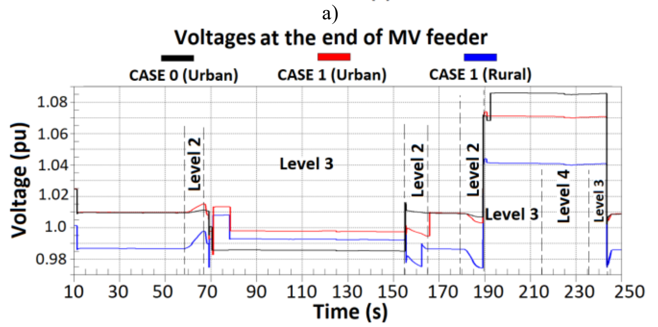
*) Demand response frequency control settings (with 500 ms time delay after +/- 0.2 Hz frequency deviation i.e. disconnection/connection of passive load at level 2/3, see Fig. 2), **) Adaptation of *QU*-droop (LV DER) based on frequency level, ***) *QU*-droop (LV DER) fixed on frequency level 1-2

The PSCAD simulation results from Table 1 cases to study the effect of MV DER location and type of MV network are shown in Fig. 5-8. Fig. 5 shows the voltages of different cases (Table 1) at the HV/MV and MV/LV substations as well as at the end of LV feeder with PV and BESS. It can be seen from Fig. 5, for example, that during frequency level 3-4 under- and over-frequencies the lowest and highest voltages of CASE 0 (Urban) with MV BESS directly at HV/MV substation (Table 1) can potentially best support the power system frequency by the voltage-dependent demand response.

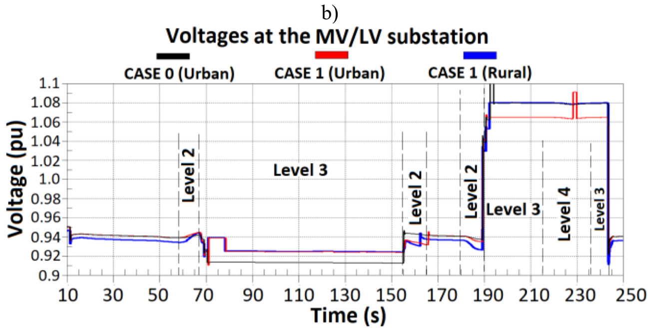
Fig. 6 presents the *P* and *Q* flows at the HV/MV substation in different cases (Table 1), Fig. 7 shows 2 MW MV BESS reactive power *Q* behavior in different study cases and Fig. 8 presents *P* and *Q* flows at the MV/LV substation. Reactive power *Q* flow differences (Fig. 6b) at the HV/MV substation are due to different MV BESS *Q*-control principles during frequency level 3-4 under- and over-frequencies (Fig. 7). These are dependent on the connection point of MV BESS as well as on the type of MV feeders (urban/cables or rural/OH lines) having different reactance values. Fig. 6c) shows the provided active power *P* flexibility through HV/MV substation in the different cases. It can be seen that due to slightly lower and higher voltages (Fig. 5) during frequency level 3-4 under- and over-frequencies in CASE 0 (Urban) also the provided active power support is highest in this case.



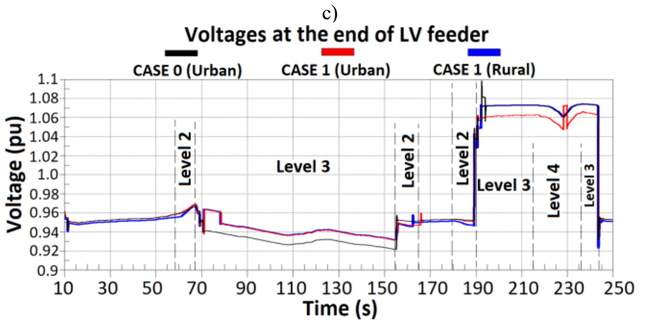
a)



b)

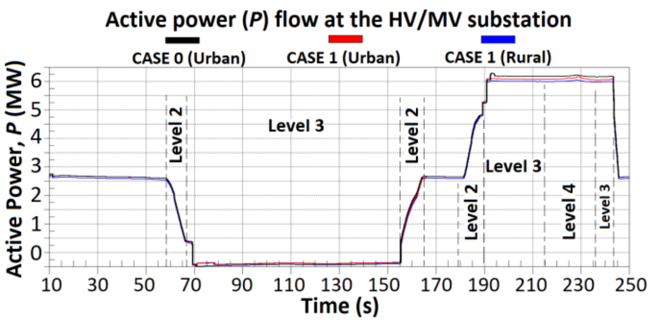


c)

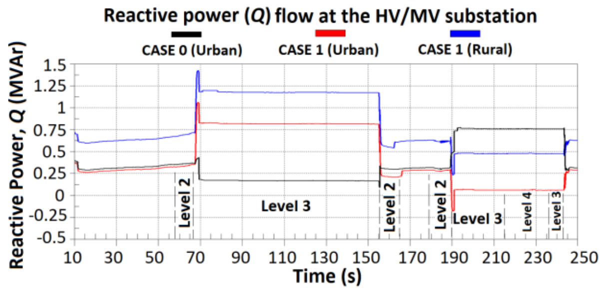


d)

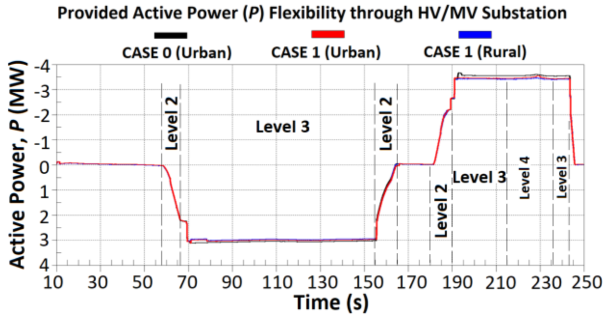
Fig. 5. Voltages in the different cases at the a) HV/MV substation, b) end of MV feeder with PV and BESS in LV network, c) MV/LV substation and d) end of LV feeder with PV and BESS (see Fig. 1-4 & Table 1).



a)



b)



c)

Fig. 6. a) Active, b) reactive power flow at the HV/MV substation and c) provided *P* flexibility through HV/MV substation in the different cases (see Fig. 1-4 & Table 1).

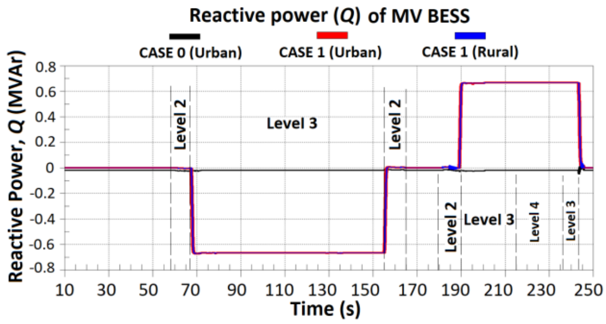
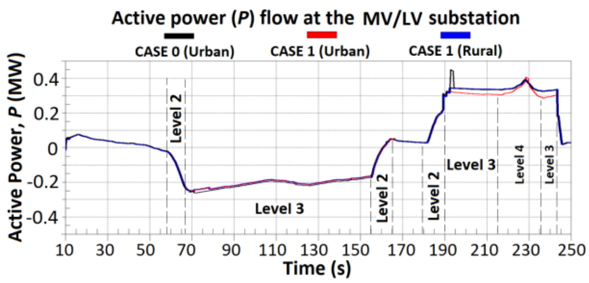
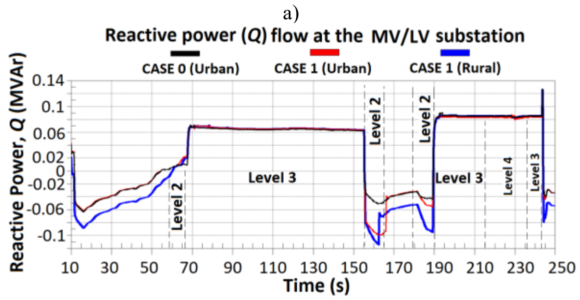


Fig. 7. 2 MW MV BESS reactive power *Q* behavior in different study cases (see Fig. 1-4 & Table 1).



a)



b)

Fig. 8. a) Active and b) reactive power flow at the MV/LV substation in the different cases (see Fig. 1-4 & Table 1).

3.2 Effect of Different DER Reactive Power Control Schemes in Urban or Rural MV Network

The simulation study cases of this Section 3.2 are shown in Table 2. Fig. 9 presents 0.45 MW LV PV's fixed reverse *Q*-setting (at frequency levels 3-4) in CASE 3 (Rural) (Table 2). In Fig. 4c), respective fixed reverse *Q*-setting was shown for the LV BESS. It was previously concluded in [8] that LV PV and BESS *QU*-droop adaptation should be delayed according to the MV/LV OLTC operation time delay i.e. 10 s to avoid rapid DER reactive power changes before actual MV/LV OLTC tapping. Therefore, in CASE 2 (Urban) and CASE (Rural) (Table 2) LV DER units' active *QU*-droop setting (Fig. 4c) activation has similar adaptation time delays as the MV/LV OLTC (Fig. 3c) i.e. 10 s. Also MV BESS has active *QU*-droop setting adaptation delay of 5 s in these cases which is similar to HV/MV OLTC operation time delay (Fig. 3a) during frequency levels 1-2 (adaptation of *QU*-droop setting is done correspondingly as for LV BESS, see Fig. 4c).

Table 2. Cases to study the effect of different DER reactive power control schemes in urban or rural MV network (see Fig. 1-4 for more information).

Case*), o)	**Type of MV network**	**DER *QU*-control (LV DER)**	**Adaptation of *QU*-droop (LV DER) ***)**	**DER *QU*-control (LV DER) at level 3-4**
CASE 2 (Urban) oo)	Urban	*QU*-droop (adaptive, level 1-2) **)	MV/LV OLTC set value & Freq. level	Fixed cos(*φ*)=1
CASE 2 (Rural) oo)	Rural			
CASE 1 (Urban)	Urban	*QU*-droop (fixed, level 1-2)	Frequency level	
CASE 1 (Rural)	Rural			
CASE 3 (Rural)	Rural			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. 1), **) With adaptation delay similar to MV/LV OLTC operation time delay, ***) Based on, o) OLTC control (at level 1-2) *PQ* flow-based / Time delay (HV/MV)/5 s & MV/LV)/10 s, oo) MV BESS with adaptation delay similar to HV/MV OLTC operation time delay

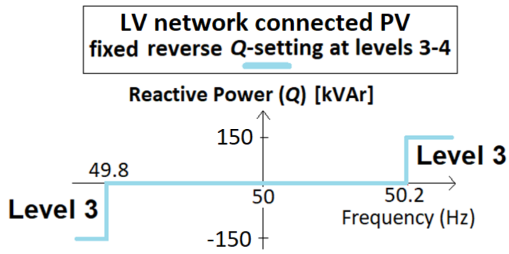


Fig. 9. 0.45 MW LV PV's fixed reverse *Q*-setting (at frequency levels 3-4) in CASE 3 (Rural) (see Fig. 1-4 & Table 1 and 2).

The PSCAD simulation results of Table 2 cases, to study the effect of different DER reactive power control schemes in urban/rural MV network, are shown in Fig. 10-12. It can be seen from Fig. 10 that the type of MV network (urban/cables or rural/OH lines) did not much affect to the voltages. Instead the differences were due to MV and LV DER reactive power *Q* control scheme differences (Table 2).

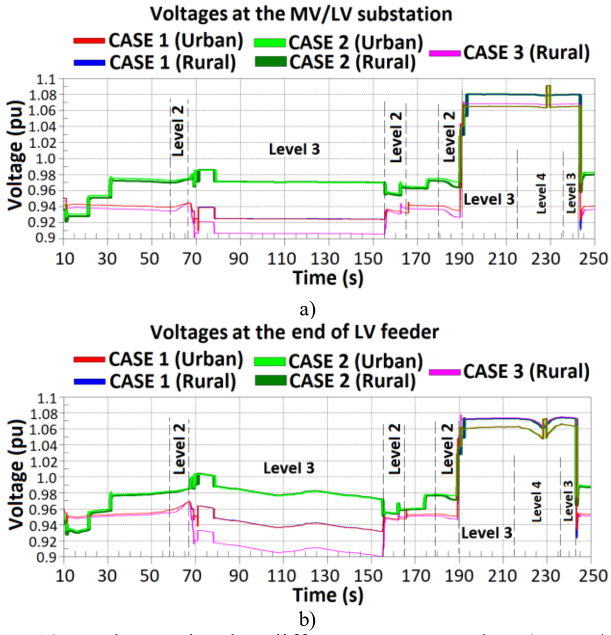


Fig. 10. Voltages in the different cases at the a) MV/LV substation and b) end of LV feeder with PV and BESS (see Fig. 1-4 & Table 1 and 2).

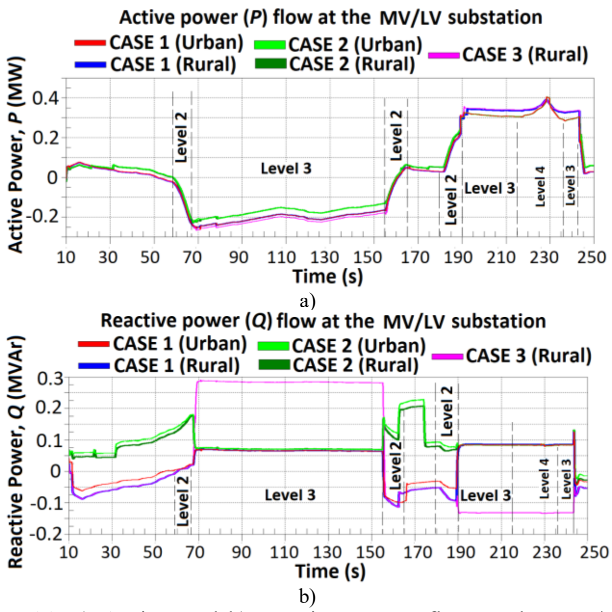
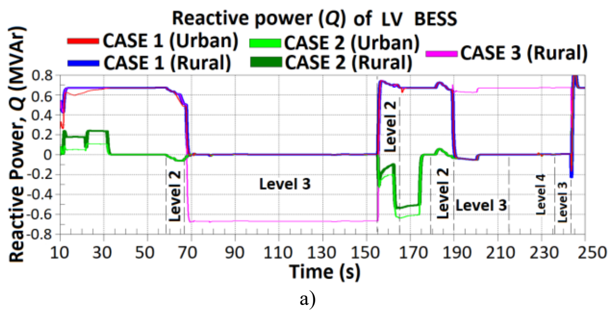
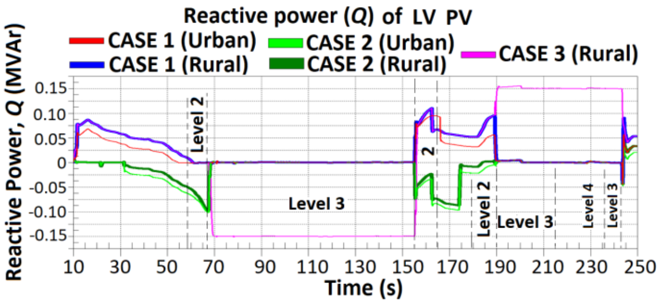


Fig. 11. a) Active and b) reactive power flow at the MV/LV substation in the different cases (see Fig. 1-4 & Table 1 and 2).





b)

Fig. 12. a) 0.2 MW LV BESS and b) 0.45 MW LV PV reactive power Q behavior in the different study cases (see Fig. 1-4 & Table 1 and 2).

From Fig. 11a) it can be seen that due to lower local voltages in CASE 3 (Rural) with the LV DER having fixed reverse Q-setting (Table 2, Fig. 4c and 9) during level 3-4 under-frequencies, the contribution of voltage-dependent LV network loads and DER to the frequency support is better (i.e. active power flow from the MV/LV substation is higher) than in the other Table 2 cases. Fig. 12 presents the LV network-connected BESS's and PV unit's reactive power Q behavior in the different study cases (Table 2). It can be seen from the Fig. 11b) that due to higher local voltages (Fig. 10 a and b), the direction of the reactive power flow at the MV/LV substation is opposite in CASE 2 (Urban) and CASE 2 (Rural) with adaptive QU-droops (Table 2) during frequency levels 1-2 when compared to the other cases of Table 2.

In overall, it can be concluded that the utilization of MV and LV DER QU-droop adaptation based on the simultaneous MV/LV or HV/MV OLTC setting (CASE 2 (Urban) & (Rural), Table 2) is not recommended from the TSO frequency support viewpoint. From the LV network voltages (Fig. 10) and PV hosting capacity viewpoint similar conclusions can be drawn i.e. CASE 1 (Urban) & (Rural) & CASE 3 (Rural) can better enhance PV hosting capacity during normal operation at levels 1-2 than CASE 2.

3.3 Multi-use of Rural MV Network-Connected BESS with PV or EV

The simulation study cases of this Section 3.3 are presented in Table 3. Fig. 13 shows the MV DERs' fixed QU-droops (at frequency levels 1-2) and MV EV's and BESS's fixed reverse Q-setting (at frequency levels 3-4) when the MV BESS is located in the middle of MV feeder simultaneously with the PV or EV at the same connection point i.e. CASE 1 PV (Rural) and CASE 1 EV (Rural) in Table 3 (see also Fig. 1-4 & Table 1). MV BESS's Pf-droops in the different cases (Table 3) are presented in Fig. 14. Related to those it should be noted that the used BESS control scheme limits the maximum active power P of the MV BESS to ± 2 MW in the simulations. In Fig. 15, the PU-droops of the MV PV and EV at the frequency levels 1-2 and 3-4 can be seen.

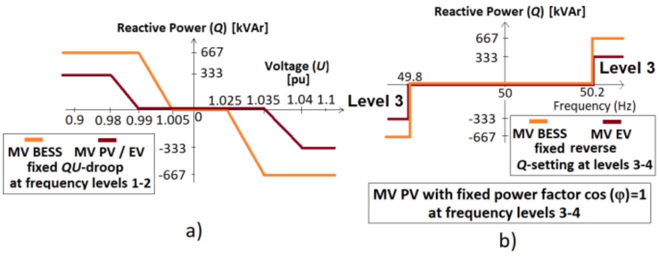


Fig. 13. MV DER's a) Fixed QU-droops (at frequency levels 1-2) and b) MV EV and BESS fixed reverse Q-setting (at frequency levels 3-4) when MV BESS is located in the middle of MV feeder simultaneously with PV or EV at the same connection point (see Fig. 1-4 & Table 1 and 3).

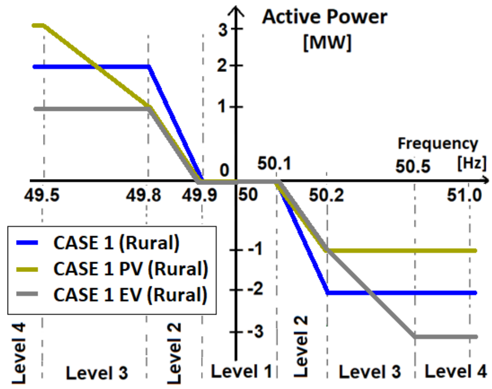


Fig. 14. MV BESS's Pf-droops in different cases (see Fig. 1-4 & Table 1 and 3), BESS control scheme limits the maximum P of MV BESS to ± 2 MW.

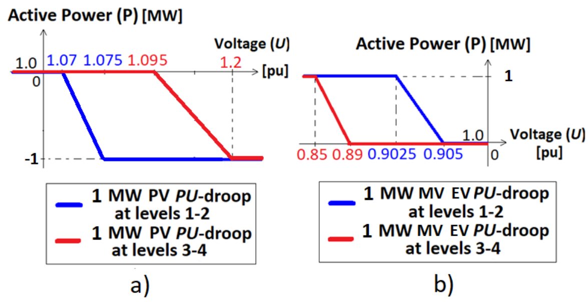


Fig. 15. a) MV PV's and b) EV's PU-droop at frequency levels 1-2 and 3-4 (see Fig. 1-4 & Table 1 and 3).

Table 3. Studied CASE 1 (Rural) (Fig. 13-15 & Table 1 and 2) related cases with the PV (CASE 1 PV (Rural)) or EV charging unit (CASE 1 EV (Rural)) and their differences.

Cases	Differences to CASE 1 (Rural)
CASE 1 (Rural)	-
CASE 1 PV (Rural)	- PV unit at the middle of MV feeder at the same connection point with MV BESS - MV BESS with more sensitive QU-droop (level 1-2) than PV - MV PV Q-control at frequency level 3-4: Fixed cos(φ)=1 - MV BESS P-control compensates MV PV active power fluctuations and provides unsymmetrical frequency support (Fig. 14, different new MV BESS Pf-droop than with EV)
CASE 1 EV (Rural)	- Fast EV charging unit at the middle of MV feeder at the same connection point with MV BESS - MV BESS with more sensitive QU-droop (level 1-2) than EV - MV EV Q-control at freq. level 3-4: Fixed reverse Q-setting - MV BESS P-control compensates MV EV active power consumption and provides unsymmetrical frequency support (Fig. 14, different new MV BESS Pf-droop than with PV)

The PSCAD simulation results from the Table 3 cases in order to study the multi-use of rural MV network-connected BESS with PV or EV are presented in Fig. 16-18.

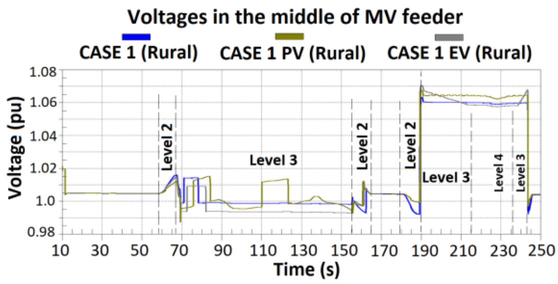


Fig. 16. Voltages in the different cases at the connection point of MV DER unit(s) (Fig. 1-4 & Table 1 & 3).

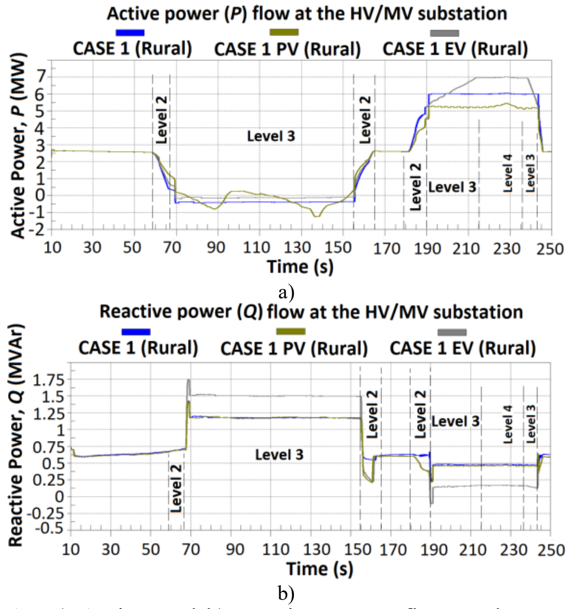
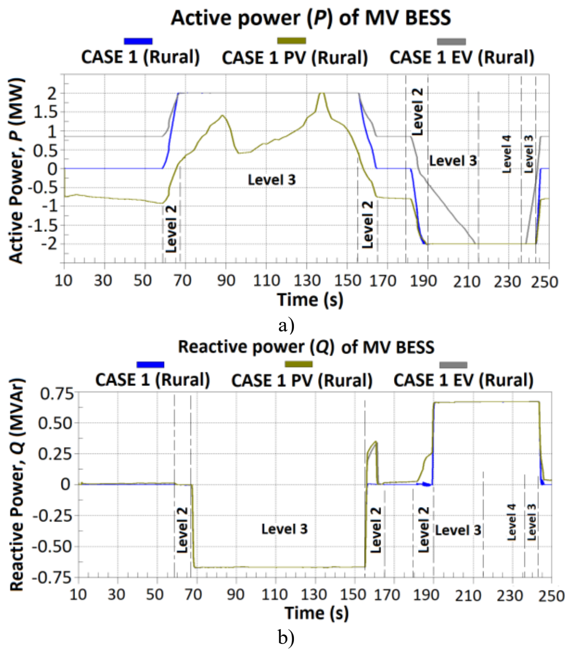


Fig. 17. a) Active and b) reactive power flow at the HV/MV substation in the different cases (Fig. 1-4 & Table 1 & 3).



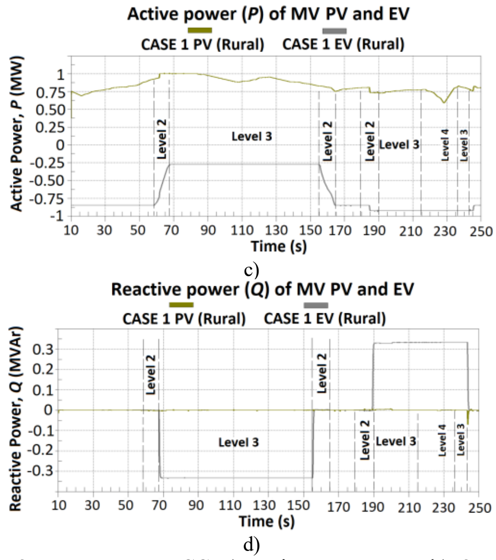


Fig. 18. 2 MW MV BESS a) active power *P*, b) 2 MW MV BESS reactive power *Q*, c) 1 MW MV EV and PV active power *P* and d) 1 MW MV EV and PV reactive power *Q* behavior in the different study cases (Fig. 1-4 & Table 1 & 3).

It can be seen from Fig. 16 that there is a momentarily voltage increase in the CASE 1 PV (Rural) during level 3 under-frequency (at *t*= 67-155s, Fig. 2). This is due to the fluctuating *P* flow at the HV/MV substation (Fig. 17 a) which affects on the HV/MV OLTC setting (Fig. 3). The reason for this fluctuating *P* flow (Fig. 17a) is the MV BESS's *Pf*-droop (Fig. 14) which in this case makes the BESS *P* to fluctuate depending on both frequency and MV PV *P* output during level 3 under-frequency (*t*= 67-155s, Fig. 2) as shown in Fig. 18 a). In overall, the fluctuating *P* support from the MV network to the HV network during severe level 3 under-frequency is not optimal. Correspondingly, in the CASE 1 EV (Rural) during level 3 over-frequency at *t*=189-217 s (Fig. 2) MV BESS's *P* support is not optimal (Fig. 17 a) & Fig. 18 a). Therefore, utilization of more sensitive *Pf*-droop settings with the MV BESS than in Fig. 14 could be more beneficial from the whole power system stability and TSO viewpoint. This could be realized by allocating all remaining *Pf*-control capacity of the MV BESS to the frequency level 2 or even partly also to level 1 like in [15] and [17]). Simultaneously, voltage fluctuations in the local DSO MV network could be also reduced during level 3-4 frequency deviations (Fig. 16).

4 Conclusions

This paper studied further the previously proposed [8] novel adaptive, coordinated and frequency level-dependent DER inverter and adaptive OLTC management scheme to enable prioritized flexibility services provision for the TSOs and DSOs. In the proposed scheme, DER *QU*-, *PU*- and *Pf*-droops and OLTC management principles were adapted depending on the frequency deviation severity. In overall, the target was to increase DER hosting capacity of the DSO network as well as increase the availability of the distribution network connected DER for the TSO flexibility services provision at levels 1 and 2. In this paper, the effect of different LV and MV DER reactive power control schemes, effect of MV DERs (BESS, BESS+PV or BESS+EV charging) location in the middle of MV feeder as well as the effect of type of MV network (urban or rural) were studied. The following conclusions were made based on the PSCAD simulations of Section 3:

- When MV BESS was connected in the middle of MV feeder instead of connecting it directly at the HV/MV substation, slightly smaller frequency support was achieved during more severe (level 3-4) frequency deviations (Section 3.1).
- The type of MV feeder (cable or OH line) did not affect the voltages much, whereas voltage differences depended on the DERs' *Q* control schemes (Section 3.1 & 3.2).
- Use of MV and LV DER *QU*-droop adaptation during frequency levels 1-2 based on simultaneous MV/LV or HV/MV OLTC's setting was 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 $\cos(\varphi)=1$ or fixed reverse *Q*-settings at levels 3-4 were recommended (Section 3.2).
- Regarding multi-use of rural MV network (with OH lines) connected BESS with PV or EV it was concluded that utilization of more sensitive *Pf*-droop settings with MV BESS could be more beneficial from the TSO frequency stability support viewpoint. This could be realized by allocating all remaining *Pf*-control capacity to frequency level 2 or even partly to level 1. Simultaneously also voltage fluctuations in the local DSO MV network during level 3-4 deviations could be reduced (Section 3.3).

Local measurements-based fixed DER *Q* settings seemed to be the most promising ones. In addition, these cases do not need any communication for the settings adaptation. Stable, accurate and fast local frequency measurement like e.g. in [17] could be used also in this paper's scheme for the BESSs, EV chargers, load demand response, frequency-dependent OLTCs etc. in order to improve their response speed and TSO frequency stability support. However, in the future studies the possibilities of, for example, AI-based edge-level monitoring, forecasting, protection, control and operation optimization methods with 5G/6G communication and time-synchronized measurements should be further explored.

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