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Novel DER and OLTC Management Scheme for Coordinated TSO-DSO Flexibility Services Provision

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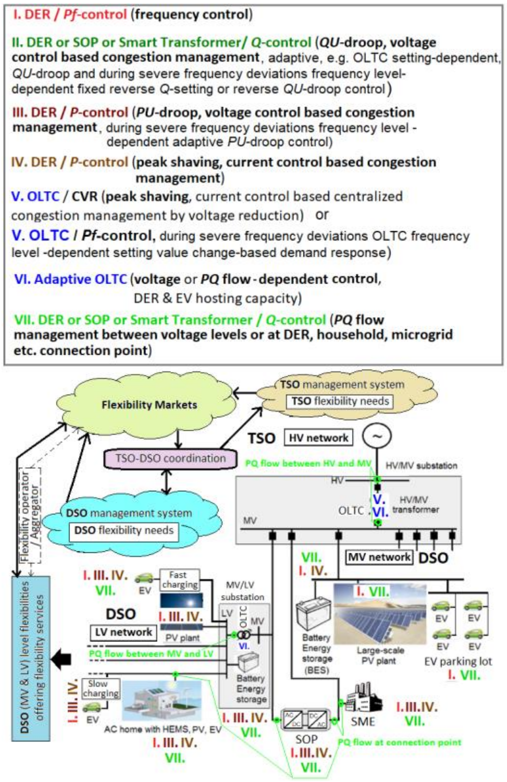
***Abstract*—In the future, increasing amount of flexibility is needed to fulfill the management needs of renewables and electric vehicles (EV) -based power systems. This paper presents a novel adaptive and coordinated management scheme for distributed energy resources (DER) and on-load-tap-changers (OLTCs) that enables coordinated and prioritized flexibility services provision by distribution network (DN) connected DER for the transmission and distribution system operators (TSOs and DSOs) by considering frequency deviation severity i.e. frequency level. Also the location and type of DER in the DN is taken into account in its active control methods and droop settings. The aim of the proposed scheme is to increase DER hosting capacity of the DN and the availability of the DN connected DER for the flexibility services provision during smaller frequency deviations as well as prioritize and maximize support for the TSO needs during larger frequency deviations. The simulation studies are done with HV/MV/LV network PSCAD model including active DER units at MV and LV networks as well as OLTCs at HV/MV and MV/LV substations.**

***Index Terms*-- Distributed energy resources, Flexibility services, Frequency control, Voltage control, Active network management**

I. INTRODUCTION

In the future, flexible DER control and active network management (ANM) functionalities (e.g. coordinated voltage control with OLTCs) can be increasingly used for flexibility services provision to the needs of the DSOs and TSOs. Flexible DER can consist of controllable distributed generation (DG), battery energy storage systems (BESSs), controllable load/demand response (DR) or controlled charging/discharging of EVs. Typical flexibility services provided by DER can support the power system frequency (*f*) and local voltage (*U*) or congestion management at the corresponding voltage levels. The effective utilisation of different active (*P*) and reactive power (*Q*) control or voltage level control -based flexibility services requires coordinated utilisation of different types and sizes of DER at all voltage levels (LV, MV and HV) with the OLTCs. Effective ANM and DER utilisation for different local and system-wide flexibility services provision requires also new collaborative DSO and TSO operation and planning principles based on active utilisation of flexibilities. Possible conflict of interest between DSO and TSO in utilisation of the *P* and *Q* control related flexibility services from distribution network connected resources should be avoided by improved TSO-DSO coordination, state-monitoring and state-forecasting. For example, different DER units' *P* and *Q* control modes, settings and coordination with OLTC settings and other ANM functionalities should be increasingly considered already at the planning stage. Fig. 1 shows active DER and OLTC management possibilities to increase flexibility services availability for the TSOs and DSOs and enhance photovoltaic (PV) and EV hosting capacity in DSO networks. [1]-[6]



I. DER / *Pf*-control **(frequency control)**

II. DER or SOP or Smart Transformer/ *Q*-control (***QU*-droop, voltage control based congestion management**, adaptive, e.g. OLTC setting-dependent, *QU*-droop and during severe frequency deviations frequency level-dependent fixed reverse *Q*-setting or reverse *QU*-droop control)

III. DER / *P*-control (***PU*-droop, voltage control based congestion management**, during severe frequency deviations frequency level - dependent adaptive *PU*-droop control)

IV. DER / *P*-control (**peak shaving, current control based congestion management**)

V. OLTC / CVR (**peak shaving**, current control based centralized congestion management by voltage reduction) or

V. OLTC / ***Pf*-control**, during severe frequency deviations OLTC frequency level -dependent setting value change-based demand response)

VI. Adaptive OLTC (**voltage** or ***PQ* flow-dependent control**, DER & EV hosting capacity)

VII. DER or SOP or Smart Transformer / *Q*-control (***PQ* flow management between voltage levels or at DER, household, microgrid etc. connection point**)

Figure 1. Active DER and OLTC management possibilities to increase flexibilities availability for services provision / hosting capacity enhancement.

Previously, different kind of coordination between OLTC and DER inverter reactive power-voltage (*QU*)-droop settings have been studied e.g. in [7]-[10]. However, this paper proposes a novel adaptive, coordinated and frequency level-dependent DER inverter and adaptive OLTC management scheme to 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 (see Fig. 2 of Section II for the different frequency levels) so that in case of larger frequency deviation at level 3 or 4 (Fig. 2) support for the whole power system and TSO needs is prioritized. In addition, the connection point of each DER in the distribution network is considered when its feasible active control methods and droop settings are determined and chosen. During smaller frequency deviations at level 1 or 2 (Fig. 2), as part of the proposed management scheme (Fig. 2), HV/MV and MV/LV OLTCs are controlled based on real-time *P* and *Q* flows between different voltage levels (Fig. 5) and DER units *QU*-droops are adapted based on OLTC setting changes (Fig. 4c). The target is to increase DER hosting capacity of the distribution network as well as increase the availability of the distribution network connected DER for the flexibility services provision at level 1 and 2 (Fig. 2). Part of the proposed management scheme principles have been initially proposed in [4]-[6] as an idea, but they have not been studied in detail e.g. to compare them with other traditional management methods, find out possible mutual effects between different management and control methods at different voltage levels etc.

II. STUDY SYSTEM AND CASES

The simulation studies are done with simplified HV/MV/LV network PSCAD model including active DER units at MV network (1 MW PV, 2 MW BESS, 1 MW hydrogen electrolyzer / fast EV charging station) and 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. 2. DER average models, similar to models in [11] and [12], have been used in this paper. Fig. 2 presents also 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. 3 shows the simulated frequency behavior and the frequency level changes (Table II) during the 250 s simulation in the different study cases (Table I). In Fig. 4a), HV/MV substation transformer's adaptive *PQ* flow -based OLTC settings for frequency levels 1-2 are shown. Fig. 4b) presents demand response -based HV/MV OLTC operation logic and settings for frequency level 3. Correspondingly, Fig. 4c) shows MV/LV substation transformer's adaptive *PQ* flow -based OLTC settings for frequency levels 1-2 and Fig. 4d) MV/LV OLTC operation settings for frequency level 3. Fig. 5 presents DER *Pf*-, *PU*- and *QU*-droops at different frequency levels in detail. For example, in CASE_1A and CASE_2A instead of reverse *QU*-droop like in [5], the 0.2 MW BESS at the MV/LV substation has fixed reverse *Q*-setting during frequency level 3 and 4 (Fig. 2) and in other cases LV DER units have fixed cos(φ)=1 setting at frequency level 3 and 4 in order to prevented unwanted effects in some LV network loading situations.

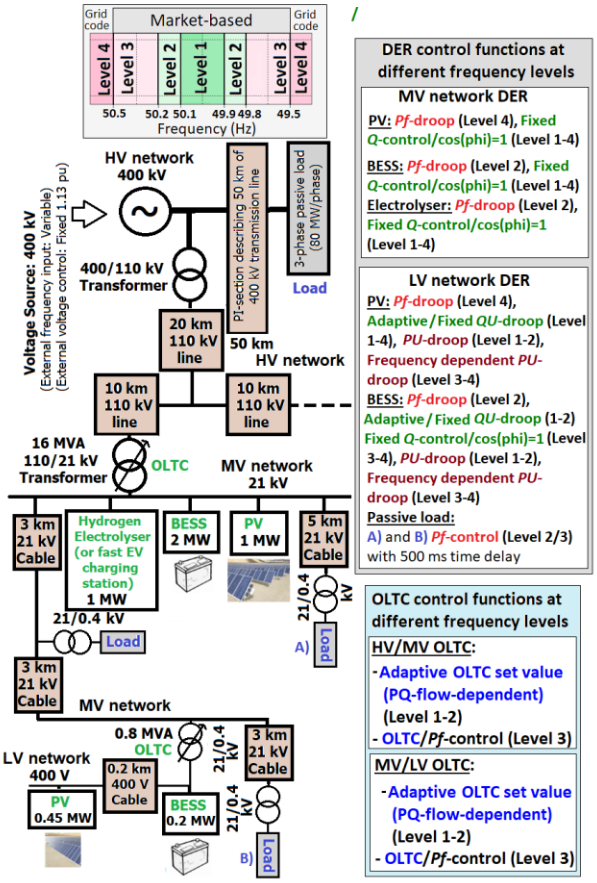


Figure 2. Studied HV/MV/LV network model with active DER units and their control methods at MV and LV networks as well as OLTCs and their control principles at HV/MV and MV/LV substations as part of the proposed novel management scheme (see Table I, Fig. 4 and 5).

TABLE I
DIFFERENT STUDY CASES DER & OLTC CONTROL FUNCTIONS AT FREQUENCY LEVELS 1-2 (SEE FIG. 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_1A	*QU*-droop (fixed, PV: level 1-4, BESS: 1-2)	BESS: Frequency level	BESS: fixed reverse *Q*-setting	Fixed 20.5 kV (HV/MV)/5 s & 0.41 kV (MV/LV)/10 s
CASE_1B	*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_2A	*QU*-droop (fixed, PV: level 1-4, BESS: 1-2)	BESS: Frequency level	BESS: fixed reverse *Q*-setting	*PQ* flow-based (HV/MV)/5 s &MV/LV)/10 s
CASE_2B	*QU*-droop (adaptive, level 1-2)	MV/LV OLTC set value & Freq. level	Fixed cos(φ)=1	*PQ* flow-based (HV/MV)/5 s & MV/LV)/10 s
CASE_2C	*QU*-droop (fixed, level 1-2)	Frequency level	Fixed cos(φ)=1	*PQ* flow-based (HV/MV)/5 s & MV/LV)/10 s

[*)] 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), [**)] Based on

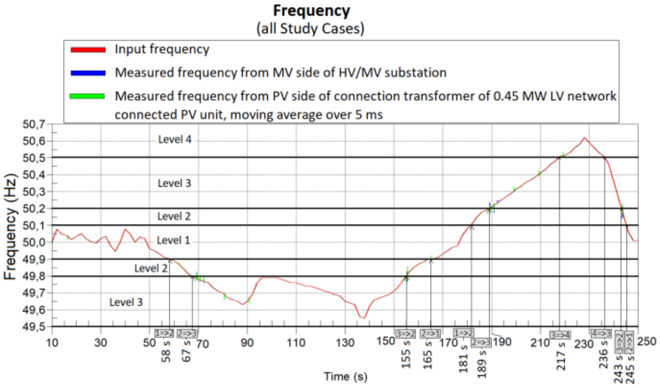


Figure 3. Frequency behavior and frequency level changes in the simulations with all different study cases (see Fig. 2, Table I and II).

TABLE II
FREQUENCY LEVEL CHANGES IN THE SIMULATION CASES (SEE FIG. 2 & 3 AND TABLE I), TOTAL SIMULATION TIME 250 S.

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

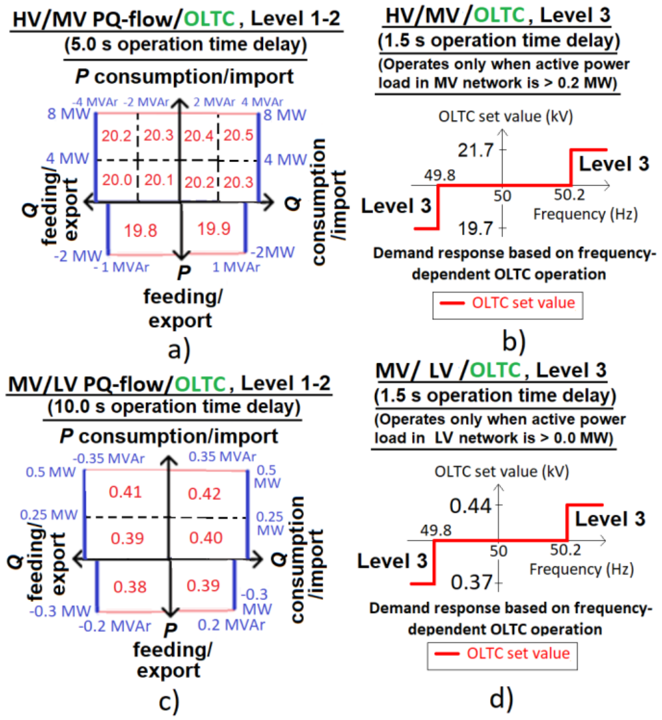


Figure 4. a) HV/MV substation transformer's adaptive *PQ* flow -based OLTC setting at levels 1-2, b) demand response -based HV/MV OLTC operation logic and settings at level 3, c) MV/LV substation transformer's adaptive *PQ* flow -based OLTC setting at levels 1-2 and d) demand response -based MV/LV OLTC operation logic and settings at level 3 (see Fig. 2, 5 and Table I).

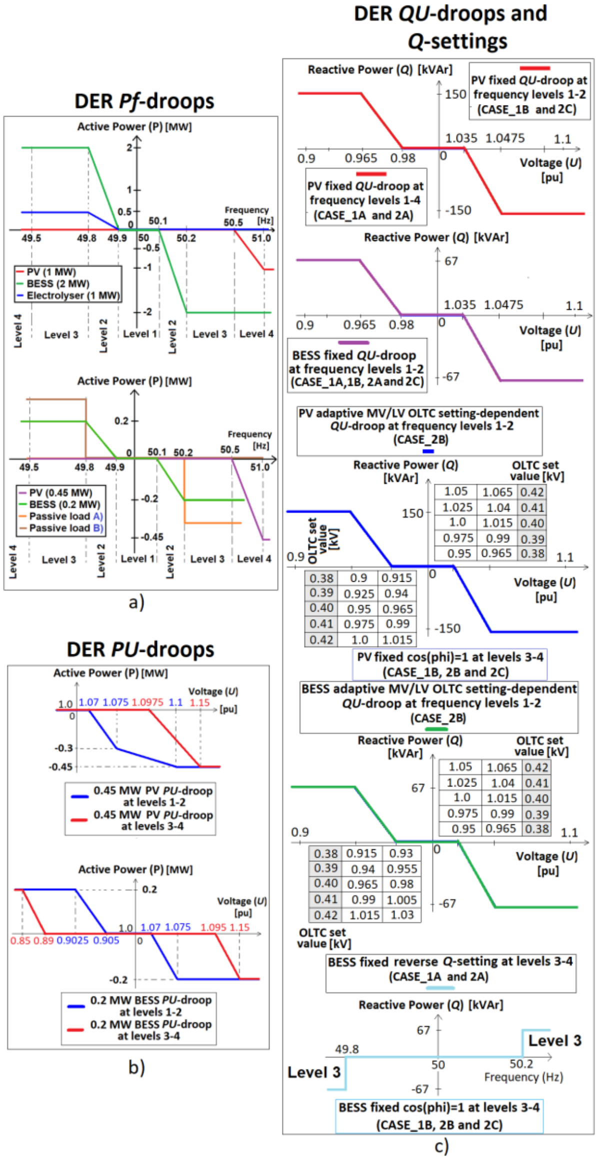


Figure 5. a) DER *Pf*-, b) *PU*- and c) *QU*-droops (see Fig. 2 and 4 and Table I).

The different study cases (Table I) were chosen to enable comparison of the traditional fixed DER *QU*-droop and OLTC settings with the proposed adaptive frequency- and *PQ* flow-dependent settings (CASE_2B and 2C in Table I) as well as to find out potential mutual unwanted effects of the controls etc. It can be also highlighted that in CASE_1B and CASE_2C the adaptation of LV DER *QU*-droop settings at frequency levels 1-2 do not require communication from MV/LV OLTC, because the locally measured voltage at DER connection point is used for the settings adaptation.

III. SIMULATION RESULTS

In this Section III, the main simulation results from different study cases (Table I) are presented. The total simulation time in all cases was t=250.0 s and frequency behavior between t=10.0 s and t=250.0 s was as shown in Fig. 3. The main PSCAD simulation results are presented in Fig. 6-11. Fig. 6 shows the voltages of different cases (Table I) at the HV/MV, MV/LV substation and end of LV feeder with PV and BESS. It can be seen from Fig. 6 that CASE_2B can maintain steady voltages during frequency levels 1-2. However, in CASE_2C voltages can be maintained lowest in LV network during frequency levels 1-2 which is beneficial from the PV hosting capacity viewpoint. In addition, during frequency level 3-4 under- and over-frequencies lowest and highest voltages in CASE_2C can potentially best support the system frequency by voltage-dependent demand response.

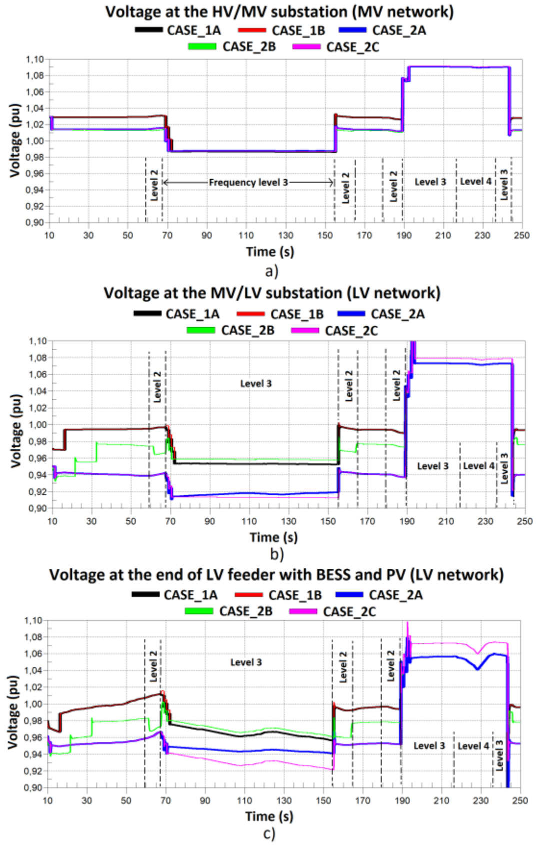


Figure 6. Voltages in different cases at the a) HV/MV substation, b) MV/LV substation and c) end of LV feeder with PV and BESS (see Fig. 2-5 & Table I and II).

Fig. 7 presents the *P* and *Q* flows at the HV/MV substation in different cases (Table I) and Fig. 8 respectively *P* and *Q* flows at the MV/LV substation. Reactive power *Q* flow differences (Fig. 7b) at HV/MV substation are also resulting from the different DER unit *QU*-droop settings as well as from the different HV/MV and MV/LV OLTC control principles in the studied cases (Table I, Fig. 5). From Fig. 8a) it can be seen that due to lower local voltages in CASE_2C (Table I, Fig. 6b and 6c) during level 3 or 4 under-frequencies, the contribution of voltage-dependent LV network loads and DER to frequency support is better (i.e. active power flow from MV/LV substation is higher) than in other cases. In addition, Fig. 8b) shows how the reactive power flows from the MV/LV substation during level 1-2 frequencies are higher in CASE_2A and 2C due to fixed LV network connected PV and BESS *QU*-droop settings (Table I, Fig. 5, see also Fig. 9). It can be also seen that due to higher local voltages (Fig. 6 b and c) the direction of reactive power flow at MV/LV substation is opposite in CASE_2B with adaptive *QU*-droops (Table I) during level 1-2 frequencies to CASE_2A and 2C.

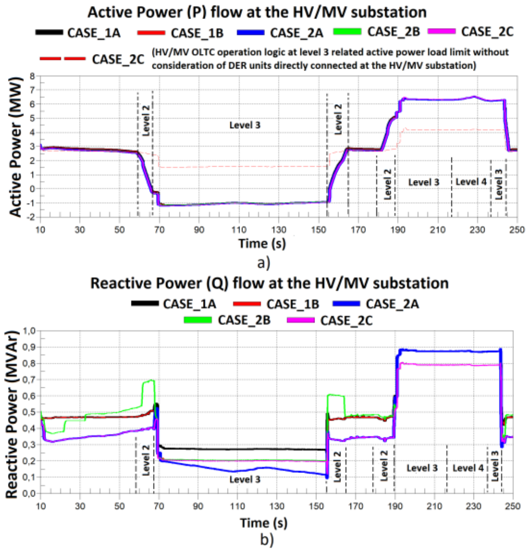


Figure 7. a) Active and b) reactive power flow at the HV/MV substation in the different cases (see Fig. 2-5 & Table I and II).

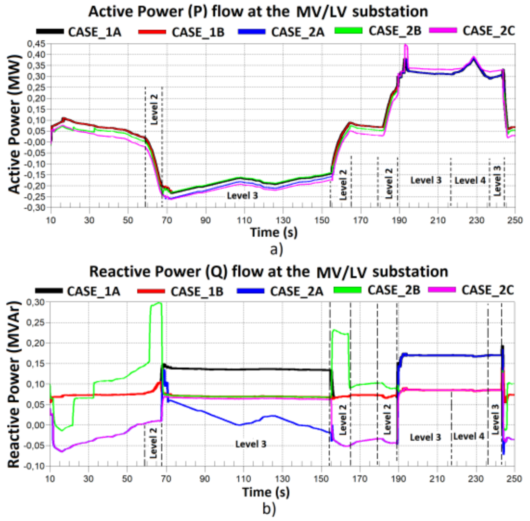


Figure 8. a) Active and b) reactive power flow at the MV/LV substation in the different cases (see Fig. 2-5 & Table I and II).

Fig. 9 presents LV network connected BESS's and PV unit's reactive power *Q* behavior in different study cases (Table I). Fig. 9b) presents how the the reactive power *Q* contribution of PV in CASE_2C with *PQ*-flow based control of OLTCs and fixed DER *QU*-droop control participates in local voltage control at level 1-2 frequencies as well as does not affect negatively to the local voltage during level 3-4 frequencies (i.e. fulfills TSO frequency support needs better). From Fig. 9 it can be also seen that in CASE_2B, PV and BESS *QU*-droop adaptation should be delayed according to MV/LV OLTC operation delay i.e. 10 s (Table I) in CASE_2B in order to avoid rapid DER reactive power changes before actual MV/LV OLTC tapping. In order to further minimize rapid voltage fluctuations in DNs, steeper *QU*-droops or *QPU*-droops [13] could potentially also be used with the DER units. In Fig. 10 the active power *P* behavior of MV and LV network connected DERs in CASE_2C are shown. One can see, for example, from Fig. 10b) that the active power *P* flow changes at the MV/LV substation during simulated frequency level changes are mainly resulting from the LV network connected DER units' (PV and BESS) active power *P* changes (like *Pf*-droop-based response of the BESS during level 2-4 frequencies, see Fig. 5a).

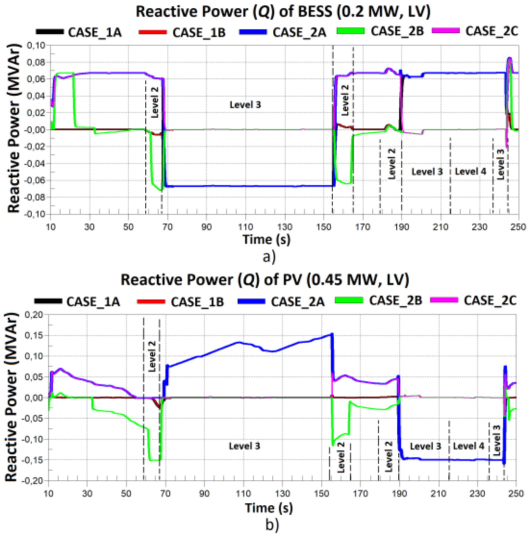


Figure 9. a) 0.2 MW BESS and b) 0.45 MW PV reactive power *Q* behavior in different study cases (see Fig. 2-5 & Table I and II).

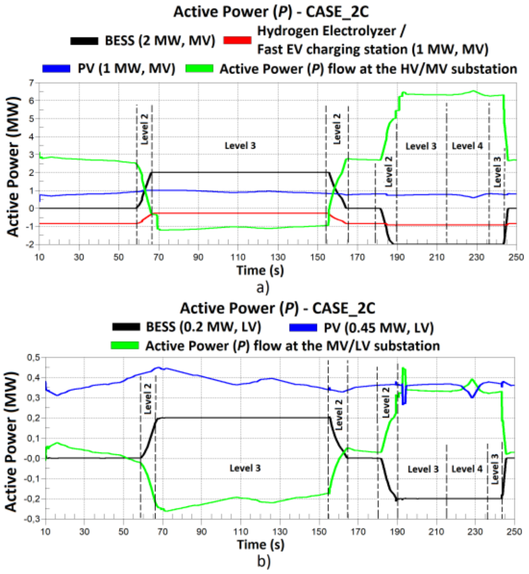


Figure 10. Active power behavior of a) MV network and b) LV network connected DERs in CASE_2C (see Fig. 2-5 & Table I and II).

IV. CONCLUSIONS

This paper proposed novel adaptive, coordinated and frequency level-dependent DER inverter and adaptive OLTC management scheme to prioritized flexibility services provision for the TSOs and DSOs. In general, it was shown by the simulations that the proposed scheme can increase DER hosting capacity of the DN and the availability of the DN connected DER for the flexibility services provision during smaller frequency deviations as well as prioritize and maximize support for the TSO needs during larger frequency deviations. Based on the simulation results of this paper, CASE_2C (Table I) with *PQ*-flow based control of OLTCs, fixed DER *QU*-droop control at level 1-2 frequencies and fixed cos(φ)=1 setting at level 3 and 4 frequencies seems to be the most feasible OLTC and DER control scheme, because I) In CASE_2C voltages can be maintained lowest in LV network during frequency levels 1-2 (beneficial from the PV hosting capacity viewpoint), II) During frequency level 3-4 under- and over-frequencies lowest and highest voltages in CASE_2C were shown to best support the system frequency by voltage-dependent demand response (i.e. active power flow from MV/LV substation is higher) and III) In CASE_2C the adaptation of LV DER *QU*-droop settings at frequency levels 1-2 do not require communication from MV/LV OLTC, because the locally measured voltage at DER connection point is used for the settings adaptation.

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