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Integration of PV and EVs in unbalanced residential LV networks and implications for the smart grid and advanced metering infrastructure deployment

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ABSTRACT

Voltage unbalance is a relevant problem that causes a less efficient operation of the system due to higher energy losses and lower hosting capacity. Unbalance has often been neglected by distribution system operators due to the lack of monitoring data in the low voltage (LV) grid. However, the massive deployment of smart metering in recent years in many countries provides very valuable information to detect unbalance. Moreover, in the current context of increasing presence of single-phase distributed energy resources connected to LV networks, such as electric vehicles (EVs) and photovoltaic (PV) generation, unbalance is bound to increase.

This article investigates the technical impact of future integration of EV and PV in LV unbalanced networks. This paper has assessed the daily energy losses and voltage problems as load unbalance gradually increases, based on load flow analysis on an hourly basis, considering residential demand and homogeneously distributed EV and PV. The analysis has been carried out for several rural and semi-rural LV networks and various scenarios of demand level and penetration degree of EV and PV. The three-phase load flow analysis is computed using the forward-backward sweep algorithm.

Furthermore, this work discusses the implications for the deployment of supervision and monitoring solutions based on advanced metering infrastructure (AMI). Their implementation should be prioritized in more loaded and longer networks where high integration of distributed energy resources is expected so that unbalance can be detected and corrective actions can be applied.

1. Introduction

As the smart grid gradually turns into a reality, new solutions have become available to increase the observability and controllability of distribution networks [1,2]. Smart metering has already been implemented in several countries across Europe such as Italy, Finland, and Sweden, and is currently on-going in many other (e.g.: Spain, the Netherlands, UK, Ireland). Actually, it is expected that by 2020 around 70% of European consumers will have a smart meter [3]. Smart meters can register real-time energy consumption including voltage, phase angle and frequency measures. Thus, Automatic Meter Infrastructure (AMI) systems can be used to create a distributed monitoring system of the low voltage (LV) grid [4]. Monitoring provides very valuable information that may be used by distribution companies to perform power quality and fault analysis and detect issues such as non-technical losses and voltage unbalance [5].

Voltage unbalance is actually a relevant problem that results in higher energy losses, higher neutral currents (which in turns contributes to voltage drop), a less efficient utilization of network assets (a highly unbalanced grid reaches its hosting capacity limit much sooner than a balanced grid so that network reinforcement costs are moved forward in time [6]) and possible damage to electric equipment [7] (overheating and vibrations in motors[1]) [8].

Voltage unbalance is mainly caused by the difference between the single-phase loads connected to each phase. In higher voltage levels both generation and demand are typically three-phase and

[1] For every 10 °C a motor is operated over its rated temperature, its insulation life (and therefore motor life) decreases by half. NEMA motor standards recommend a maximum voltage unbalance of 1% without derating the motor.

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balanced[2]. Unbalance is especially relevant in LV networks, where most consumers are single-phase loads. Originally, at the time of connection, single-phase loads are assigned to the three phases in a balanced manner, but the loads are asymmetrical and vary differently in time. Furthermore, when new consumers are connected to the grid, the phase allocation may not be optimal. In practice, high values of current unbalances are observed. Moreover, the presence of single-phase distributed energy resources (DER), such as electric vehicles (EVs) and photovoltaic (PV) generation connected to LV networks is bound to increase further unbalance.

Unbalance has often been neglected by distribution system operators (DSOs) due precisely to the lack of monitoring data in the LV grid [9,10]. The work of [10] develops a methodology to estimate unbalance using probability based on historical data for the MV network. However, the use of AMI and smart meters to detect unbalance is already proposed and discussed by several authors [8,11,12]. Furthermore, unbalance has often been neglected in the operation of the system, assuming a fully balanced system when carrying out one-phase power flow analysis for voltage control. Some works acknowledge the impact of unbalance and thus propose to use three-phase power flow analysis to determine optimal operation of distribution networks [13,14]. Another example is the algorithm proposed in [15] for voltage control which explicitly incorporates the restriction of unbalance limits.

The increasing presence of DER has further motivated the explicit consideration of unbalance in voltage control. In the case of the EV, the work of [16] analyzes the impact of EV on distribution networks and compares the results obtained in balanced and unbalanced systems. The authors of [17] determine smart charging strategies for EVs adding regulatory unbalance limits as constraints in the three-phase optimal power flow analysis. Similarly, [18] include unbalance in their proposal to determine the charging strategy of minimal cost based on a multi-period, rolling optimization technique with the updated information on demand and EV connection for an unbalanced three-phase load flow analysis. The participation of PV in voltage control has been addressed by [19], which proposes a multi-objective optimal power flow that explicitly considers the restriction of unbalance within acceptable limits. Further work on the interaction of PV integration and unbalance in LV grids includes [20], which investigates the effect of PV units of different capacity connected at different nodes in a residential LV network on voltage unbalance along the line, and the assessment of voltage unbalance sensitivity to set the requirements of maximum capacity of PV units to be connected in LV networks [21].

In order to mitigate unbalance, different solutions have been proposed in the literature. The reconnection or re-phasing of loads is discussed in [8,22–24], and different algorithms have been proposed to optimize the load assigned to each phase, such as ant colony optimization in [8]. However, DSOs may not be able to afford too many phase moves due to the limitation imposed by the architecture of the LV grid, cost of manual re-connection, interference and potential service interruption of consumers, etc. More recent works propose to make use of automation to perform reconfiguration for re-phasing [8,23,24]. The work of [25] shows that an ideal reactive source can control positive sequence magnitude and cancel any negative phase sequence terms and propose the use of thyristor-switched capacitors (TSCs) for this purpose. The work of [20] discusses the increase of feeder cross-section, installing capacitors at phases with lower voltage and controlling PV converters to reduce unbalance in LV residential networks with PV. The authors then propose in [26] the application of series (DVR) and parallel (DSTATCOM) custom power devices. The use of Battery Energy Storage Systems (BESS) for load levelling across the three phases has also been proposed and tested. Single-phase BESS in combination with PV units have been addressed by [27]. The work presented in [13] studied a three-phase BESS connected to the LV distribution grid through a three-phase inverter and [28] proposed a day-ahead dispatch of BESS for peak load shaving and load levelling using Characteristic Daily Load Profiles (CDLPs) in each phase.

In the future, as higher volumes of DER are integrated in the LV grid, it will be of the utmost importance to prioritize monitoring in those areas where the hosting capacity of the network is more limited and problems are more likely to arise. Rural networks are usually more sensitive to unbalance in loads, since in more densely populated urban areas LV networks are typically much shorter and loads tend to be more balanced. Therefore, the objective of this paper is to assess the effect of unbalance on DER integration in rural LV networks. For this purpose, analyses are conducted to determine energy losses and voltage profiles in several rural and semi-rural LV networks under different degrees of unbalance in the system and varying penetration degrees of distributed generation (DG) in the form of PV panels and EV in the form of slow charging connections. Accordingly, the reminder of the paper is structured as follows: Section 2 defines the methodology applied to carry out the analyses. Then, Section 3 describes the case study and Section 4 discusses the results obtained, together with the implications for the use of AMI and LV supervision solutions for monitoring. Finally, Section 5 concludes with the final remarks.

2. Methodology

This section describes the methodology applied for the study of the integration of EVs and PV in unbalanced LV networks, based on three-phase unbalanced power flow analyses.

2.1. Measuring unbalance in the LV network

Unbalance can be quantified following different approaches. Most commonly, regulation uses the percentage voltage unbalance factor (VUF), defined by the International Electrotechnical Commission (IEC) as the coefficient between the negative and the positive component of voltage. Other indices include the phase voltage unbalance rate (PVUR) defined by Institute of Electrical and Electronics Engineers (IEEE) and the line voltage unbalance rate (LVUR) defined by the National Equipment Manufacturer's Association (NEMA). An exhaustive comparison and assessment of the suitability of different indices for voltage unbalance may be found in [29].

The European Standard EN 50160 states that the 95% of the 10 min average voltage unbalance must not exceed a value of 2%, or up to 3% for some specific locations, over a one-week period [30]. Other countries impose even stricter limits to unbalance, such as the UK or Malaysia, where the statutory limit for voltage unbalance is 1.3% and 1%, respectively. However, these standards are usually not enforced since voltage unbalances are hardly ever measured in practice.

For the sake of simplicity, this work follows the PVUR approach to measure voltage (and current) unbalance u_U, defined as the maximum deviation from the mean, according to (1), where U_m is the mean of the RMS values of voltage (current) of the three phases and U_j is the RMS value of the voltage (current) at each phase.

$$u_U = \frac{\max_{j}(U_j - U_m)}{U_m} \cdot 100\% \quad (1)$$

Load unbalance will be directly translated into current unbalance, as voltage variations in each node due to load unbalance

[2] It must be noted that distribution networks in Europe are generally based on secondary substations with three-phase MV/LV transformers (as opposed to the USA, where MV networks frequently feature single-phase or two-phase systems in lateral branches) [40].

are assumed to be negligible. Voltage unbalance changes along the network and may be calculated once the voltage profile is determined through power flow computation.

This work aims to assess the effect of increasing unbalance caused by unbalanced load and the introduction of DER, so load unbalance is the input used to define the scenarios for load flow analysis. Unbalance scenarios have been defined to cover a wide range of possible operational situations. The baseline is a fully balanced system, where the total load is equally distributed across the three phases at all nodes. The degree of unbalance is gradually incremented by transferring a share of the load from two of the phases to the other one, up to a completely unbalanced network, where all the load is connected to the same phase and the current circulates exclusively through one phase. Therefore, the degree of load unbalance u_Z ranges from 0% to 100%, increasing gradually by 5% and is defined according to (2), where Z_A, Z_B and Z_C are the loads connected to phases A, B and C respectively, and Z is the load connected to each phase in the balanced system.

$$\begin{aligned} Z_A &= Z + 2 \cdot u_Z \\ Z_B &= Z - u_Z \\ Z_C &= Z - u_Z \end{aligned} \tag{2}$$

It must be noted that this definition of load unbalance based on the share of load transferred differs from the approach of PVUR where maximum deviation is measured. Thus, for a certain degree of load unbalance, the corresponding value of the phase current unbalance rate would be twice the load unbalance degree (e.g.: a fully unbalanced system, with a load unbalance degree of 100% would have a load distribution of $Z_A = Z + 2 \cdot Z$ and $Z_B = Z_C = 0$ and the corresponding currents $I_A = 3 \cdot I$ and $I_B = I_C = 0$ would then have phase current unbalance rate of $u_I = \frac{\max_j(I_j - I_m)}{I_m} \cdot 100\% = \frac{(3 \cdot I - I)}{I} \cdot 100\% = 200\%$).

2.2. Technical analysis: unbalanced three-phase power flow

The effect of unbalance on DER integration in rural LV networks has been studied through load flow analysis to assess energy losses and voltage profiles in several rural and semi-rural LV networks under different degrees of load unbalance. Additionally, the analysis is carried out for scenarios of different penetration levels of EVs and PV generation and varying demand. The diagram in Fig. 1 illustrates the procedure followed for this work.

For each studied network, a load flow analysis is run for each phase[3]. The analysis is performed on an hourly basis to cover a full day considering the average net demand for each of the 24 h. The hourly net demand at each node is determined for each scenario based on the registered maximum demand of each consumer and considering the corresponding demand level and penetration degree of PV and EV. The degree of load unbalance is used to determine the share of load located at each phase. The losses of each phase and hour are added to determine the daily energy losses. Similarly, the voltages at each node, in each phase, at each hour, are compared to allowed voltage limits to determine the daily occurrence frequency of over- and under-voltages.

The load flow analysis has been solved using the *forward/backward sweep* or *ladder* algorithm, which is a simple, efficient and robust three-phase power flow algorithm for radial distribution networks proposed and described in [31]. For the work presented in this paper, the algorithm has been implemented in Matlab environment. This algorithm uses iterative forward and backward propagation to calculate branch currents and bus voltages as illustrated in the flowchart in Fig. 2.

The network is modelled by the network impedance of each branch, i.e. section of the network connecting two nodes, and by the power demand at each demand node. LV distribution feeders are radial, so each network node has one predecessor (parent node) and may have multiple successor (children nodes). The nodes must be numbered to adequately reflect the parent–child paths.

At the first iteration, nominal voltage is assumed for all nodes. Then, at each iteration, a backward sweep is completed by starting at the children nodes going in a descending order of nodes, passing 'backward' over each branch of the network to compute branch currents. Branch currents are the sum of the contributions of the node and downstream branches. Next, a forward sweep is carried out to compute node voltages by starting at the head of the LV feeder and moving in ascending node order, passing 'forward' over each branch. These steps are repeated until convergence is reached for the voltages obtained.

The main results of the analyses performed include the energy losses and compliance with voltage limits expressed through the share of consumers who experience under-voltages and the share of consumers who experience over-voltages.

3. Case study

Table 1 summarizes the main characteristics of the grids considered for the case study. The selected networks include five purely rural LV networks and two semi-rural ones. These hypothetical networks have been elaborated according to public data gathered in [32] so that the resulting grids are realistic for distribution in European countries.

Distinct degrees of load unbalance have been considered (in total, 21 different values) in order to cover a wide range of possible operational situations. The baseline is a fully balanced system, where the total load is equally distributed across the three phases at all nodes. The degree of unbalance is gradually incremented by transferring a share of the load to one phase at all nodes, up to a completely unbalanced network, where the current circulates exclusively through one phase. The same degree of load unbalance is maintained along the network so that conclusions can be derived for the results of the load flow analysis. For this purpose, the load at each node (i.e., each consumer) is assigned to the three phases according to the input of load unbalance considered for each analysis scenario. A more realistic approach connecting each consumer to one phase in a random distribution would lead to a non-homogeneous unbalance degree and any given total unbalance degree would correspond to a wide range of possible combinations of phase-distribution of loads.

The hourly demand profile considered represents an average working day based on the data published by the Spanish TSO, Red Eléctrica de España (REE) [33]. All end consumers have been assumed to be residential and follow the same consumption pattern, represented in Fig. 3 as load coefficients. Sensitivity to the level of loading of the network has been addressed by considering four different scenarios of demand consumption, expressed as a percentage of the peak demand recorded for each consumer. Thus, the four values of this parameter assessed are 50–75–100–125%, which are applied as a coefficient to the demand profile, as can be seen in Fig. 3. The loading level of 125% has been included in order to identify potential problematic situations under more unfavorable scenarios.

This work studies the integration of EVs in LV residential networks in the form of single-phase slow charging during the night, excluding vehicle-to-grid capabilities. EVs are considered as an addition to the domestic load. The typical charging power of EVs

[3] A wye (Y) arranged three-phase system is assumed. The flows at each phase are determined separately, and the unbalanced neutral current is obtained as the inverted vector sum of the currents of the three phases.

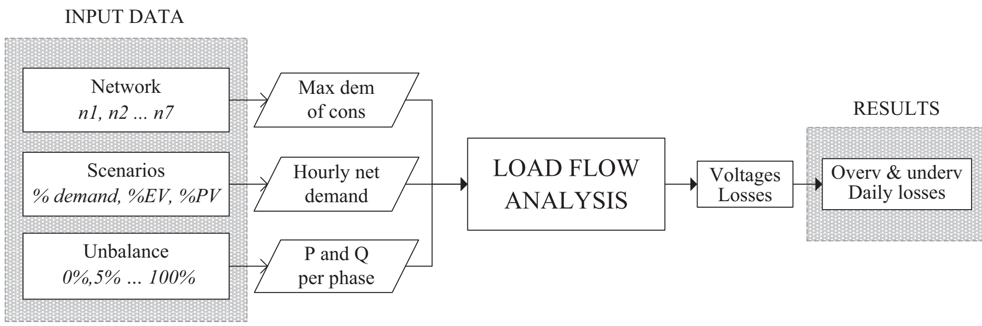

Fig. 1. Diagram of performed analyses.

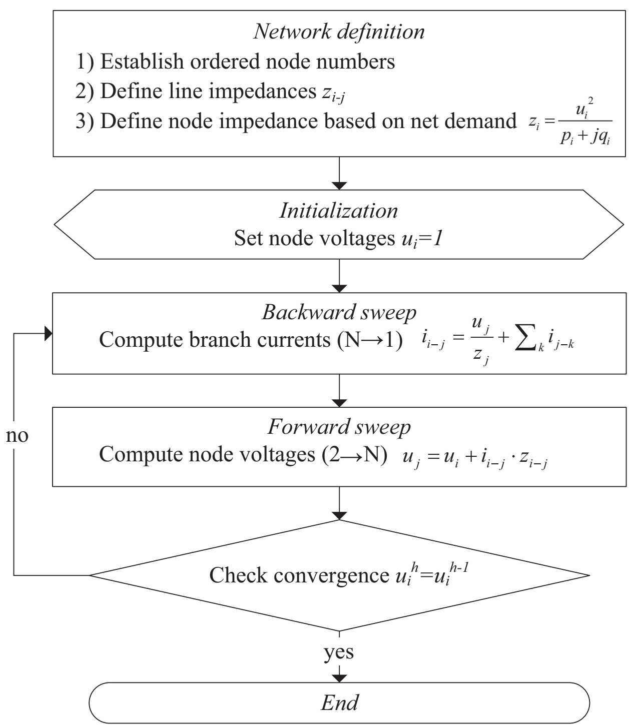

Fig. 2. Flow chart of forward/backward sweep load flow algorithm, where: N is the number of nodes in the network; subsets i, j, k represent nodes so that $i < j < k$ and $i - j$ and $j - k$ are connected; subsets $h - 1$ and h represent two successive iterations; p_i, q_i and z_i are the net active and reactive power demand and impedance in node i respectively; z_{i-j} is the impedance of the branch connecting nodes i and j; u_i is the voltage in node i; i_{i-j} is the branch current in the branch connecting nodes i and j.

is 3.68 kW[4] for slow charging sustained throughout the whole charging period, which lasts around 8–10 h, depending on the initial state of charge of the battery. Four scenarios of EV integration have been studied, considering an EV penetration degree of 15%, 30%, 45%, and 60%, expressed as the total EV charging power with respect to the total peak demand in the network.

EV charging constitutes a very large load in comparison to domestic appliances and other LV loads connected to a single point of the network. Therefore, the connection of EVs in certain nodes and phases may result in a heterogeneous and unbalanced loading degree along the LV lines and among the three phases, where a big share of the total load is concentrated in a few nodes or phases of the LV feeder. In order to isolate the effect of load unbalance degree and avoid the interference of the effect of different locations of EV charging points and lumpiness in EV penetration degree due to discrete EVs, this work has assumed that the EV demand is distributed proportionally to the demand in the system. This means that (i) for each network and EV penetration degree, the total EV power has been computed, (ii) the total amount of EV charging power has been allocated to each and every node of the network proportionally to their demand, (iii) the total amount of EV charging power has been equally distributed in the three phases, as has been done with the demand so the unbalance degree considered for the analyses corresponds to net load (i.e. demand plus EV charging). This way, general conclusions can be extracted from the analysis and the trends of the impact of unbalance can be observed.

Fig. 4 shows the four net load profiles used for the case study, considering a loading level of 100% for demand plus the charging of EVs for the different values of penetration degree contemplated.

Considering distributed generation, this work has analyzed the penetration of solar PV, which is the technology most widely connected to the LV networks. The production of PV has been determined based on typical irradiation levels for southern Europe during summer using PV-GIS [34,35]. As in the case of EVs, four scenarios of solar PV penetration have been evaluated, including 25–50–75–100% of the total peak demand. The load profiles selected for the case study with PV integration are based on a loading level of 50%, a lower level than in the case of EV penetration to tackle a more unfavorable case (lower demand to absorb the PV production, where excess generation may increase voltage in the networks). The resulting net demand curves are depicted in Fig. 5.

The PV has been assumed to be homogeneously located, assuming the same percentage of generation given by the PV penetration degree at each node, in order to assess the effect of a certain degree of load unbalance in the network, as in the case of EV penetration. Actual PV units in rural residential areas are typically rooftop panels of around 10 kW, depending on the available rooftop area, which means a very high maximum power injection with respect to the typical demand of residential consumers and EV charging power.

In conclusion, the analyses have been carried out for the seven networks listed in Table 1 for a total of twelve scenarios: four demand-only scenarios, four EV penetration scenarios and four PV penetration scenarios. The load flow analyses have been run for the three-phase systems, for the 24 h of an average day and for 21 values of load unbalance ranging from a totally balanced system to the case of having all the load connected to one phase. Section 4 presents the most relevant results from these analyses and discusses the extracted conclusions. Additionally, the effect of regulatory voltage limits has been analyzed, comparing compliance with different voltage margins for the considered scenarios in Section 4.4. To summarize, Table 2 lists the results presented in Section 4.

[4] According to IEC62196 standard Type 2, EV single-phase LV connections includes a 16A-3.68 kW connection for slow charging (mode 2) [41].

Table 1
Technical parameters of the representative LV networks.

Network	Type	Length (km)	Underground (%)	Pinst (kVA)[a]	#cons	ΣPmax (kW)[b]	#LV feeders
n1	Rural	1.89	0	630	39	281.4	3
n2	Rural	4.57	0	250	24	121.1	4
n3	Rural	1.48	0	75	21	128.0	3
n4	Rural	0.58	100	100	27	128.3	3
n5	Rural	0.87	41	100	14	123.8	3
n6	Semi-rural	1.75	100	630	233	487.7	5
n7	Semi-rural	2.16	100	800	214	685.9	7

[a] Pinst: Rated capacity of the MV/LV transformer.
[b] ΣPmax: Sum of the maximum demand registered.

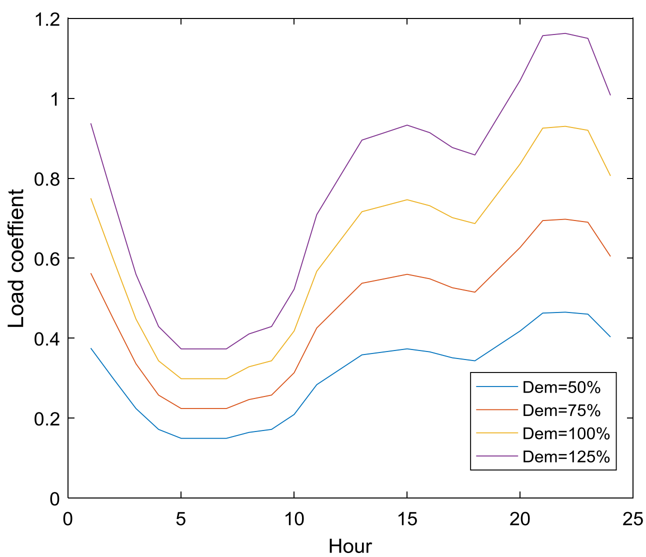

Fig. 3. Total demand profile for scenarios of different loading levels (50%, 75%, 100% and 125% of peak demand for each consumer).

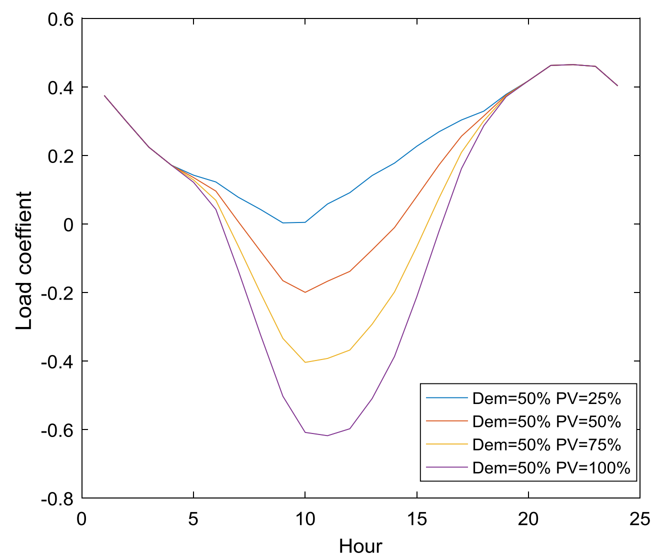

Fig. 5. Total load profile for scenarios of different penetration of PV (25%, 50%, 75% and 100% of total peak demand) for a demand of 50% of total peak demand.

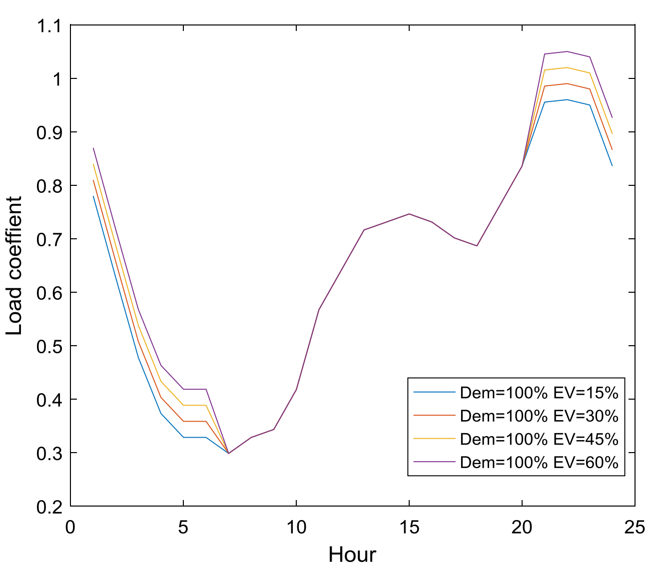

Fig. 4. Total load profile for scenarios of different penetration of EV (15%, 30%, 45% and 60% of total peak demand) for a demand level of 100% of total peak demand.

4. Results and discussion

This section presents the results obtained for the analyses carried out and discusses the interaction of phase unbalance with the integration of EV and PV, and their effect on energy losses and voltage profiles. Furthermore, Section 4.4 discusses the implications for monitoring and the implementation of LV supervision solutions.

4.1. Phase unbalance and loading level

The graphs in Fig. 6 depict the results obtained for the different LV grids considered under different loading levels. It can be observed that the increase in phase unbalance results in higher energy losses. This effect has an exponential behavior so that the losses of a completely unbalanced system range from 2.5 up to 3.8 times the losses for a fully balanced network. Therefore, the problem of increasing energy losses may not be very relevant for moderate levels of unbalances (typically below 25–30%). Nonetheless, in case unbalances exceed this threshold a significant increase in LV energy losses is to be expected and DSOs should implement measures to mitigate it.

Moreover, higher loading levels lead to a deeper impact of unbalance so that energy losses are higher. Since energy losses increase with the square of the current, scenarios with higher load have higher losses and the increase of energy losses due to phase unbalance is much higher. Therefore, the impact of unbalances on losses is particularly relevant in networks which are more heavily loaded. It can be seen that for shorter and less loaded grids (e.g. *n4* and *n5*), lower values of the losses factor have generally been obtained, whereas the opposite effect is observed for the semi-rural networks (i.e., *n6* and *n7*), which tend to be more heavily loaded.

Table 2
Scenarios and results presented in Section 4.

Objective of the analysis	Scenarios	Results presented in Section 4
Effect of load unbalance and level of loading	Demand: 50%, 75%, 100%, 125%	Losses in networks n1–n7 Under-voltages in networks n1–n7
Integration of EV	Demand: 100% EV penetration: 50%, 75%, 100%, 125%	Losses in networks n1–n7 Under-voltages in networks n1–n3, n6–n7
Integration of PV	Demand: 50% PV penetration: 25%, 50%, 75%, 100%	Losses in networks n1–n7 Under-voltages in networks n1–n2 Over-voltages in networks n1–n2
Effect of regulatory voltage limit	Voltage limit: 5%, 7%, 10%	Under-voltages in networks n2–n3 for (i) demand of 100% and (ii) demand of 100% with 60% EV penetration Under-voltages in networks n2–n3 for (i) demand of 50% and (ii) demand of 50% with 100% PV penetration

The degree of phase unbalance also affects bus voltages. The higher the unbalance, the more noticeable the effect of loading levels on bus voltages, so that the voltage drop along the line is increased. European regulation establishes that voltage in the LV network must remain within 10% of its nominal value during 95% of the time [30]. Fig. 7 illustrates compliance with voltage limits as load unbalance increases depicting the share of consumption points that experience a voltage below 90% of its nominal value at a certain hour in a day, considering the voltage at each of the three phases.

It must be noted that according to the definition of load unbalance, as the load is transferred to a phase from the other two phases, the voltage drop increases in the more loaded phase, but decreases in the other two phases as they are relieved from a part of the load. This effect can be observed in Fig. 7 for network *n1* under a demand of 125% with respect to peak demand when comparing the totally balanced system to an unbalance degree of 5%.

It can be seen that voltage drop is mainly a problem in long overhead feeders such as *n1*, *n2* and *n3*; where unbalance results in significant voltage constraint violations. Network *n1* would be an extreme case in which network may need reinforcing, as under-voltage is observed even with degrees of phase unbalance

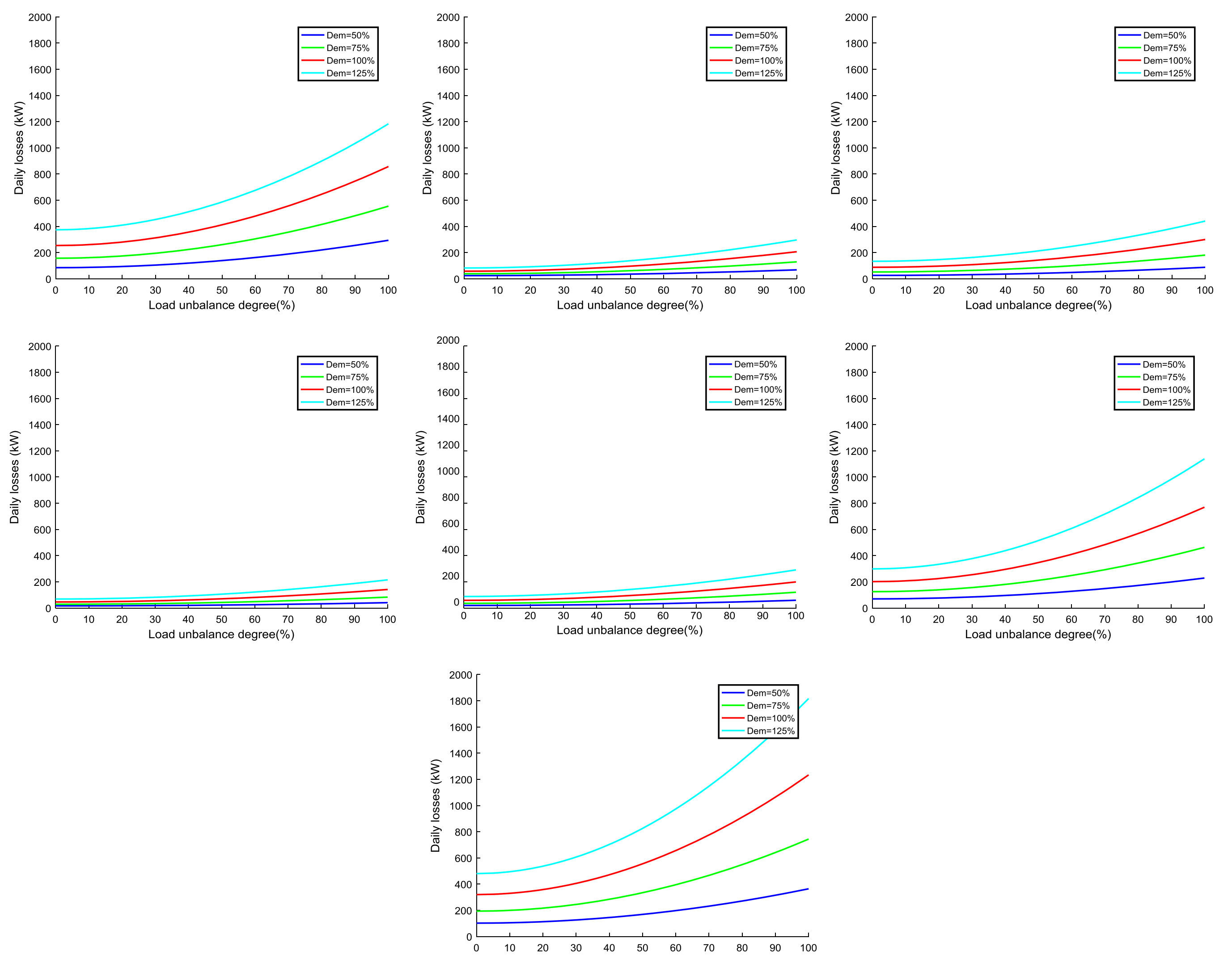

Fig. 6. Daily energy losses under different loading levels and degree of unbalance in the LV networks. From left to right: first row *n1*, *n2*, *n3*; second row *n4*, *n5*, *n6*; third row *n7*.

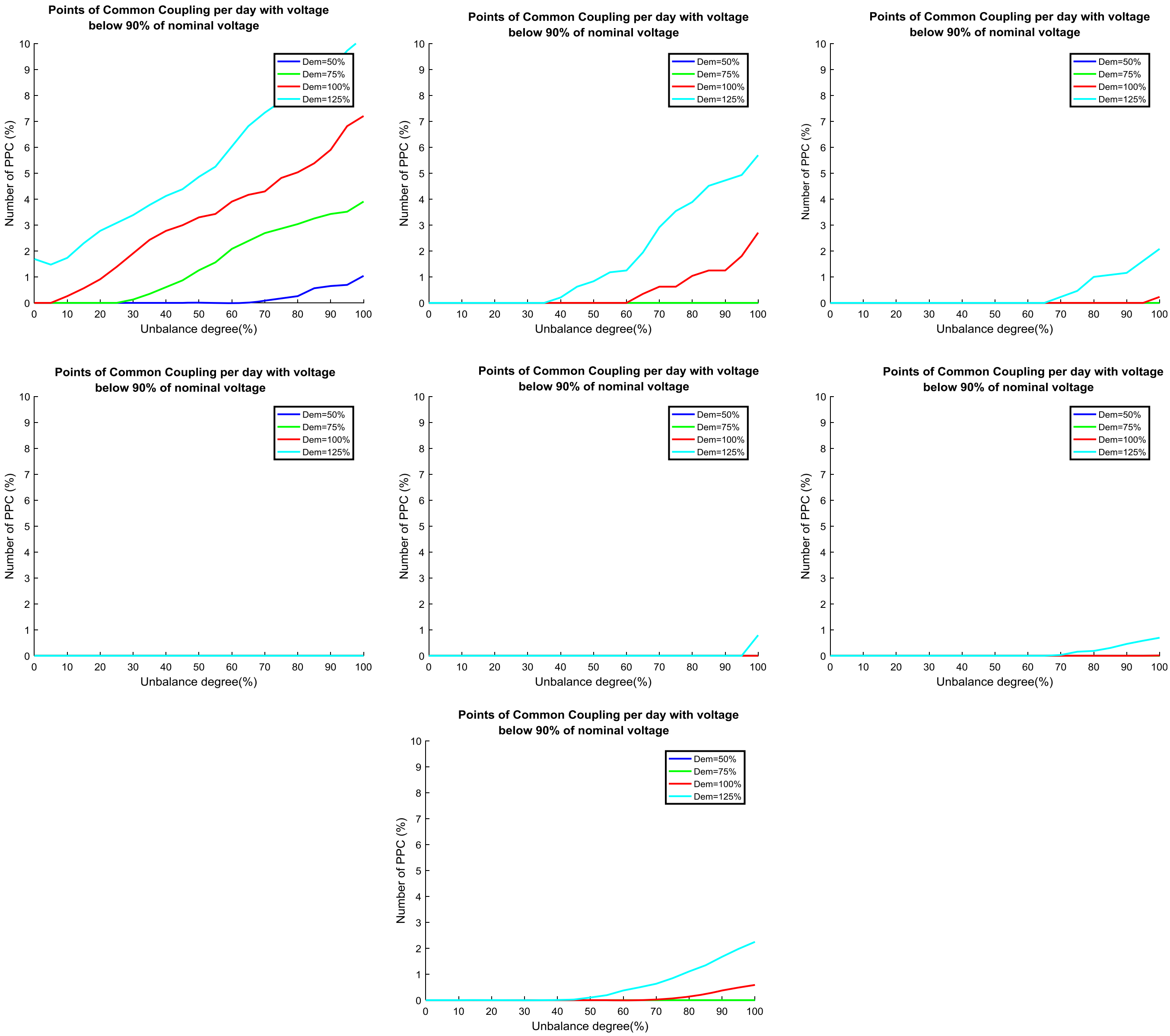

Fig. 7. Share of buses experiencing under-voltages under different loading levels and degree of unbalance in the LV networks. From left to right: first row *n1*, *n2*, *n3*; second row *n4*, *n5*, *n6*; third row *n7*.

as low as 5% in the case of maximum demand (loading of 100% of peak demand), or under an increase of demand. The effect of unbalances on under-voltages in the other networks, much shorter and largely underground in the case of *n4*, *n6* and *n7* and reinforced with conductors of a much wider section in the case of *n5*, is limited to situations with a very high load and very highly unbalanced grids.

4.2. Integration of electric vehicle

The introduction of electric vehicles is an added demand for the LV grid. EV charging in residential areas is expected to take place during the night, where the demand is low. Therefore, the impact of EV integration on energy losses and voltage profiles in unbalanced LV networks is prone to be very similar to the previously discussed cases.

The total effect on losses for different penetration levels of EV is low. The same exponential behavior discussed above is observed. Thus, unbalance drives a fast increase in LV distribution losses in all EV penetration scenarios. Notwithstanding, reaching higher values of unbalance degree becomes more likely under larger penetration levels of EVs as they constitute a relatively large single-phase load that increases the heterogeneity in load profiles of individual consumers, i.e. consumers with EVs will show a much different load profile as compared to those without an EV. Fig. 8 shows the daily losses that correspond to a residential demand level of 100% with an EV penetration degree of 15%, 30%, 45% and 60% with respect to total peak demand in comparison to the case of demand and no EV penetration (red curve). It must be noted that, unlike in Fig. 6, each of the diagrams in Fig. 8 is represented in a different scale so that the increment in losses driven by EV integration can be better appreciated.

In the case of bus voltage profiles, shown in Fig. 9, the effect of EV charging is an increase of voltage drop during the charging hours. In residential areas, EV charging adds to the peak of domestic demand in the evening, where consumers arrive home. There-

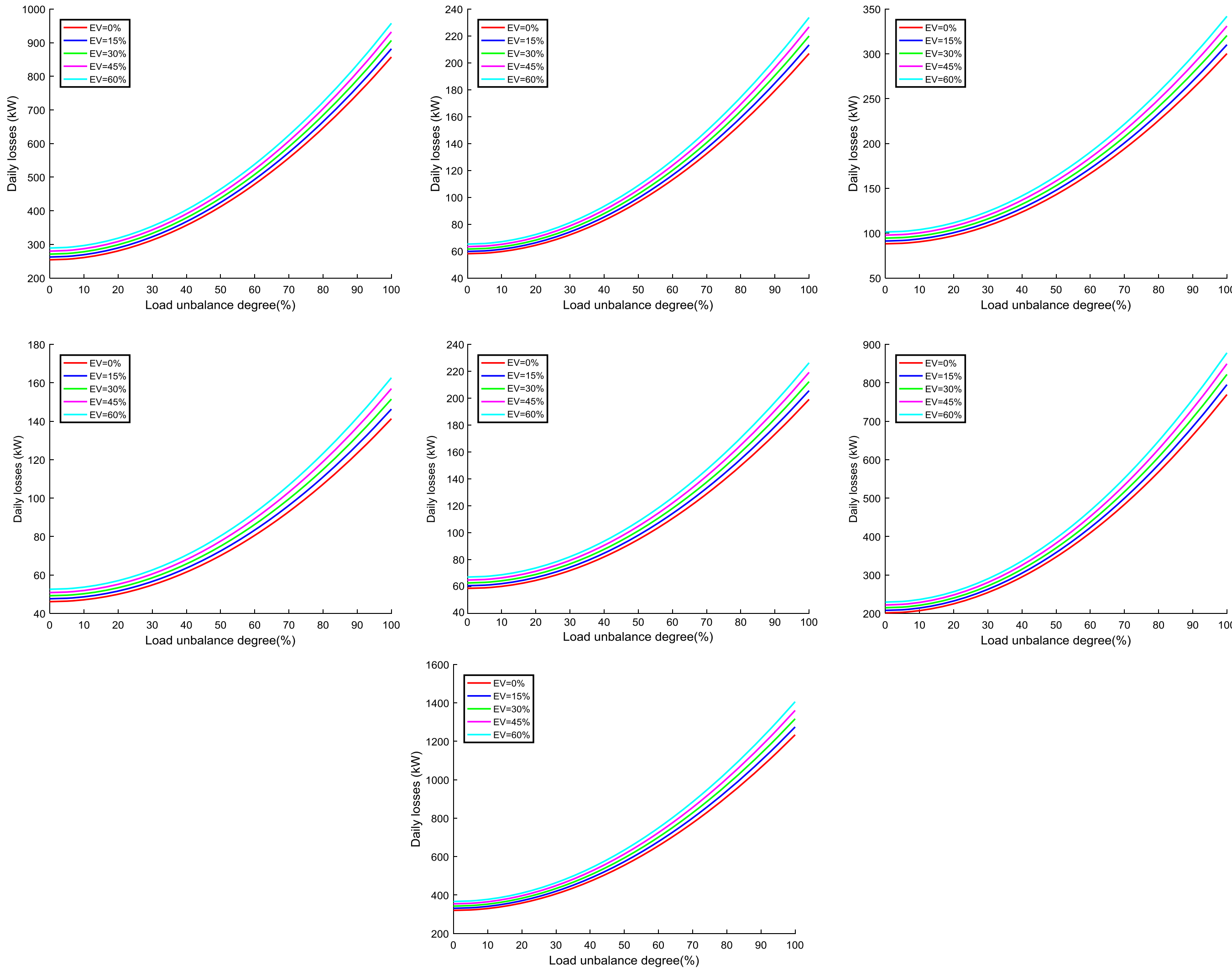

Fig. 8. Daily energy losses under different EV penetration levels and degree of unbalance in the LV networks. From left to right: first row *n1*, *n2*, *n3*; second row *n4*, *n5*, *n6*; third row *n7*.

fore, the occurrence of under-voltages follows a similar pattern to the case with only load previously analyzed too. Under-voltages were only observed in five of the networks analyzed, namely *n1*, *n2* and *n3*, due to the physical characteristics of these networks which present long overhead feeders; and, to a lesser extent, *n6* and *n7* because these are much more heavily loaded, so that given EV penetration degrees represent a very large volume of additional demand.

Note that different charging strategies may result in a different impact on the system, depending on the interaction with demand. For instance, if EV charging took place starting later in the night, where residential demand is lower, the number of buses experiencing voltage levels below the minimum threshold would be presumably lower. By contrast, in a commercial area, maximum demand and EV charging would be coincident and take place during working hours, so losses would be further increased and under voltage problems would be more frequent. Furthermore, it must be noted that fast charging has not been considered because due to the high required capacity, fast charging points would most probably be connected as a three-phase, and even directly to the MV grid. Therefore, in spite of rising network loading and losses, system unbalance would not be affected.

4.3. Integration of solar PV

The generation of PV connected to the LV network is consumed by the local demand, so that net demand is reduced and consequently energy losses are reduced as well. In residential areas, the demand is relatively low during the hours of PV production, especially in working days. However, further integration of PV may result in PV generation surpassing demand, so that power flows are reversed. As observed in Fig. 5, for low loading of the lines and high PV penetration degrees, the net peak generation is higher than the peak demand during the evening. Consequently, the total daily energy losses are slightly reduced for a 25% and 50% PV penetration but then increase again for 75% or 100% penetration, as can be seen in Fig. 10.

With respect to the effect of unbalance on energy losses, comparing these results with those previously obtained in the scenarios without generation, it can be observed that moderate penetration levels (of up to 75%) actually mitigate the increase in losses driven by system unbalances. The steep increase in daily losses that previously occurred beyond a threshold of 30–40% degree of unbalance, now takes place for unbalance degrees beyond a threshold of 50–60%. On the contrary, higher PV penetra-

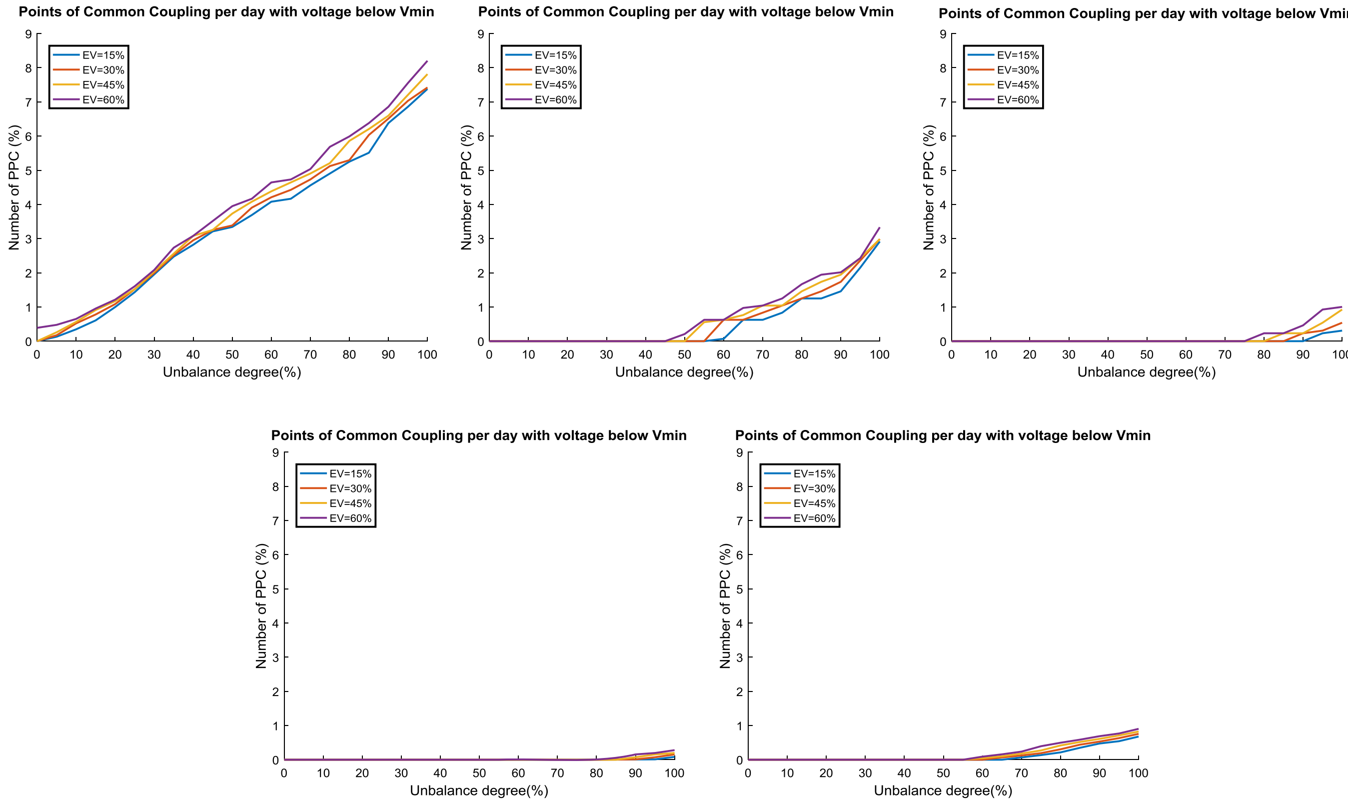

Fig. 9. Share of buses experiencing over-voltages under different EV penetration levels and degree of unbalance in the LV networks. From left to right: first row *n1*, *n2*, *n3*; second row *n6*, *n7*.

tion levels (100% PV scenario) the exact opposite happens. In these scenarios, the slope of the exponential curves starts increasing sharply for lower levels of unbalance degrees, generally around a value of 20%, in all the LV networks analyzed.

Considering voltage profiles, the impact of PV penetration and system unbalance significantly differs from the scenarios where only loads were connected to the LV grid. On the one hand, the problem of under-voltages is generally mitigated thanks to the penetration of solar PV. The networks for which this was previously a major problem for high demand scenarios, a much lower number of buses would experience under-voltages. Furthermore, this problem is virtually non-existent for the remaining grids. Note that they may happen in other periods of the year with very high load and little PV production, as in the case of residential consumers with electric heating during winter periods. During these hours, the effect of unbalances to be expected would be closer to the situation depicted in Fig. 7. On the other hand, the progressive penetration of PV may cause over-voltages in those hours with higher local production in those buses with a larger installed capacity, especially for lower demand levels.

Fig. 11 shows the compliance with voltage levels for a loading level of 50% of peak demand and the different scenarios of PV penetration studied in networks *n1* and *n2* where overvoltages limit the amount of PV that can be integrated into the network. The degree of unbalance clearly causes a higher number of voltage violations due to excessively high bus voltages. In network *n1* a degree of phase unbalance around 15% causes problems for high PV penetration. Note that the connection of PV units at the LV level is bound to increase the likelihood of high degrees of unbalanced for the same reasons mentioned about EVs. In the remaining networks, over-voltages only arise for very large PV penetration levels and unbalance degree in very specific buses.

Lastly, the selected scenarios assumed that for fully unbalanced systems current flows in one single phase, but there may exist other unbalanced scenarios where loading current flows in one phase and PV injections in another phase. These extreme scenarios would result in even more limited PV hosting capacity.

4.4. Analysis for different voltage limits

The previous analyses have considered the voltage limits established by current European regulation with a margin of 10% of its nominal value [30]. Other countries impose stricter limits, such as in the case of Spain, where voltage drop cannot exceed 7% of the nominal value [36]. The effect of considering different regulatory limits or operational standards has been assessed for the studied networks and scenarios. Stricter voltage regulation limits the network hosting capacity, resulting in network reinforcement requirements to accommodate increasing shares of DER. Furthermore, the effect of phase unbalance becomes more noticeable, since technical constraint violations occur at an earlier stage.

Fig. 12 illustrates the share of nodes experiencing under voltages for a loading level of 100% (depicted in dashed lines), and adding to the demand an EV penetration degree of 60% (depicted in continuous lines). Under voltage is defined considering a maximum voltage deviation of 5%, 7% and 10% of nominal value in networks *n2* and *n3*. As seen in Sections 4.1 and 4.2, network *n2* experienced voltage problems only for high degrees of phase unbalance above 60%. The introduction of EVs resulted in higher voltage drops, so that voltage problems already appeared for a 45% degree of load unbalance. However, if the voltage limitation is set to 7% of nominal value, an unbalance degree of 20% already causes overvoltage problems, and the introduction of EV would not be possible for an unbalance degree above 15%. An even stricter limit would not allow the introduction of EVs, since demand alone would already cause overvoltages. No voltage problems were previously identified for network *n3* for a minimum voltage of 90% of nominal value, unless very high levels of unbalance were consid-

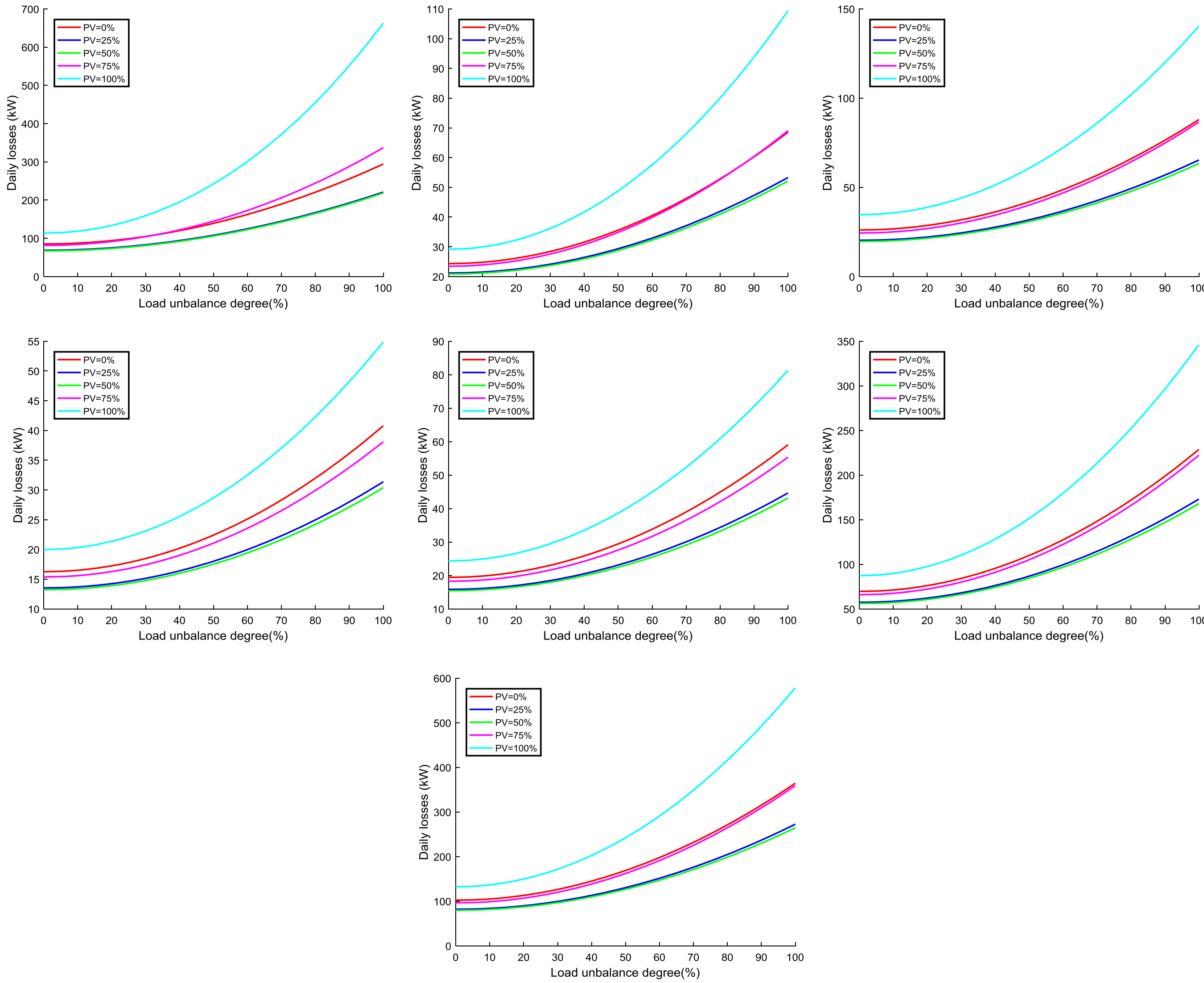

Fig. 10. Daily energy losses under different PV penetration levels and degree of unbalance in the LV networks. From left to right: first row *n1*, *n2*, *n3*; second row *n4*, *n5*, *n6*; third row *n7*.

ered. Considering voltage limits of 7% and 5% results in overvoltages for mild load unbalance degrees.

The same conclusions may be extracted in the case of PV integration in LV networks. As an illustrative example, Fig. 13 shows the share of nodes with voltage below the minimum and above the maximum thresholds for a penetration degree of PV of 100% of peak demand for a loading level of 75%. As previously observed, no under voltage problems are detected for a low level of load. Rather, the opposite problem may be expected, when a very high penetration degree of PV leads to overvoltage problems, as is the case of network *n2* for an unbalance degree above 75%. Considering voltage margins of 5% and 7% of nominal value results in overvoltage problems for mild levels of phase unbalance (15% and 40% respectively). In the case of *n3*, such PV penetration degree results in voltages above the 105% threshold for phase unbalance above 40%.

Yet a very relevant issue is the duration of voltage problems caused by the integration of DER in LV networks. Regulation typically establishes that voltage limits must be complied during most of the time, leaving a certain buffer of time where limits may be surpassed. Due to the different behavior of PV and EV, this will affect the integration of each type of DER differently. PV may cause high voltage rises leading to overvoltage problems during peak production hours, i.e. at noon. However, the assumed EV charging is a flat demand curve, so that under voltages caused will be sustained in time, leading to higher degrees of violation of voltage limits than in the case of PV.

4.5. Implications for the implementation of LV supervision solutions

The results presented throughout this section underline the fact that phase unbalance limits significantly the hosting capacity of LV networks. Even though high penetration degrees of EVs and PV may be achieved, load unbalance highly increases the voltage drops during EV charging and the voltage rise caused by excess of PV production, so that voltage limits may be surpassed with volumes of DER lower than expected. Furthermore, in order to allow the connection of DER, distribution companies must reinforce the feeders and transformers in the network. Thus, phase unbalance brings forward in time the need for reinforcement, which in turn leads to higher network costs, as highlighted by the authors of [6], where a model is developed to quantify the additional reinforcement cost. The detection of unbalance is the first step to allow mitigation solutions as an alternative to early reinforcement. Available solutions for load unbalance mitigation include reconnection or re-phasing of loads and planning for connection of new DER to

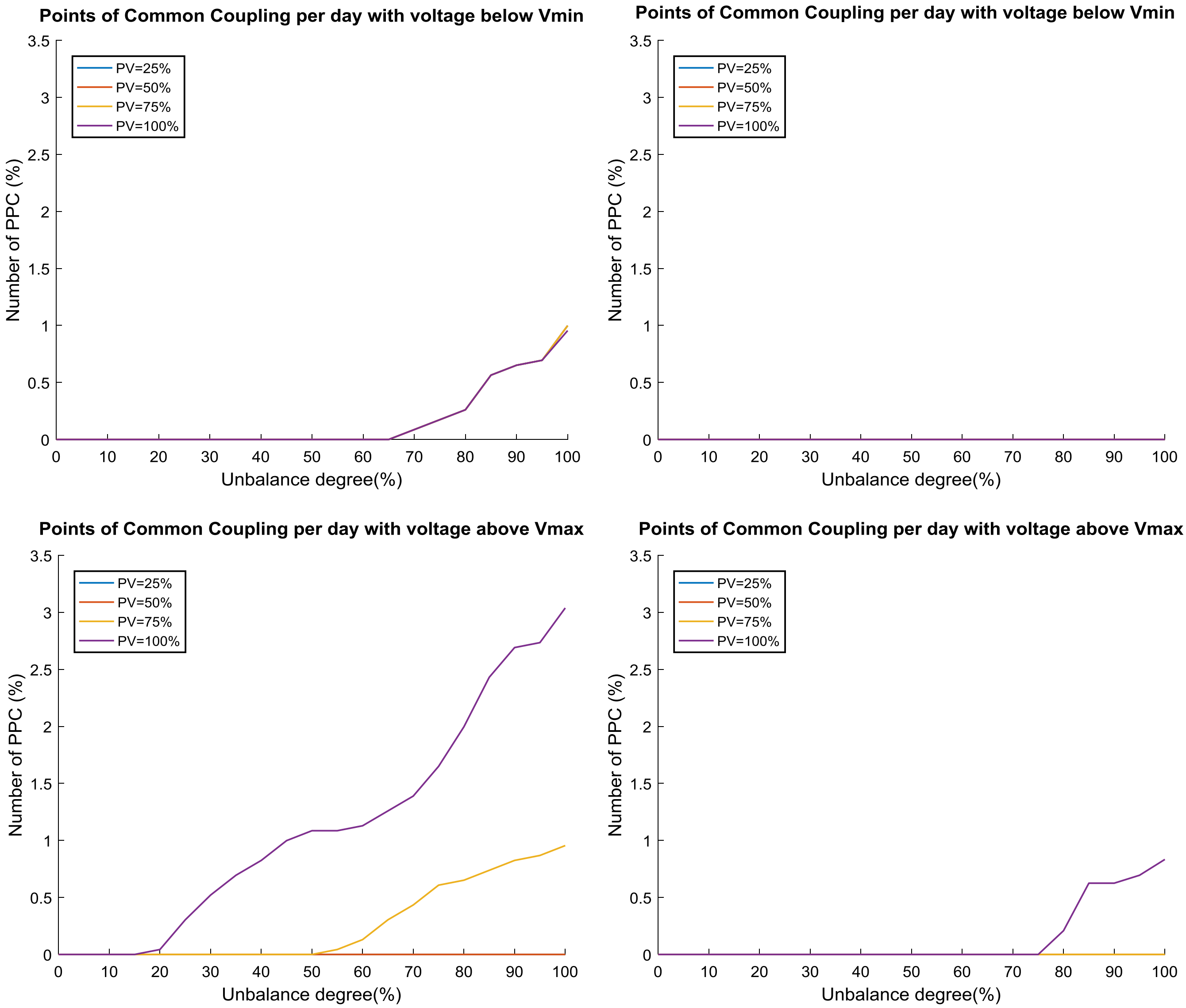

Fig. 11. Share of buses experiencing under voltages (top row) and overvoltages (bottom row) under different PV penetrations and degree of unbalance in the LV grids in networks n1 (left) and n2 (right).

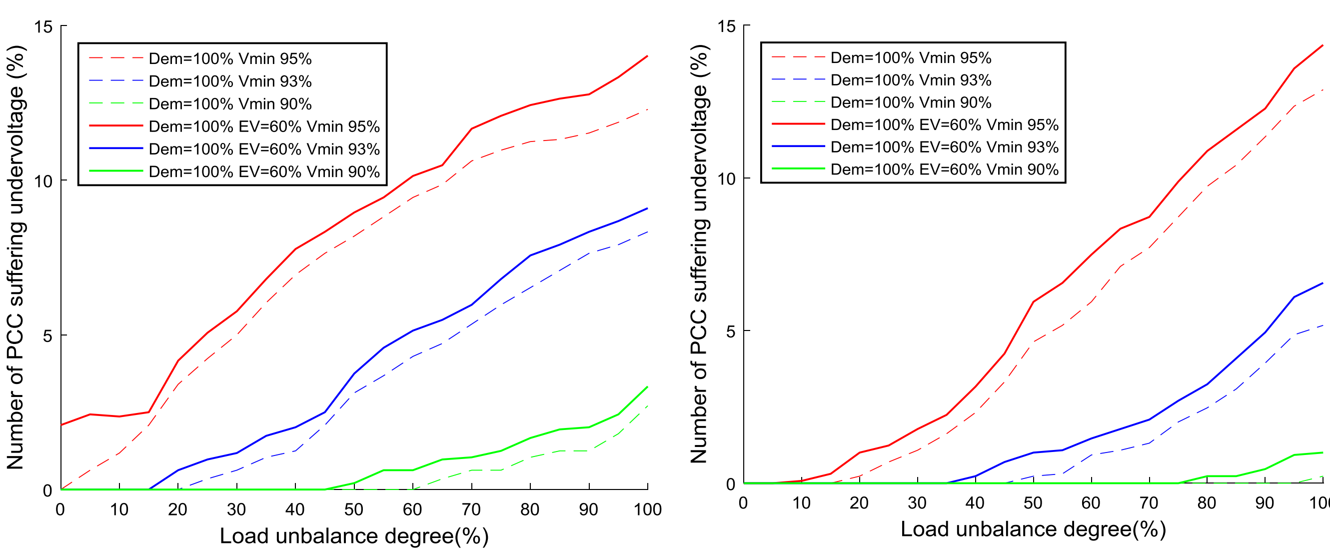

Fig. 12. Share of buses experiencing under voltages with and without EV integration considering different voltage limits. Networks *n2* (left) and *n3* (right).

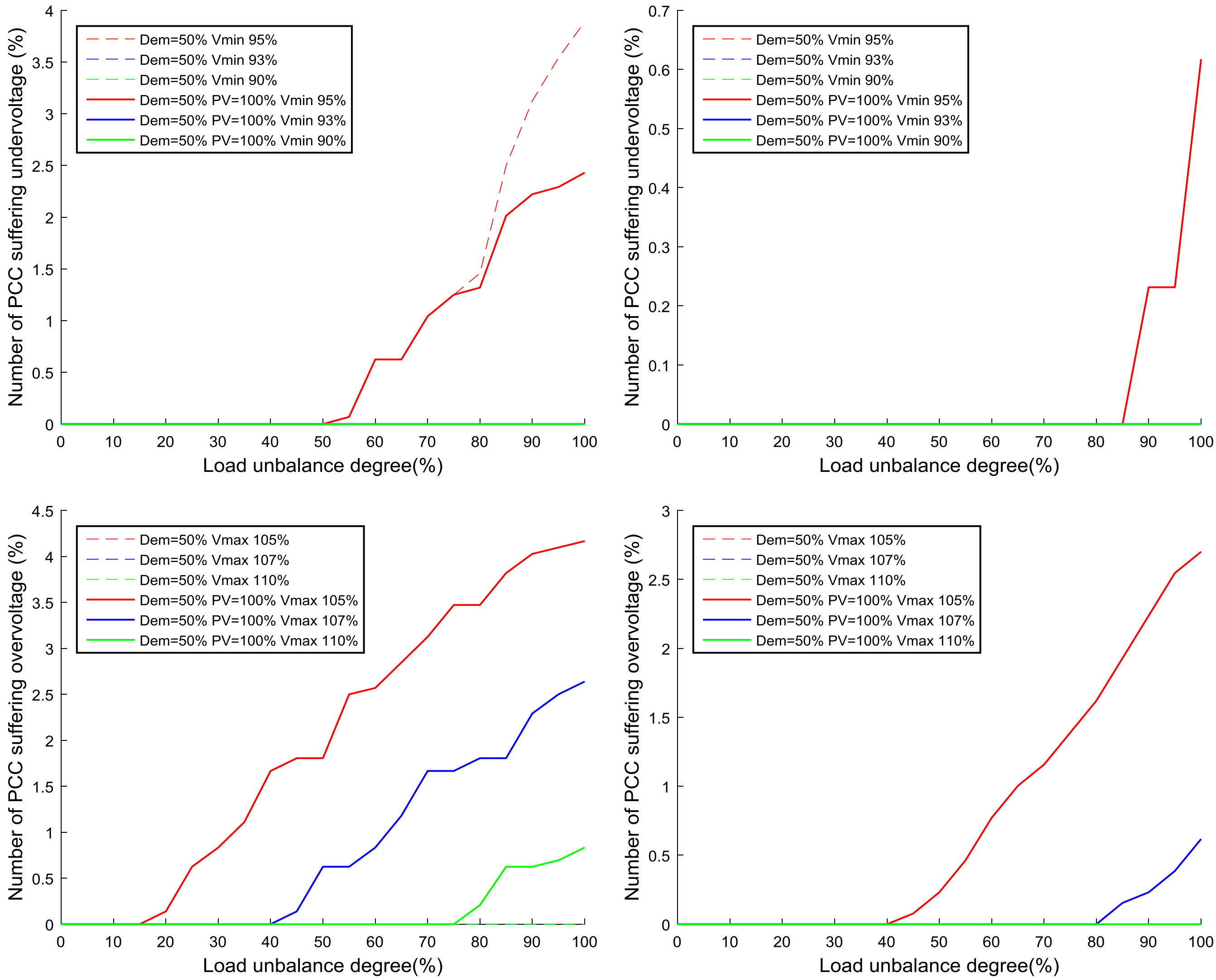

Fig. 13. Share of buses experiencing under voltages (top row) and overvoltages (bottom row) with and without PV integration considering different voltage limits. Networks *n2* (left) and *n3* (right).

the optimal phase according to their loading, as well as other solutions such as the use of thyristor-switched capacitors, series (DVR) and parallel (DSTATCOM) custom power devices and battery storage.

Different LV supervision solutions have been tested in smart grid projects to integrate and process the information provided by different elements in the LV network, such as AMI infrastructure and smart meters, monitoring devices in the LV outgoing LV lines at secondary substations and LV cabinets. Clearly, the implementation of such LV supervision solutions can bring many benefits for the operation of the LV grid, including the detection of unbalance. Furthermore, the information from smart meters can help distribution companies identify the association between consumers and the feeders and phases they are connected to and thus keep an updated inventory, which is often not the case for LV infrastructure[5]. However, there are several aspects that must be taken into account for the implementation of LV monitoring and potential barriers that could hinder their exploitation.

There is a potentially enormous amount of data that could overload the operator and hinder the detection of problems in the LV network. It is therefore very important to carefully select the relevant data. Furthermore, an overlying intelligent system may be needed in order to make sense of all the data and manage events and alarms.

AMI infrastructure can acquire and record different measures and data. However, the list of functionalities to be incorporated into smart metering systems is not standardized across the EU. The EC recommendation 2012/148/EU enumerates a list of minimum functionalities, among which power quality monitoring is not included [37]. The EC smart meter benchmarking report states that most Member States leave at the discretion of roll-out responsible parties (most frequently DSOs) the inclusion of alternative functionalities [38]. Therefore, potentially limited smart meter functionalities may be an important barrier to LV monitoring. Otherwise, billing information and historical consumption may be suitable for planning applications and network studies, but not for operation. Similarly, the potential of such solutions may be hampered if this deployment does not reach a significant share of end consumers.

Furthermore, the possibility of using AMI data for LV network supervision depends on the model for meter ownership and data

[5] Up until now, the information systems of distribution companies often lack of a complete and updated inventory of LV distribution assets due to (i) the large amount of LV network elements, (ii) the frequent modifications in the networks due to operation and maintenance, and (iii) the low degree of monitoring.

management. In most Member States where smart metering has been or is being deployed, the DSO are in charge of deploying and owning the meters [39]. However, in countries with independent metering point operators, the access of DSOs to the information may be limited.

5. Conclusions

This article studies the effect of future integration of DER in the LV network, namely PV generation, and EVs, where phase unbalance is often neglected but relevant nevertheless. This work is focused on the evaluation of energy losses and voltage profiles in residential LV grids in rural and semi-rural areas. The technical analysis carried out is based on three-phase load flow analyses using the forward-backward algorithm for average hourly profiles for residential demand, PV production and EV charging during the night. A wide range of scenarios has been considered to cover for different levels of demand, and penetration degrees of PV and EV. Phase unbalance has been studied by considering gradually increasing degrees of unbalance for the net load in the system.

It can be concluded from the results obtained in the technical analysis of this work that the increase in phase unbalance results in exponentially higher energy losses, particularly in networks that are more heavily loaded. The degree of phase unbalance also affects voltages so that higher unbalance leads to higher voltage variations along the line. Voltage constraints violations may occur especially in long overhead feeders. The penetration of EV and PV may increase unbalance of distribution networks, as these are relatively large single-phase loads or power injections. The interaction of EV charging strategies and demand is key: since EV charging is expected mainly in the load in valley hours (during the night), no under-voltage problems are expected. If EV charging took place during peak demand, energy losses would increase much more, and voltage problems could arise. The penetration of PV slightly reduces the losses in the system for low penetration degrees and mitigate the increase in losses driven by the system, but higher shares of PV produce the opposite effect. For high shares of PV, when PV production exceeds the demand, over-voltage problems may arise and limit network hosting capacity, especially in the case of longer lines. As unbalance causes higher voltage variations, it further reduces network hosting capacity, since voltage limits are surpassed for lower degrees of penetration of DER. Logically, the hosting capacity of networks will be constrained by the regulatory voltage limits and the criteria to monitor compliance. As a result from limited hosting capacity, network reinforcement will be required as more DER is connected to the grid, so it can be concluded that load unbalance brings network reinforcement costs forwards in time.

It is clear that the effect of unbalance is not negligible, and it is becoming more and more relevant under the current context of increasing connection of single-phase DER in the LV grid. In the context of the smart grid, AMI can help DSOs monitor the network and thus identify high degrees of unbalance, so that corrective actions may be taken. The results from this work show that where high integration of DER is expected, the monitoring of more loaded and longer networks should be prioritized. However, the information available for network operation will depend on the type of monitoring devices and smart meters, their degree of implementation and the accessibility of DSOs to these data.

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