Voltage Regulation Under Unbalanced Power Flow in Active Four-Wire Low Voltage Distribution Grids

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***Abstract*—The increasing penetration of distributed energy resources in Low Voltage Distribution Grids (LVDGs) has a severe impact on the grid's voltage profile. In active LVDGs the controllable assets are mainly single-phase inverters which most often they are unevenly distributed amongst the supply phases. The majority of voltage support schemes in the literature assume that the phases are decoupled and utilize the single-phase inverters in per-phase regulation methods. However, the particularities of LVDGs, namely the inductive coupling from the distribution lines and the neutral coupling from the fourth wire, can result to a strong phase coupling. Consequently, conventional voltage support schemes by single-phase inverters in active LVDGs can cause unbalanced power deviations in one phase and due to the phase coupling it can have a significant impact on the voltage of a different phase. In this paper, the phase coupling, its impact on voltage regulation, and the factors that contribute to its intensity are analysed. In addition, it is demonstrated how two traditional voltage regulation schemes become ineffective due to the phase coupling. Finally, a reactive power compensation scheme is presented that exploits the mutual voltage deviations induced by the phase couplings in order to improve the voltage regulation capabilities in LVDGs.**

Keywords— Four-wire, low voltage distribution grid, neutral coupling, phase coupling, voltage regulation.

I. Introduction

Incentive schemes and lower costs by technological advancements have led to a significant increase of Distributed Energy Resources (DERs) in Low Voltage Distribution Grids (LVDGs). However, to achieve the target of net-zero emissions it is expected that the penetration of DERs, with mainly rooftop Photovoltaic (PV) systems, and electric vehicles (EVs) in LVDGs will increase further [1]. From a technical prospective, high penetrations of PV systems and EVs can introduce several challenges to the reliable operation of the distribution grid [2]. These include the increase of system losses, the thermal and voltage limits violations and the increase of system asymmetry.

In LVDGs, consumers mainly have a single-phase connection. This creates an inherent network asymmetry as most often the consumers are not equally distributed amongst the supply phases. PV inverters and chargers for EVs commonly follow the same connection as the corresponding household. Therefore, in LVDGs the PV inverters and EV chargers are also mostly single-phase connected. For the PVs this can create an imbalance in the generation capacity of each phase. Under high PV penetration the reverse power flow that occurs during the hours of peak PV generation, which are also the hours that a residential load has a low consumption, can lead to an asymmetrical voltage rise. On the other hand, the uncoordinated EV charging can increase the peak demand and load asymmetry of the network, it can lead to congestion of the distribution transformer and can create under-voltage conditions within the LVDG.

In the literature several works have been proposed for managing active LVDGs by utilizing the ancillary services and flexibility that the PVs and EVs can offer. Typically, the voltage rise induced by the PV generation is mitigated by reactive power provision from the inverters [3]. In [4], a combination of the local power factor/Watt and Var/Volt droop based methods is presented aiming to coordinate the inverters near the substation for providing reactive power support when violations occur. This method is improved in [5] by reducing the overall reactive power deployment by considering the sensitivity of each node to reactive power absorption. A distributed and model free method based on sensitivity analysis is presented in [6] with five modes of operation. In addition, active power curtailment is used only if the available reactive power is not sufficient for preventing voltage violations. In [7], a rule based distributed method is presented for regulating the positive-sequence voltage with three-phase controllable inverters. Strategies that coordinate the charging of EVs in order to prevent thermal and voltage limit violations are presented in [8]-[9].

In the aforementioned management schemes, single-phase devices (PV inverters, EV chargers) connected at phase i alter their power set points according to the phase-neutral voltage of the specific phase. On the other hand, three-phase devices regulate their balanced power output according to the positive-sequence of the grid voltage. Consequently, the mutual voltage deviations (MVD), which refer to the impact to a phase-neutral voltage when power is altered at a different phase due to phase coupling, is ignored. Further, the particularities of LVDGs, namely the inductive coupling from the distribution lines and the neutral coupling from the fourth wire, can result to a strong phase coupling. Therefore, a power deviation at one phase can have a significant impact on the voltage at a different phase. This, as shown later, can render conventional voltage regulation schemes ineffective.

The contributions of this paper are: (1) the impact of the MVDs to the voltage regulation is analysed and the factors to its severity are revealed for different earthing types for active LVDGs, (2) based on this analysis, recommendations are made of how the MVDs due to the phase coupling can be exploited for more efficient voltage regulation and (3) a centralized reactive power provision scheme that coordinates single-phase PV inverters based on the established sensitivity analysis framework is presented.

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The structure of the paper is as follows. In Section II the phase couplings and MVDs in LVDGs are analysed. Two traditional voltage regulation schemes are presented and evaluated in Section III along with the reactive power provision scheme based on sensitivity analysis. Finally, the paper concludes in Section IV.

II. Phase Coupling and Mutual Voltage Deviations

Most LVDGs are four-wire networks with three wires for phases *a*, *b*, and *c* and one additional wire for the neutral conductor *n*. Figure 1 illustrates the two main earthing configurations that are used in most LVDGs. The most notable difference is that the neutral conductor in TN-C-S networks is earthed with auxiliary earth electrodes within the LVDG at set intervals. In a TT network, the neutral conductor is only grounded at the transformer. In Fig. 2, the voltage deviation due to the voltage drop across the self and mutual impedance of the distribution line is illustrated when the power of phase *a* is altered for both types of earthing. For this analysis a simplified LVDG is considered with three single-phase loads connected at the end of the feeder. The loads are served by a three-phase voltage source through a 0.5 km over-head line. The parameters of this line are given in Table I and are calculated with the Carson's equations [10] for a vertical *abcn* layout with 30 cm spacing between 100 mm^2 conductors.

From Fig. 2, it can be seen that in a TT network both the self and mutual voltage deviations are higher compared to a TN-C-S type network. Further, Fig. 2(b) shows that there is a strong phase coupling between P_a and V_b. From similar investigations for other phases it is concluded that an active power deviation at phase i will have a strong impact on the voltage of the phase that is $\theta_i - 120°$. A similar observation can be made in Fig. 2(f) regarding the reactive power with however the voltage of the phase that is $\theta_i + 120°$ affected the most. In fact, from Fig. 2(a), (d) and Fig. 2(b), (f) it can be seen that the MVDs are almost as strong as the self-voltage deviations. Further, Fig. 2(f) shows how a strong phase coupling can render traditional voltage management solutions ineffective. By absorbing inductive reactive power (positive sign) at phase *a* the voltage of phase *c* rises. Thus, the reactive regulation of phase *a* can be beneficial for phase *a*; however, it negatively affects the regulation of phase *c*.

On the other hand, the phase coupling can be utilized to share resources between phases. For example, if phase *c* is problematic and experiences regular overvoltage conditions, the reactive power resources at phase *a* can be utilized in a counter-intuitive manner. By injecting capacitive reactive power at phase *a*, the voltage of phase *c* decreases. This requires that there is available voltage headroom at phase *a* as the voltage of this phase will rise. In addition, the phase coupling regarding the active power can be utilized for fair PV curtailments. While most curtailment schemes consider the upstream/downstream fairness for voltage regulation [11], a strong phase coupling allows for more fair schemes as the curtailment requirements can also be shared between phases. Similarly, EV charging strategies can be enhanced so that under-voltage conditions in one phase can be mitigated through management of the charging power across all phases.

A. Contributing Factors

In this subsection the key contributing factors to the phase coupling phenomena in LVDGs are analysed.

1) Neutral Coupling: The power supply to consumers in an LVDG is established through one or three supply phases and the neutral wire. Therefore, the neutral voltage that is induced across this conductor is common and influences all consumers. By varying the power at phase i it results to a current variation ΔI_i but also to a neutral current variation. In turn, this neutral current variation induces a neutral voltage variation, indicated in (1), which, as shown in Fig. 3 and expression (2), influences all phase-neutral voltages,

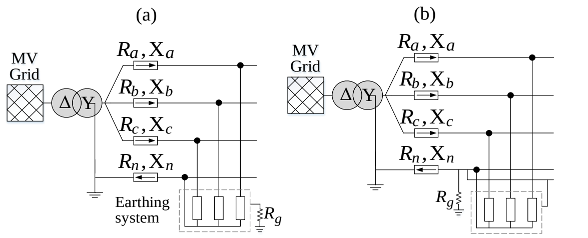

Fig. 1. Main earthing configurations for LVDGs: (a) TT and (b) TN-C-S.

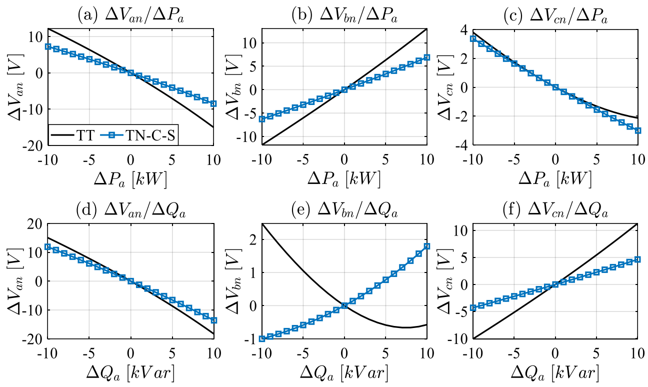

Fig. 2. Self (a), (d) and mutual (b)-(c) (e)-(f) voltage deviation for TT and TN-C-S systems with variation in the active/reactive power of phase *a*.

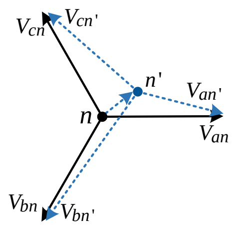

Fig. 3. Impact of varying neutral voltage on all voltage phasors.

TABLE I
R, X Values of a Four-Wire Line with 30 cm Vertical Spacing

R (Ω/km)				X (Ω/km)			
0.3157	0.0482	0.0482	0.0483	0.7854	0.5058	0.4618	0.4367
0.0482	0.3157	0.0483	0.0483	0.5058	0.7854	0.5058	0.4618
0.0482	0.0483	0.3157	0.0483	0.4618	0.5058	0.7854	0.5058
0.0483	0.0483	0.0483	0.3157	0.4367	0.4618	0.5058	0.7854

$$V_n = Z_{nn} I_n + \sum_i Z_{ni} I_i \tag{1}$$

$$|V_{in}| = \big||V_i|\measuredangle\theta_i - |V_n|\measuredangle\theta_n\big| = \sqrt{|V_i|^2 + |V_n|^2 - 2|V_i||V_n|\cos(\theta_i - \theta_n)} \tag{2}$$

where Z_{nn} is the self-impedance of the neutral wire and Z_{ni} the mutual impedance between the neutral and phase $i \in \{a, b, c\}$. The neutral coupling can be considered as form of phase coupling as the injection/absorption of power in one phase influences all phases. In TN-C-S systems, the earth electrodes provide parallel paths for the neutral current back to the substation via the earth. As a result, the induced neutral

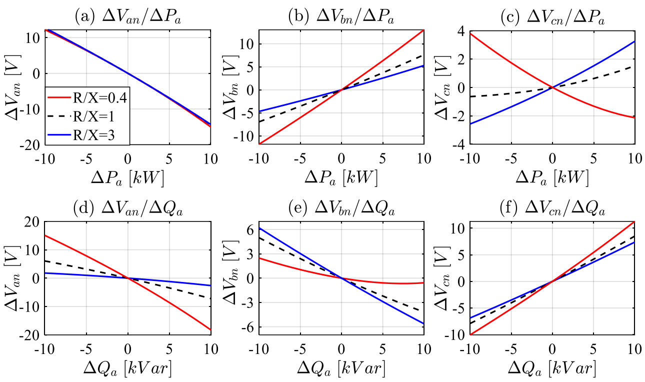

Fig. 4. Voltage response for different R/X ratios for a TT type LVDG.

voltage in these systems is limited as the neutral current that is flowing through the conductor is reduced. This explains why the MVDs are stronger in TT systems (Fig. 2), as the neutral coupling is mostly negligible in TN-C-S systems.

2) Inductive Coupling: An additional source of coupling between the phases is the inductive coupling introduced by the distribution line. Note that, as indicated in Table I, a distribution line can also have a resistive coupling between the phases. However, the mutual resistance is usually negligible and therefore the resistive coupling can be ignored. When balanced conditions are assumed then regulating the positive sequence is adequate for voltage management. This is because the impedance matrix can be simplified to a diagonal matrix with $Z_s + Z_m$ as the diagonal, where Z_s and Z_m are the self and mutual impedance of the line respectively. As indicated by [10], the strength of the mutual coupling is determined by the type and geometry of the line. In three-wire MV distribution grids the neutral coupling does not exist and the line configuration and conductor type can be such that the inductive coupling between conductors is minimal [12]. In this case the MVDs become negligible and management solutions based on a per-phase approach are effective. In LVDGs, the conductors in distribution lines are placed closer, and as shown in Table I by the off-diagonal elements, a significant inductive coupling between phases is introduced.

Figure 4 shows the self and mutual voltage deviations of the TT based LVDG with distribution lines of different R/X ratios. Note that the distribution line given in Table I has an R/X ratio of approximately 0.4. For R/X ratios of 1 and 3, the inductive elements of this line are scaled appropriately while the resistive elements remain constant. Therefore, for an R/X ratio equal to 3, the mutual terms of the distribution line are greatly reduced. Consequently, the MVDs are also greatly reduced, as indicated in Fig. 4.(b), (f). Note that for $R/X = 3$, the MVDs are mostly induced by the neutral coupling and therefore, in a TN-C-S system they can be negligible. Further, with a high R/X ratio, reactive power compensation for voltage regulation is not a viable option as shown in Fig. 4(d). In this case the voltage regulation is insensitive to reactive power flow since the voltage drop across the self-inductive component is insufficient to achieve any significant voltage regulation. Consequently, most conventional voltage management schemes usually resort to active power management, through PV curtailments or by charging/discharging energy storage systems, for voltage regulation. However, in a TT based system even under high R/X ratios the MVDs, due to the neutral coupling, can be leveraged in unconventional manner by utilizing the reactive power capacity at one phase in order to regulate the voltage of a different phase.

III. Impact on Voltage Management Solutions

To investigate the impact of the unintended MVDs in voltage management solutions, the simplified TT type LVDG system illustrated in Fig. 1(a) is utilized. The distribution line has a length of 0.5 km, which is the typical end-of-feeder distance in residential LVDGs, and its parameters are shown in Table I. Each residential load is also equipped with a single-phase PV system. Two scenarios are examined to investigate the impact of the unintended MVDs.

In the first scenario a balanced PV capacity (42 kW total) is assumed. Under these conditions it is expected that the traditional compensation schemes will be effective in managing the grid voltage as the MVDs will mostly balance out. It is noted that this scenario is equivalent to having three-phase controllable assets regulating the positive sequence. For the second scenario an unbalanced PV capacity is considered with 15, 8 and 10 kWp in phases *a*, *b* and *c* respectively. In both scenarios two traditional voltage management solutions (presented in Section III.A) based on reactive power compensation from PV inverters are evaluated. To illustrate how voltage management solutions for active LVDGs can be improved, a reactive power compensation scheme is presented in Section III.B that leverages the MVDs. The considered reactive power compensation schemes are evaluated in Section III.C.

A. Traditional Reactive Power Compensation Schemes

System voltage rise due to excessive PV generation is conventionally mitigated by operating the PV inverters in a non-unity lagging power factor. Local methods for Var compensation include constant power factor and droop-based control of reactive power with either power factor/Watt $cos\phi(P)$, power factor/Watt-Volt $cos\phi(P,V)$ or Var/Volt $Q(V)$ curves [3]-[4]. While relatively simple and easily applicable, the methods that are based on the active power generation by the PVs can result to unnecessary reactive power flow when the grid voltage is within the admissible limits. This increases the overall grid losses as well as the stress on the PV inverters which can reduce their lifespan. In addition, local methods lack an upstream/downstream node coordination (in the case of Var/Volt scheme) which can lead to saturation of the inverters at the end of the feeder while inverters near the transformer can still be operating at a unity power factor. Central and distributed methods leverage a higher network observability to coordinate the provision of reactive power across the whole grid. These methods reduce the amount of reactive power needed for voltage management and fully utilize the available resources when needed but require a two-way communication between different assets.

Expression (3) shows the basis for a per-phase voltage regulation where it is assumed that the phases are decoupled,

$$|V_k| \approx |V_{k-1}| - \frac{R_{k,k-1}P_k + X_{k,k-1}Q_k}{|V_{k-1}|} \quad (3)$$

where P_k and Q_k is the total active and reactive power of node k, $R_{k,k-1}$ and $X_{k,k-1}$ is the line resistance and inductance, and $|V_k|$, $|V_{k-1}|$ the voltage magnitude at nodes *k* and *k-1*. To illustrate how the effectiveness of methods based on (3) can be reduced under unbalanced reactive power flow originating from asymmetrical single-phase PVs, the local $cos\phi(P)$ and $Q(V)$ methods are considered. The settings and set points of these droop-based schemes are given in Fig. 5 while the active power generation profile in the numerical simulations corresponds to a sunny day during summer in Cyprus [2].

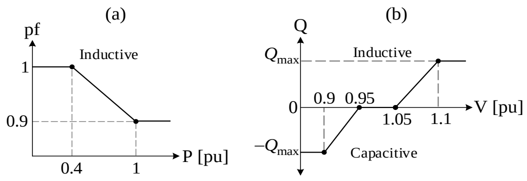

Fig. 5. Settings of local reactive power compensation modes for smart inverters: (a) $cos\phi(P)$, (b) $Q(V)$.

B. Reactive Power Compensation with Cross-Phase Voltage Response Using Sensitivity Analysis

The MVDs in active LVDGs can be leveraged for an effective and unconventional voltage management. In recent works, the MVD impact in LVDGs has been ignored or not explicitly exploited by either assuming a balanced operation [6], conducting voltage regulation in each phase individually [13] or by considering only three-phase inverters as the controllable assets [7]. In a different direction, an optimization problem for controlling the reactive power of the single-phase PV systems in a centralized manner is presented in (4)-(8). The objective function (4) aims to minimize the overall deployment of reactive power which results to lower grid losses and less stress on the PV inverters. The decision variables are the required reactive power deviations $\Delta Q_i(t)$, with $i \in \{a, b, c\}$, of each single-phase inverter such that there aren't any voltage violations (7) while the inverter limits for reactive regulation (8) are satisfied for the current time step t.

$$\min\ Q_a^2(t) + Q_b^2(t) + Q_c^2(t) \rightarrow \min \sum_i Q_i^2(t) \tag{4}$$

$$\text{s.t} \qquad Q_i(t) = Q_i(t-1) + \Delta Q_i(t) \tag{5}$$

$$\begin{aligned} V_i(t) &= \hat{V}_i(t) + \Delta V_i \\ &= \hat{V}_i(t) + q_{ia}\Delta Q_a(t) + q_{ib}\Delta Q_b(t) + q_{ic}\Delta Q_c(t) \end{aligned} \tag{6}$$

$$\underline{V} \le V_i(t) \le \overline{V} \tag{7}$$

$$\underline{Q_i} \le Q_i(t) \le \overline{Q_i} \tag{8}$$

The above optimization problem, referred to as Q_{opt}, is based on sensitivity factors $q_{ij} = \partial V_i / \partial Q_j$, with $j \in \{a, b, c\}$, that indicate how the voltage magnitude V_i at phase i is affected by deviations of reactive power at phase j, as given in (6). Note that $\hat{V}_i(t)$ from (6) refers to the voltage magnitude of phase *i* at time step *t* before the control decision for this time step is applied. This value can be extracted by either a power flow solution, it can be measured by the local sensors of inverters, or it can be provided by a monitoring system based on advanced metering infrastructure with smart meters [14]. The sensitivity factors q_{ij} can be determined either by inverting the Jacobian matrix after a Newton-Raphson power flow or by a perturb-and-observe approach [15]. In the latter method, a radial power flow method is utilized by altering the power set points at the node and phase of interest and determining through the power flow results the impact on the voltage magnitude across the system. Another approach to directly calculate q_{ij} is by the use of the linearized power flow equations for radial distribution grids [16].

The formulation in (4)-(8) is similar with the optimal power flow approach with linearized power flow equations for radial unbalanced MV grids. However, in LVDGs the available controllable assets are mostly single-phase and the MVDs can be more severe. This allows to exploit the MVDs in a counter-intuitive and unconventional manner which results to a more effective and more efficient utilization of the available reactive power resources as shown in Section III.C.

C. Case Studies

In Fig. 6 the phase-neutral voltages are illustrated for the case with balanced PV capacity across the phases under the different reactive power compensation schemes. Note that the *No PRC* refers to the case that the single-phase PV inverters operate in a unity power factor and hence there is no reactive power control for overvoltage mitigation. Under these conditions the voltage in all three phases exceeds the overvoltage limit $\bar{V} = 253\,V$. From Fig. 6 it can be concluded that all reactive power compensation schemes manage to restore the grid voltage within the admissible limits. Unlike the local modes, Q_{opt} deploys inductive reactive power only when there are voltage violations, as explained in Section III.C. As a result, it requires the least amount of reactive energy, only 58 kVar·h in comparison with 113 and 127 kVar·h of the $cos\phi(P)$ and $Q(V)$ modes respectively. The $Q(V)$ mode in this case uses the most reactive energy as the grid voltage remains above 1.05 p.u for a significant amount of time. The $cos\phi(P)$ mode reduces its deployment of reactive power based on the active power generation (which after solar noon starts to decrease), while $Q(V)$ continues to absorb reactive power until the local grid voltage is below 1.05 p.u. Nonetheless, under balanced PV capacity the considered reactive power control schemes are effective and operate in the expected manner as the MVDs are balanced out.

In Figs.7-8 the phase-neutral voltages and reactive power per phase are illustrated for the case with unbalanced PV capacity. From these figures several observations can be made. First, under these conditions, only the voltage in phase a and c exceed the upper voltage limit (asymmetrical voltage rise). Second, in Fig. 7(c) it can be seen that both the $cos\phi(P)$ and $Q(V)$ modes fail to restore the grid voltage V_{cn} within the acceptable limits. In fact, under the $cos\phi(P)$ mode, despite of a maximum reactive power absorption of $\bar{Q}_c = 4.8\ kVar$ $\left(\bar{Q}_i = P_{PV}^i \cdot \tan(\text{acos}(pf = 0.9))\right)$ from the inverter, there is negligible voltage regulation at phase *c*. This happens because the impact of reactive power absorption at phase *c* is reduced by the MVDs. Let t_{sn} be the time when solar noon occurs. At this time all PV inverters absorb maximum reactive power and V_{cn} is expressed as,

$$V_{cn}(t_{sn}) = V_{cn}^{bs}(t_{sn}) + q_{ca}\bar{Q}_a + q_{cb}\bar{Q}_b + q_{cc}\bar{Q}_c \tag{9}$$

where V_{cn}^{bs} is the voltage of the base scenario with no reactive power compensation, the sensitivity factors q_{ca}, q_{cb}, q_{cc} are calculated using the perturb-and-observe approach and are equal to 1.04, -0.24 and -1.32 V/kVar respectively, $\bar{Q}_a = 7.2\ kVar$ and $\bar{Q}_b = 3.9\ kVar$. From the above it can be calculated that the voltage regulation is less than 0.5 V as the impact of $\bar{Q}_c$ is cancelled by phase coupling between $\bar{Q}_a$ and V_{cn} ($|q_{ca}\bar{Q}_a| \approx |q_{cc}\bar{Q}_c|$). This means that the voltage regulation at phase *c* is actually provided by the reactive power at phase *b*. Because of the weak phase coupling between V_{cn} and Q_b ($|q_{cb}| \ll |q_{cc}|$) and because of the lower PV capacity at phase *b*, the overall voltage regulation at phase *c* is negligible. Third, the previous observation is also valid for the $Q(V)$ mode. Note that the voltage regulation at phase *c* is higher under $Q(V)$ because, as it is evident in Fig. 8(a), the maximum reactive power Q_a is lower than $\bar{Q}_a$ while Q_c is saturated at $\bar{Q}_c$. In addition, under the $Q(V)$ mode it is

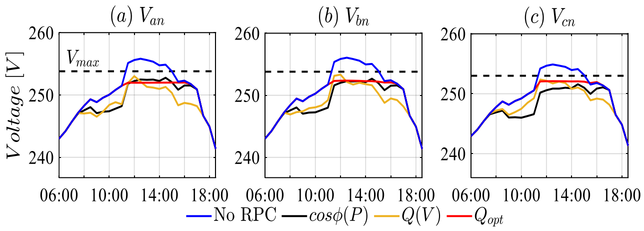

Fig. 6. Balanced PV capacity: Phase-neutral voltages.

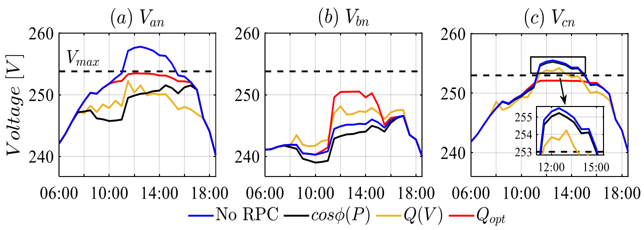

Fig. 7. Unbalanced PV capacity: Phase-neutral voltages

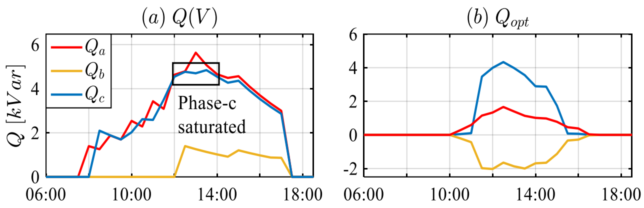

Fig. 8. Unbalanced PV capacity: Reactive power per phase.

observed in Fig. 7(b) that while reactive power is absorbed at phase b the voltage, counter-intuitively, increases. This is due to the low reactive power absorption Q_b as this phase does not exhibit over-voltage conditions as well as due to the high reactive power absorption at phase c. The relationship between $\Delta V_{bn}/\Delta Q_c$ is similar to $\Delta V_{cn}/\Delta Q_a$, illustrated in Fig. 2(f), and therefore absorption of reactive power at phase c results to a voltage rise at phase b.

Finally, Q_{opt} is the only reactive power compensation scheme that manages to restore all phase voltages within the admissible limits and with minimal use of reactive power. In fact, the total reactive energy deployed under Q_{opt} is 27 kVar·h while $cos\phi(P)$ and $Q(V)$ use 94 and 69 kVar·h respectively and still failed to manage the grid voltage. The Q_{opt} scheme provides an unconventional and counter-intuitive phase coordination of the single-phase PV inverters. The strong phase coupling between Q_b and V_{an} ($q_{ab} = 1.17$ V/kVar) is exploited in an effort to share the voltage regulation of phase a between two phases (a and b). The available voltage headroom at phase b is utilized by injecting capacitive reactive power as illustrated in Fig. 8(b). This results to a voltage rise at phase b but also to a reduction of V_{an}. The aim of this operation is to reduce the voltage rise introduced to V_{cn} by the voltage regulation at phase a such that the available reactive power capacity at phase c is sufficient to mitigate the local overvoltage. Injecting capacitive reactive power at phase b reduces the amount of voltage regulation needed at phase a which in turn decreases the voltage rise at phase c due to the MVD between V_{cn} and Q_a. This is shown in Fig. 8(b) as the reactive power Q_a is significantly lower with Q_{opt}, in comparison with Fig. 8(a) and the $Q(V)$ mode. As Q_a is now substantially lower, the reactive power capacity at phase c is sufficient ($|q_{ca}Q_a| < |q_{cc}Q_c|$) and all grid voltages are restored within the admissible limits.

IV. Conclusions

The controllable assets in active LVDGs are mostly single-phase connected and their installed capacity is most often uneven across the phases. The particularities of these networks can lead to a strong phase coupling voltage phenomena arising from the neutral coupling in TT based networks as well as by the inductive coupling of the distribution line. An analytical investigation in this work demonstrates that voltage regulation schemes based on a per-phase approach may become ineffective in such LVDGs when the available assets have predominantly a single-phase connection and operate under unbalanced conditions. However, by exploiting the MVDs arising from strong phase couplings it allows for unconventional voltage regulation schemes where the provision of reactive power or the burden of PV curtailments can be coordinated in a centralized manner and shared across the three phases. An example of such voltage regulation scheme based on reactive power provision by single-phase PV inverters has been presented in an optimization framework utilizing a sensitivity analysis.

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