

Coordination of Single-Phase Rooftop PVs in Unbalanced Three-phase Residential Feeders for Voltage Profiles Improvement

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Abstract—Installation of single-phase rooftop photovoltaic (PV) systems in low voltage (LV) distribution networks is gaining increasing popularity in many countries including Australia. However, installation of rooftop PVs in residential feeders without controlling their ratings and locations may deteriorate the overall grid performance including power flows, losses and voltage profiles. Therefore, in recent years the utilities have adopted limitations on the maximum allowable number of PVs in LV networks. To overcome these issues, this paper proposes an intelligent and communication-based voltage profile regulating technique which is composed of three different steps. This technique relies on the availability of smart meters at the buses. The first objective of the method is to minimize voltage rise along the feeder by reducing the voltage at secondary side of distribution transformer. This is achieved by utilizing a distribution transformer with on load tap changing capability and a master controller located at the transformer. The algorithm also considers reactive power exchange and active power curtailment by the inverters of the single-phase rooftop PVs as the main steps for voltage profile regulation, as second objectives. The effectiveness and limitations of the proposed intelligent method are also investigated in this paper by the help of MATLAB-based simulation studies.

Keywords—Rooftop PV, on load tap changing transformer, active power curtailment, reactive power exchange, residential feeder.

I. INTRODUCTION

Most low voltage (LV) distribution networks were constructed a few decades ago and are reaching their capacity limits due to the natural load growth. On the other hand, customer load demand and power quality expectations have increased considerably in recent decades. When single-phase loads and rooftop photovoltaic (PV) systems are used, although voltages are usually well balanced at the supply side, they can become unbalanced at the customer level due to the unequal distribution of single-phase loads and PVs [1]. In addition, most of the residential rooftop PV systems are single-phase units and their integrations into the three-phase networks might also cause unbalance issues due to their random locations and ratings [2-3].

Reference [4] has investigated the voltage unbalance issue at different locations along the LV feeders populated with rooftop PVs using Monte Carlo analysis. This research indicates that rooftop PV installations will have minor effect on the voltage unbalance at the beginning of a LV feeder designed with engineering judgments; however, the voltage unbalance might increase at the end of the feeder to more than the standard limit. Reference [5] has analysed the voltage variation sensitivity due to PV power fluctuation in

unbalanced line configuration and phase loading levels in the network. This research considers several factors such as upstream sources, phase loads, PV power fluctuation, distribution line length and geometries, phase sequences and conductor types.

The high number of rooftop PVs can also change the direction of power flow and lead to voltage rise along the feeder. These are some of the main issues and challenges that most electrical utilities are currently encountering.

Many different techniques have been proposed in literature to overcome these problems. References [6-9] have proposed a new control algorithm for the inverters of the PVs to exchange reactive power with the grid in order to prevent voltage rise along the LV feeders. Reference [4] has concluded that a 16% increase in the capacity of the PV inverters is sufficient to accommodate the reactive power exchange that is required for voltage profile improvement in the LV feeders. References [10-12] have discussed the possibility of preventing voltage rise by curtailing the generated power by the PVs. References [13-14] have utilized droop-based and optimal control-based active power curtailment to prevent overvoltage conditions in LV feeders. Reference [15] introduces an active droop control-based method to achieve high efficiency transient responses during voltage profile regulation. Reference [16] has proposed to modify the control of the residential PV inverters to work at two different modes at day time and evening periods. It is suggested that at day time PVs generate active power and at evening/night periods the PV inverters operate as a reactive power source to improve the voltage profile at network peak periods. References [17-20] have discussed the possibility of utilizing distribution transformers with on load tap changing (OLTC) mechanism to step-up and step-down the transformer output voltage at network peak and off-peak periods to prevent non-acceptable voltage drop and voltage rise while maximizing the penetration level of PVs in the LV feeder. They have also presented some power-electronics-based OLTC techniques. References [21-25] have proposed to utilize batteries in addition to each PV system to prevent voltage fluctuations in the LV feeders and have carried out some analyses to determine the appropriate and optimal size and rating of the batteries for such applications. Reference [26] have proposed to utilize power-electronics-based devices such as distribution static compensators (DSTATCOMs) and dynamic voltage regulators (DVRs) to regulate the voltage profile at their point of common couplings (PCCs) and hence indirectly limit the voltage deviation from the nominal level and voltage unbalance along the LV feeder. It is demonstrated that a DVR

is better to be located at $1/3^{\text{rd}}$ of the feeder beginning and a DSTATCOM is better to be located at $2/3^{\text{rd}}$ of the feeder to provide effective voltage regulation all along the feeder. Reference [27] has proposed to use a power-electronics-based static transfer switch in the main supply for each house which can dynamically change the phase from which one house is supplied in 15-min time intervals so that the voltage profile along the feeder is improved in both network peak and off-peak periods in addition to voltage unbalance improvement. References [28-29] have proposed a method to circulate the excess power generated by the rooftop PVs of one phase to the other phase(s) using a DSTATCOM. In this method, the DSTATCOM can be connected in parallel to the LV feeders or among the phases to circulate the power among the phases without causing any short-circuit among them.

This paper presents an intelligent voltage regulation technique, which is based on the availability of smart meters at different buses in the network. The method is composed of three steps (sub-modules). First, the distribution transformer reduces the voltage at its secondary by the help of its OLTC capability such that the voltage along the feeder is within the allowable limits. This is verified by the voltage sensors installed at the beginning and end of the feeder to measure the voltage magnitude at these two ends. Following that, the inverters of the PVs are coordinated such that they exchange reactive power with the feeder to minimize the voltage unbalance at each bus. If reactive power exchange is not successful, the method applies active power curtailment as the last and final approach to minimize the voltage unbalance along the feeder. In this approach, it is assumed that smart meters, proper voltage monitoring and transmitting devices are available throughout the feeder to provide data transfer to the controllers of the rooftop PV inverters. The proposed approach is demonstrated and validated for a test network based on MATLAB simulations and its effectiveness and limitations are discussed.

The main contributions of this paper are:

- to develop the idea and the operation mechanism of a communication-based intelligent method for coordination of single-phase PVs in unbalance three-phase residential LV network,
- to increase the total power generated by rooftop PVs (i.e. allowing higher penetration levels of PVs as well as minimum active power curtailment) while minimizing the non-standard voltage deviation and voltage unbalance problems in the network,
- to validate the performance of the proposed method at difference penetration levels and ratings of PVs and their unequal distributions among the three phases of the LV feeder, and
- to investigate the limitations of the proposed method.

The rest of the paper is organized as follows: Section II introduces the network under consideration. The developed load flow approach is discussed in Section III. Section IV presents the proposed voltage regulation method. Several MATLAB-based simulation case studies are discussed in Section V to evaluate the performance of the proposed method. Section VI discusses the limitation of the proposed method. The main conclusions of the paper are highlighted in the last section.

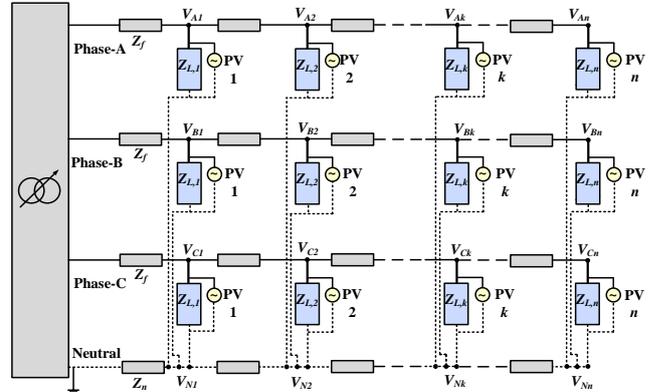


Fig. 1. The simulated three-phase unbalanced residential LV network with single-phase rooftop PVs.

II. NETWORK UNDER CONSIDERATION

The selected test network is a 415 V three-phase four-wire LV residential feeder that is supplied from an 11 kV three-phase medium voltage feeder through a three-phase distribution transformer. The distribution transformer is a three-phase 150 kVA Dyn type transformer with common multiple earth neutral (CMEN) system [30]. All residential loads are assumed as single-phase type which are distributed equally among the three phases of the network. The network conductors are assumed to be of bare All Aluminium Conductor (AAC) overhead type that are distributed over cross-arms with vertical configurations over the poles. Assuming the after diversity maximum demand (ADMD) of 4.7 kVA for each single house and length of 400 meters for the lines, the transformer ratings and conductor cross sections are selected based on Engineering judgments, using the Australian Standards [31].

The network is shown schematically in Fig. 1. It is to be noted that although this type of LV distribution networks is common in Australia and many parts of Asia, Europe and Africa, it is not the common practice in northern American countries.

All residential loads are assumed as constant power type for simplicity. It is to be noted that although the number of houses is same for all phases, their instantaneous power consumption is different which makes the system unbalanced. It is assumed that each house may have a rooftop PV system connection. However, the PVs may have different ratings which will further make the system unbalanced.

The network data is provided in details in Table A1 in the Appendix.

III. UNBALANCED LOAD FLOW ANALYSIS

An unbalanced sweep forward-backward load flow method [32] is developed in MATLAB and used for the analysis of the three-phase four-wire radial LV network under consideration. The load flow calculates the bus voltages along the feeder.

First, modified Carson's equations [33] are utilized for calculation of self and mutual impedance of the conductors in 50 Hz system as

$$Z_{ii} = r_i + 0.04934 + j0.062832[7.10988 - \text{Ln}(GMR_i)] \quad (1)$$

$$Z_{ij} = 0.04934 + j0.062832[7.10988 - \text{Ln}(D_{ij})] \quad (2)$$

where i and j are the phase conductor (i.e., A, B, C or Neutral), Z_{ii} is the self-impedance of conductor i (in Ω/km), Z_{ij} is the mutual impedance between two conductors i and j (in Ω/km), r_i is the ac resistance of conductor i (in Ω/km),

GMR_{*i*} is the geometric mean radius of conductor *i* (in cm) and D_{ij} is the distance between conductors *i* and *j* (in cm). Hence, the non-transposed characteristics of the conductors, image conductors below ground and network configuration are considered in the studies. Fig. 2(a) shows the considered line configuration in this study [33].

The three-phase four-wire line segment between two adjacent buses of $k - 1$ and k is also shown in Fig. 2(b). From (1) and (2), the equivalent impedance for the line section shown in Fig. 2(b) is expressed as:

$$[\mathbf{Z}_{abcn}] = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} & Z_{an} \\ Z_{ba} & Z_{bb} & Z_{bc} & Z_{bn} \\ Z_{ca} & Z_{cb} & Z_{cc} & Z_{cn} \\ Z_{na} & Z_{nb} & Z_{nc} & Z_{nn} \end{bmatrix} \quad (3)$$

Assuming the transformer has delta/wye-grounded configuration and using Kron reduction, (3) can be rewritten as

$$[\mathbf{Z}_{abc}] = \begin{bmatrix} Z_{aa-n} & Z_{ab-n} & Z_{ac-n} \\ Z_{ba-n} & Z_{bb-n} & Z_{bc-n} \\ Z_{ca-n} & Z_{cb-n} & Z_{cc-n} \end{bmatrix} \quad (4)$$

All calculations are carried out in per unit (pu). Starting with a set of initial values (e.g. a flat voltage set), the load currents are calculated as

$$[\mathbf{I}_{abc}^{Load,k}] = (\mathbf{P}_{abc}^{Load,k} - j[\mathbf{Q}_{abc}^{Load,k}]) / \text{conj}([\mathbf{V}_{abc}^k]) \quad (5)$$

where $[\mathbf{I}_{abc}^{Load,k}]$ is a vector of three-phase load currents connected to bus k , $[\mathbf{V}_{abc}^k]$ is a vector of three-phase voltages of bus k , $[\mathbf{P}_{abc}^{Load,k}]$ and $[\mathbf{Q}_{abc}^{Load,k}]$ are respectively the vectors of three-phase active and reactive power consumption of residential load connected to bus k and $\text{conj}()$ represents the conjugate operator.

The sum of the all load currents will flow from the first bus (i.e. transformer secondary side) to the second bus. Therefore, as shown in Fig. 2(c), the current between two adjacent buses is

$$[\mathbf{I}_{abc}^k] = [\mathbf{I}_{abc}^{k-1}] - [\mathbf{I}_{abc}^{Load,k}] \quad (6)$$

Hence, the voltage of bus k can be calculated based on the voltage of bus $k - 1$ in its upstream and the current passing between two buses as

$$[\mathbf{V}_{abc}^k] = [\mathbf{V}_{abc}^{k-1}] - [\mathbf{Z}_{abc}] [\mathbf{I}_{abc}^k] \quad (7)$$

Once the voltage at bus k is calculated, the load current in that bus will be updated from (5) and then using (6) the current flowing from bus k to $k + 1$ in its downstream are updated.

Similar to the line segment, the equivalent impedance of the delta/wye-grounded distribution transformer between its primary and secondary buses is expressed as

$$[\mathbf{Z}_{abc}^k] = z_t \times \mathbf{I}_3 \quad (8)$$

where z_t is the phase impedance of the transformer and \mathbf{I}_3 is the identity matrix of 3×3 . Now, the secondary-side voltage of the transformer are calculated from its primary-side voltage as [33]

$$[\mathbf{V}_{abc}^S] = [\mathbf{A}] [\mathbf{V}_{abc}^P] - [\mathbf{Z}_{abc}^k] [\mathbf{I}_{abc}^k] \quad (9)$$

where $[\mathbf{V}_{abc}^P]$ and $[\mathbf{V}_{abc}^S]$ are respectively the primary and secondary-side phase voltages of the transformer and $[\mathbf{I}_{abc}^k]$ is a vector of three-phase current passing through the transformer and

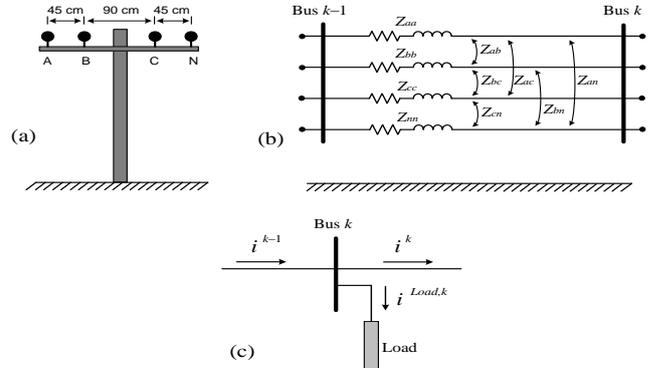


Fig. 2. (a) LV feeder configuration, (b) Impedance equivalent of a line segment between two buses, (c) PQ bus model.

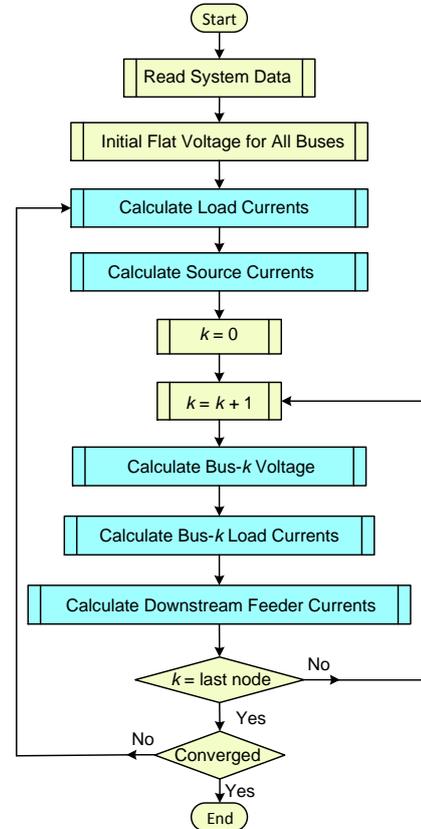


Fig. 3. Flowchart of developed unbalanced load flow analysis.

$$[\mathbf{A}] = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} \quad (10)$$

The flowchart of the load flow method is shown in Fig. 3.

IV. VOLTAGE REGULATION METHOD

Rooftop PVs inject active power during the day while most household loads are at their minimal levels. Around noon period, the output power of the PVs reaches to their maximum level. This can result in active power flow in the opposite direction towards the grid and hence causing voltage rise beyond the acceptable levels at some buses. On the other hand, unequal distribution of rooftop PVs will result in different voltage rises in the three phases of the feeder.

Utilizing OLTC transformers, injecting reactive power by the PV inverters to the grid, and curtailing the active power output of the PV inverters can be effective approaches for voltage amplitude control within the network. Recent studies have only considered three-phase PV systems; how-

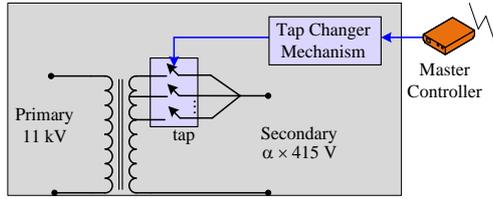


Fig. 4. OLTC LV distribution transformer.

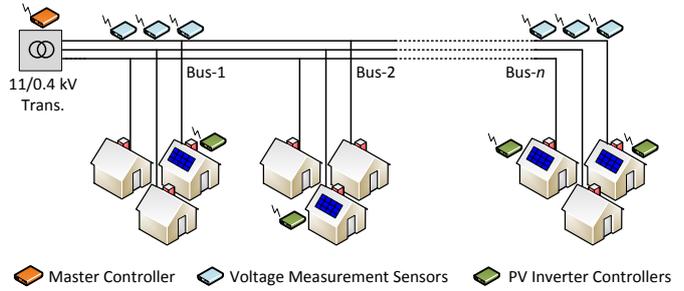


Fig. 5. Schematic representation of the controllers in the network.

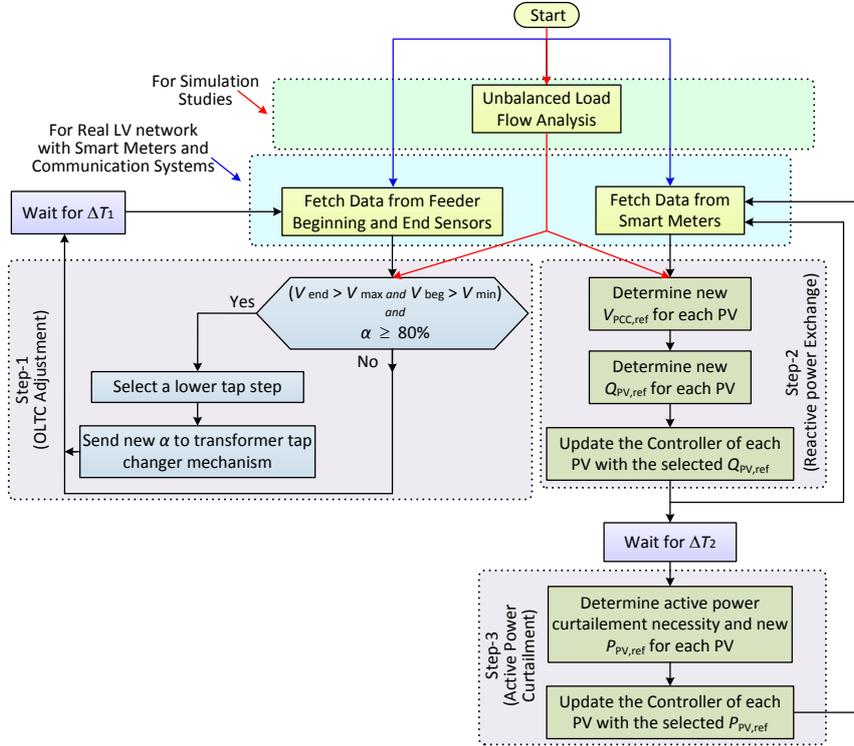


Fig. 6. Flow chart of the proposed intelligent and communication-based voltage regulating technique composed of 3 steps of OLTC adjustment, distributed reactive power exchange and active power curtailment.

ever, the situation is very different when single-phase PVs are installed unequally at different phases and buses throughout the network and have different ratings [5, 32]. In this paper, an intelligent communication-based voltage regulating technique is considered which is the combination of distributed reactive power support and active power curtailment by the inverters of the rooftop PVs as well as the OLTC control of the LV transformer.

A. Step 1: Voltage Adjustment using OLTC Transformer

Voltage profile along the LV feeder should be kept within the recommended limits of 95% and 110% of the nominal voltage [34]. By utilizing a transformer with OLTC, the turns ratio of the transformer is adjustable. Fig. 4 shows the schematic diagram of a transformer with OLTC. Assuming a constant primary voltage, the transformer secondary voltage can be increased or decreased such that the voltage all along the feeder is kept within the acceptable limits.

This method is based on the assumption that two three-phase voltage sensors are installed in the network –one set at the beginning of the feeder and another set at the end of the feeder. Both of these voltage sensors are assumed to have data communication capability such as WiFi or ZigBee to transfer the measured voltage to the master controller that is installed at the distribution transformer.

These voltage sensors are shown in Fig. 5.

First, the feeder end voltage is monitored by the help of the installed voltage sensors and this data is transferred to the master controller. Once the voltage at feeder end reaches above the allowable limit, the master controller sends a proper command to the transformer tap changing system to select and activate a lower tap. Hence, the voltage all along the feeder reduces.

After this process, the feeder beginning voltage is monitored by the help of the installed voltage sensor and its data is transferred to the master controller. This voltage should be kept above the minimum allowable limit. Then, if the voltage at the end of the feeder is still above the maximum allowable limit, the process will be repeated to ensure the voltage all along the feeder is within the acceptable limit. Hence, by the help of a transformer with OLTC, the secondary voltage can be reduced upto a minimum of 80%.

Due to the unbalance in the system, the three voltages may be different at the end of the feeder. Under such cases, the master controller reduces the tap such that all three-phase voltages at feeder end is limited below the maximum allowable limit.

It is to be noted that the OLTC does not operate instantaneously. The system allows a time delay of ΔT_1 (in few minutes range) between two consequent operations.

The flowchart of the proposed intelligent method and its submodules are shown in Fig. 6. In this figure, Step-1 illustrates the transformer tap adjustment function.

B. Step 2: Voltage Regulation by Reactive Power Support

Consider the LV feeder of Fig. 1 with 10 buses where each bus may have single-phase PVs. Currently, based on IEEE recommended practice for utility interface of PV systems [35], the PV inverters operate in constant output power mode. Under such conditions, they only inject current with unity power factor and do not affect the voltage at their PCCs. If the inverters are operated in voltage control mode, each PV inverter can correct its own PCC voltage to a desired value ($V_{PCC,ref}$) by injecting or absorbing the required amount of reactive power ($Q_{PV,ref}$). To minimize PCC voltage error from its reference, each PV inverter needs to exchange reactive power with the feeder to keep the voltage of its output equal to the desired value. This can be achieved in a decentralized method using the droop control strategy as [32]

$$Q_{PV,ref} = m(V_{PCC,ref} - V_{PCC}) \quad (11)$$

where $m > 0$ is the droop coefficient and will be assigned by the reactive power-voltage (Q - V) droop controller. The Q - V droop controller improves the dynamic oscillations between the reactive power and the voltage variation in the system. The droop control concept is demonstrated in Fig. 7. It is to be noted that for rooftop PV inverters, the active power-frequency (P - F) droop controller will not be used since frequency variation is very small in the stiff grid-connected distribution networks. The selected $Q_{PV,ref}$ in (11) must be within the inverter capacity as

$$-\sqrt{S_{PV,max}^2 - P_{PV}^2} \leq Q_{PV,ref} \leq \sqrt{S_{PV,max}^2 - P_{PV}^2} \quad (12)$$

where $S_{PV,max}$ is the maximum apparent power of the PV inverter and P_{PV} is the active power supplied by the PV at that time. If the selected (required) $Q_{PV,ref}$ is beyond the inverter maximum injection or absorption capability, it will be limited to the maximum limits. In Fig. 6, Step-2 illustrates the reactive power exchange function.

Determination of PCC Voltage Reference

An important issue in developing reactive power exchange algorithms is defining the appropriate $V_{PCC,ref}$ parameter which is later utilized in (11). In this paper, it is proposed that $V_{PCC,ref}$ to be dynamically calculated and updated to minimize the voltage unbalance among the three phases at every bus along the LV feeder. This can be achieved considering the presence of single-phase PVs on the other phases of the same bus and the voltage RMS of all phases of that bus. For this, 4 scenarios are possible, which are discussed below:

- 1- If a PV is available on all three phases of bus i , $V_{PCC,ref}$ at this bus is chosen equal to the average of the voltage magnitudes of the three phases, as

$$V_{PCC,ref,i} = \frac{1}{3}(V_{A,i} + V_{B,i} + V_{C,i}) \quad (13)$$

- For this, the PV(s) connected at bus i to the phase with higher voltages than $V_{PCC,ref}$ need to absorb reactive power while the PV(s) connected to the phase with lower voltages than $V_{PCC,ref}$ need to inject reactive power. This forces all three voltages in bus i to be equal.
- 2- If PVs are available only on two phases of bus i (e.g. on

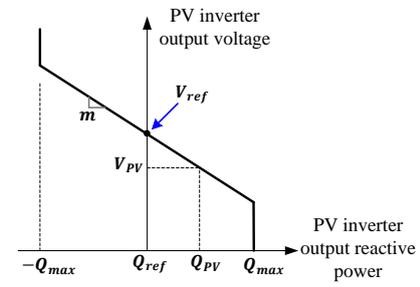


Fig. 7. The proposed Q - V droop characteristic for rooftop PV inverters.

phases “B” and “C”), $V_{PCC,ref}$ at this bus is chosen equal to the voltage magnitude of the third phase (e.g. phase “A”). This forces the two PVs to absorb/inject a proper amount of reactive power such that their PCC voltage gets equal to the voltage of the third phase (i.e. phase “A” in this case).

- 3- If a PV is available only on one phase of bus i (e.g. on phase “A”), $V_{PCC,ref}$ at bus i is chosen equal to the average of the voltage magnitudes of the other two phases, i.e.

$$V_{PCC,ref,i} = \frac{1}{2}(V_{B,i} + V_{C,i}) \quad (14)$$

In this scenario, the PV is forced to generate a voltage such that its RMS phase voltage becomes equal to the average of the other two phase voltages, resulting in a reduced voltage unbalance at bus i .

- 4- If no PV is available on any of the phases of bus i , then $V_{PCC,ref}$ will not be defined for this bus since no PV is available to directly control the voltage at this bus. However, the voltage of this bus will be affected by the change of the voltages at the other buses of the feeder.

Note that for each bus with rooftop PV, $V_{PCC,ref}$ will be determined based on the data transmitted from the installed voltmeters at each phase to the rooftop PV controller through the smart meters.

C. Step 3: Voltage Unbalance Reduction by Active Power Curtailment

The third step of the proposed control method is curtailing the output active power of the rooftop PVs, if the previous two steps were not successful in minimizing non-steady-state voltage rise and voltage unbalance along the feeder. For this, the output active power of the PVs, dictated by the maximum power point tracking (MPPT) algorithm (P_{MPPT}) will be deliberately reduced based on the error of the feeder voltage at a specific bus to minimize voltage unbalance in the feeder. To do this, the PV inverter active power output is forced to be equal to the desired value of $P_{PV,ref}$ as [32]

$$P_{PV,ref} = P_{MPPT} - n(V_{PCC,ref} - V_{PCC}) \quad (15)$$

where n is the curtailment coefficient that needs to be defined to minimize the difference between the magnitudes of all three phase voltages. Note that this step runs with a time delay of ΔT_2 (in few minutes range) where $\Delta T_2 < \Delta T_1$. In Fig. 6, Step-3 illustrates the active power curtailment function.

The above-mentioned voltage regulation methods using OLTC voltage reduction, reactive power support and active power curtailment are combined together in the proposed intelligent technique to achieve better voltage regulation results by utilizing the flexibilities that the existing smart meters provide for the system.

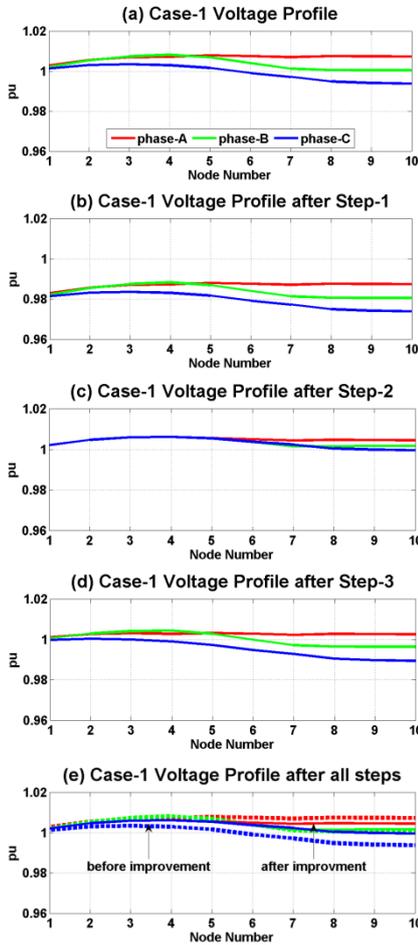


Fig. 8. Three-phase voltage profile along the feeder for Case-1.

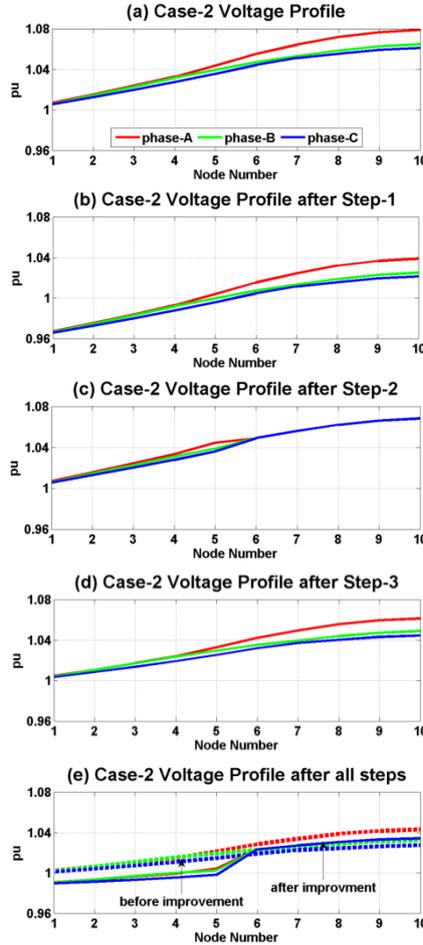


Fig. 9. Three-phase voltage profile along the feeder for Case-2.

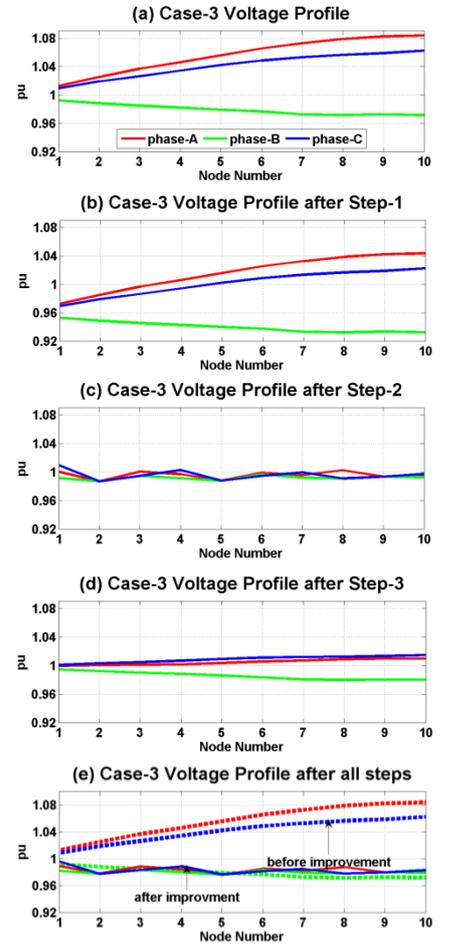


Fig. 10. Three-phase voltage profile along the feeder for Case-3.

V. PERFORMANCE EVALUATION

To evaluate the performance of the proposed method for voltage regulation, the unbalanced three-phase LV network of Fig. 1 is modelled in MATLAB. The network and load parameters are provided in Table A1. To perform the simulation studies, instead of the actual data measured from the smart meters, an unbalanced load flow analysis is carried out to define the voltages throughout the LV feeder; however, in a real system with smart meters and communication infrastructure, there is no need for the load flow analysis. Several case studies are considered, three of which discussed below:

- Case-1: Majority of the PVs are installed at the beginning buses of the feeder;
- Case-2: Majority of the PVs are installed at the middle and end buses of the feeder;
- Case-3: All houses connected to phase-A have rooftop single-phase rooftop PVs while only a small portion of the houses connected to phase-B and C have PVs.

Table A2 in the Appendix presents in details the location and rating of the PVs in each of the above cases. These three networks are used as the base cases to illustrate the effectiveness of the proposed voltage regulation method. First, the effectiveness of each of the described three steps of the proposed method (i.e. step 1: voltage adjustment using OLTC transformer, step 2: voltage regulation by reactive power support and step 3: voltage unbalance reduction by active power curtailment) are investigated individually on each case. Then, the effectiveness of the method with all three steps combined is evaluated.

Table 1. Summary of the effectiveness of each step in voltage rise and voltage unbalance control for the simulation study cases 1, 2 and 3.

	Voltage Rise Control			Voltage Unbalance Control		
	Case-1	Case-2	Case-3	Case-1	Case-2	Case-3
Step-1	✓	✓	✓	✗	✗	✗
Step-2	✓	✗	✓	✓	✓	✓
Step-3	✓	✓	✓	✗	✗	✗
Proposed Technique (Consisting of All Three Steps)	✓	✓	✓	✓	✓	✓

The unbalanced three-phase voltage profile for cases 1, 2 and 3 are shown respectively in Figs. 8, 9 and 10. In each of these figures, the voltage profile before any improvements, after each improvement step and after applying the proposed method consisting of all three steps are illustrated. Through these figures, it can be seen that:

- 1- OLTC transformer is successful in adjusting (lowering) the voltage profile along the feeder to acceptable limits of below 1.05 pu (Fig. 10b) but it cannot lead to voltage unbalance minimization (Figs. 8b, 9b and 10b).
- 2- Reactive power support of PV inverters is successful in minimizing the voltage unbalance among the three-phases (Figs. 8c, 9c and 10c) at the buses that the PVs are installed and have enough capacity to exchange reactive power with the feeder.
- 3- Active power curtailment is not effective for voltage unbalance reduction when majority of the PVs are installed at the beginning buses of the feeder (Fig. 8d).

The summary of the simulation results analysis is provided in Table 1.

To evaluate the performance of the proposed method for a network under different load and PV profiles, another

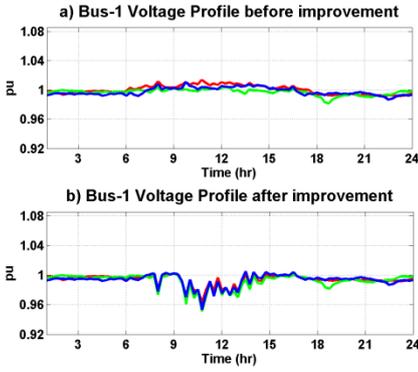


Fig. 13. Voltage profile at Bus-1 (beginning of feeder) before and after improvement.

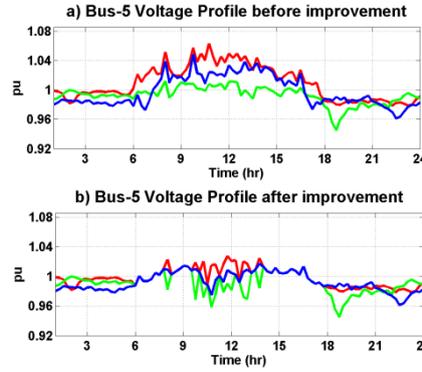


Fig. 14. Voltage profile at Bus-5 (middle of feeder) before and after improvement.

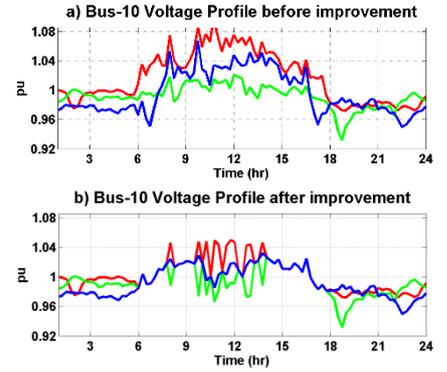


Fig. 15. Voltage profile at Bus-10 (end of feeder) before and after improvement.

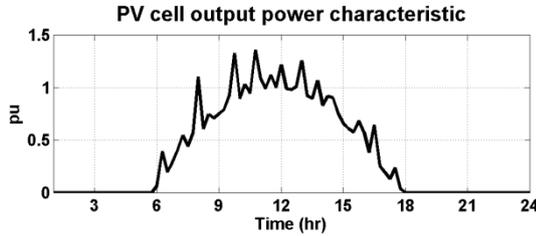


Fig. 11. The considered PV output power for the duration of study.

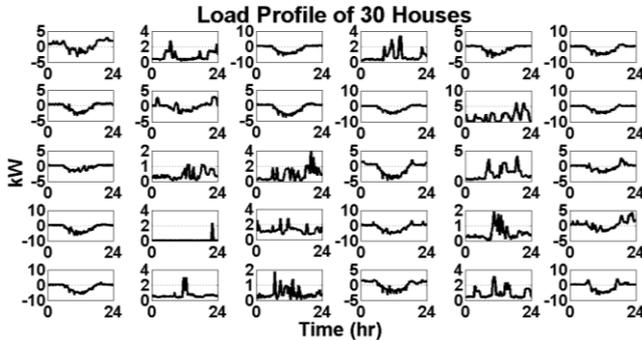


Fig. 12. Load profile of 30 houses considered in the case study.

case study is considered. In this study, the network voltage profile are evaluated over a 24-hr period. The data of an urban residential LV network in Perth, Australia is utilized for this study. The residential load profiles used in this analysis are based on the real data captured from smart meters installed in the network in 15-min intervals [27, 36]. In this study, a PV penetration level of 60% is considered which is twice of the accepted PV penetration level by Australian utilities [37] to evaluate the effectiveness of the proposed method. In addition, the considered PVs have a normal distribution with an average of 3.5 kW and a standard deviation of 1.1 kW. The number of PVs installed in each phase is also selected based on a normal distribution with an average of 33% per phase and a standard deviation of 30%.

In this study, the sunlight availability is assumed between 6 am and 6 pm while the PVs generate their maximum output at 12 pm, considering the sun radiation in Perth, Australia [38]. To consider the clouds effect on the PV output power generation, a white noise signal is added to the output power of the PVs. Fig. 11 illustrates the considered PV output power for the duration of this study. Since the PVs are located in a close geographic area (400m) the same PV output power characteristic is used for all considered PVs in the network.

Fig. 12 illustrates the load profiles of the considered 30 houses for this case study including the PVs. It can be seen that some of the houses experience a negative load profile

Table 2. Summary of the effectiveness of the proposed voltage regulating technique on voltage rise and unbalance control over 24-hr period.

	Beginning nodes	Middle nodes	End nodes
Within PV generation Period	✓	✓	✓
Outside PV generation Period	No difference	No difference	No difference

during 6am-6pm due to the PV power generation.

The 24-hr load profile of the network are illustrated for three sample buses of the network (i.e. bus-1: beginning of feeder, bus-5: middle of feeder and bus-10: end of feeder) in Figs. 13, 14 and 15. The voltage profiles are shown before and after applying the proposed voltage regulation method. Through these results, it can be seen that even for a 60% penetration level of PVs (i.e. twice of the current allowable limit for PV installation in the network by Australian utilities), the proposed method prevents high voltage rise at feeder end nodes (Fig. 15) and effectively reduces the voltage unbalance. It is to be noted that, there is no difference in the voltage profiles during 12am-6am and 6pm-12am since the PVs are not generating any power. The summary of the effectiveness of the proposed voltage regulating technique on voltage rise and unbalance control over 24-hr period is given in Table 2 for the considered system.

Fig. 16 illustrates the voltage profile before and after applying the proposed voltage regulation method for the network at 4 sample times throughout the 24-hr period (i.e. 9am, 11:15 am, 2pm and 4:30pm). All these results demonstrate the effectiveness of the proposed method in voltage profile regulation and unbalance reduction.

The tap position of the OLTC transformer is also shown in Fig. 17. From this figure, it can be seen that during 9am-3pm, the master controller has activated the OLTC mechanism to lower the tap of the transformer to prevent non-standard voltage rise throughout the feeder. A maximum of 5% tap reduction is observed in the considered case study at 10:45 am while in most cases the tap of the OLTC transformer has reduced only 1-3%.

VI. LIMITATIONS OF THE PROPOSED SOLUTION

Although the results in Section V show that the proposed voltage regulation method is successful in reducing the voltage rise and unbalance in the LV feeders, this method highly depends on the number of PVs in each phase and their ratings. The main limitation of the proposed method is when all or majority of the PVs are installed only at one phase. In addition, the second limitation of the method is when the PV inverters do not have a minimum of 10-20% higher rating compared to rated active power generated by the solar cells.

As an example, let us consider Case-4 with the network

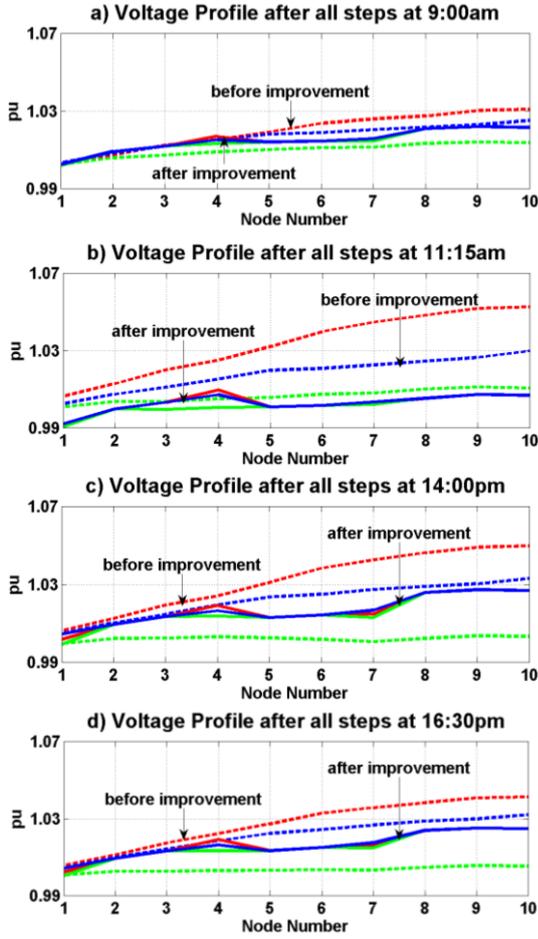


Fig. 16. Voltage profile of the considered case study before and after improvement at 4 sample times during the 24-hr period.

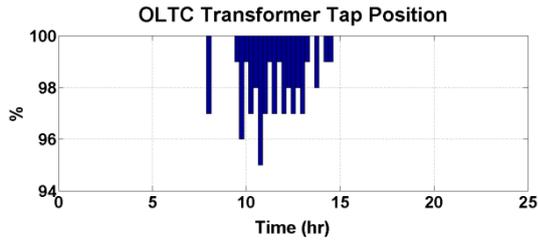


Fig. 17. Tap position of the OLTC transformer in the case study.

of Fig. 1 in which ten single-phase PVs are installed at all buses of only one phase (in this case phase “b”). Fig. 18(a) shows the voltage profile before applying the proposed method while Figs. 18(b) and 18(c) show the voltage profile after applying respectively step-2 and step-3 of the proposed method. The results clearly indicate that due to the number and ratings of the PVs, neither of these two steps are effective in improving the voltage profile and reducing the voltage unbalance.

As a second example, let us consider the network studied under the 24-hr period in Section V. Throughout the 24-hr period, there might be situations in which the PV inverters output reactive power is limited by the maximum rating of the inverter. In such cases, the voltage profile cannot be improved as effectively as expected. As an example, for the same network and sun and load profile studied in Section V, three cases are observed in which the voltage regulation was limited by the available capacity of the PV inverters for reactive power support. The voltage profile before and after applying the proposed method in these three time periods are shown in Fig. 19.

In addition, the dependency of the proposed method on

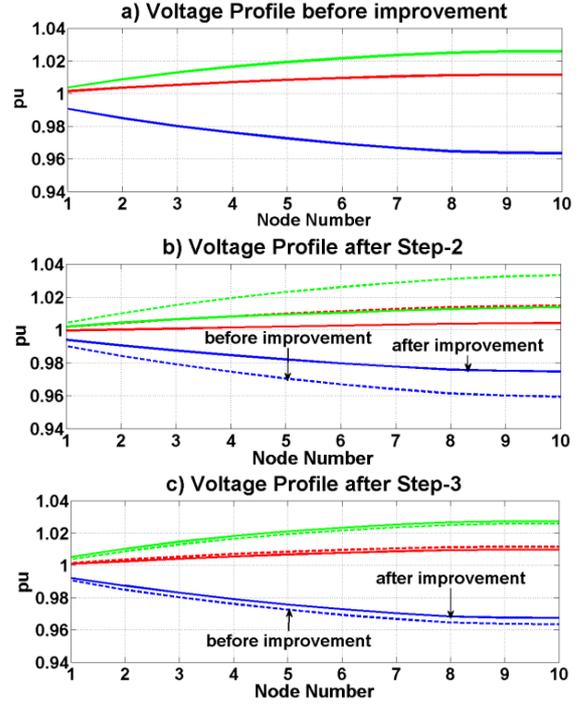


Fig. 18. Failure of proposed method in regulating voltage profile in all three phases due to unavailability of adequate number of PVs in all phases.

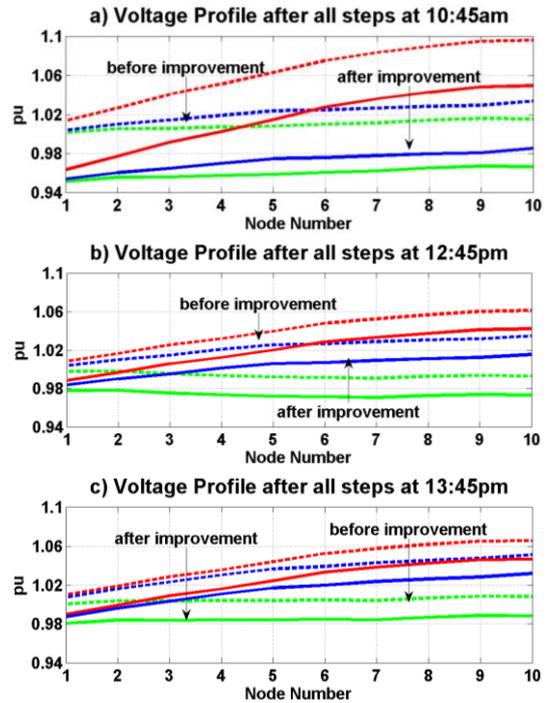


Fig. 19. Failure of the proposed voltage regulation method due to limited available reactive power capacity in PV inverters.

the communication technology can cause limitations for the proposed method if the data transfer is interrupted at any unseen situations.

It is to be noted that overcoming these limitations is beyond the scope of this paper; however, the proposed method will be successful and will not experience these limitations if the penetrations level of single-phase rooftop PVs is high in the network.

VII. CONCLUSION AND FUTURE WORKS

The number of single-phase rooftop PVs in low voltage distribution networks are increasing and the utilities have recently adopted limitations on the maximum number of rooftop PVs that can be installed by householders of a feed-

er to prevent probable voltage rise and unbalance problems.

An intelligent and communication-based voltage profile regulating technique is proposed in this paper which is capable of simultaneously performing three steps of 1) adjusting the voltage level by OLTC transformer, 2) reducing the voltage unbalance by facilitating reactive power exchange and 3) active power curtailment by the PV inverters. The proposed approach first tries to lower the tap position of the OLTC distribution transformer if non-standard voltage rise is detected at the end of the feeder. It also defines proper reference voltages for the three phases of the network at each bus which will be used by the PV inverters. The method relies on the availability of smart meters at the buses along the LV feeder to transmit phase voltage measurements to the controllers of the PV inverters.

MATLAB-based simulation results demonstrate effectiveness of the proposed method for the network with random load profiles, sun radiation and location/rating of the PVs over 24-hr periods. The proposed methods will be successful and recommended for LV networks with high penetrations of single-phase rooftop PVs.

To develop this method, a strong commitment is required by the supply authority to increase the level of technology in the distribution networks. The main limitation of the proposed method is its dependency on data communication system and also the number and ratings of PVs in each phase, particularly at low penetrations of rooftop PVs.

As a further step, the above discussed methods can be considered within an optimization problem to achieve better results in voltage regulation with minimum effort on OLTC operation and active power curtailment. Additionally, the effectiveness of the proposed method can be evaluated for different uncertain and random conditions of load profile and sun radiation with different ratings/locations of PVs using stochastic analyses.

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APPENDIX

The parameters of the simulated test network in Fig. 1 are provided in Table A1. The inverter ratings and bus numbers for the simulation cases 1, 2 and 3 are listed in Table A2.

Table A1. Technical parameters of the simulated test network of Fig. 1, considered in the simulation studies.

Transformer	11/0.415 kV, 50 Hz, 150 kVA, 50 Hz, Dyn, $z = 0.05$ pu
MV Feeder	11 kV, 3-phase 3-wire, 5 km, $z = 1.08 + j0.0302 \Omega/\text{km}$
LV Feeder	415 V, 3-phase 4-wire, 400 m, $z = 0.452 + j0.270 \Omega/\text{km}$

Table A2. PV inverter ratings (in kVA) for single-phase rooftop PVs, considered in the simulation case-1, 2, 3 and 4.

Bus No.	1	2	3	4	5	6	7	8	9	10
Phase	Case-1									
A	3	3	3	3	3					
B	3	3	3	3	3					
C	3	3	3	3	3					
	Case-2									
A						3	3	3	3	3
B						3	3	3	3	3
C						3	3	3	3	3
	Case-3									
A	3	4	5	2	3	5	4	5	3	5
B			2			4			4	
C		3			2	5		3		5
	Case-4									
A			2			2			2	2
B	2	2	2	2	2	2	2	2	2	2
C			2			2			2	2