Coordinated active and reactive power control for overvoltage mitigation in physical LV microgrids

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Abstract: The share of photovoltaic (PV) systems in the distribution networks is rapidly growing, leading to the common issue of overvoltage at the end of distribution feeders during the periods when peak generation is surplus to consumption. In this study, a hierarchical control is proposed to mitigate overvoltage at the point of connection of PV systems in physical low-voltage microgrids. The proposed mechanism is comprised of primary and secondary control layers to tackle the overvoltage problems given the communication capability is available. This mechanism employs a multi-objective optimisation approach to effectively curtail active power and absorbed reactive power of the PV inverters with the aim of minimising the active power curtailment. The feasibility of the proposed control approach is successfully verified through simulations on a simplified LV network.

1 Introduction

The low-voltage (LV) distribution network is hosting an increasing share of photovoltaic (PV) systems, mainly driven by environmental concerns, installation cost reduction, and new energy policies. Globally, the installed capacity of PV systems since 2010 is higher than in the same period in the previous four decades [1]. Despite supplying environment-friendly energy, the growing penetration of PV systems in the LV networks presents a series of operational and power quality challenges, e.g. congestions and voltage limit violations. Several distribution system operators (DSOs) have been experiencing overvoltage issues due to the high level of PV penetration, such as in Italy, Spain, Ireland, and Germany [2]. Once the peak generation of PV systems coincides with the low local loads, reverse power flow occurs and voltage gradually rises [3]. The European voltage-characteristics standard, EN 50160, stipulates that the 10-min RMS voltage values at the point of connection (POC) must stay between 0.9 and 1.1 p.u. of the nominal voltage for 95% of the time [4]. Voltage is varying from the nominal value to 1.1 p.u. is regarded as voltage rise, while voltage exceeding 1.1 p.u. is defined as overvoltage events. Lack of proper solutions to overvoltage mitigation results in the severe damages to electrical appliances in customers premises [3] and an increase in PV systems tripping [5]. Overvoltage becomes a bottleneck for the maximum power output of the inverters. Therefore, an effective control methodology is essential to mitigate overvoltage issues and maximise the power outputs. There are various solutions that can deal with overvoltage problems, such as cable reinforcement, transformer tap changer adjustment [6], active power curtailment (APC), and reactive power absorption (RPA) [7]. Cable reinforcement requires huge investment cost and takes a long time to implement, especially for countries like the Netherlands where underground cables constitute the majority of the LV distribution feeders [3]. MV/LV transformers are usually equipped with off-load tap changers [3]; accordingly, the tap changer adjustment cannot be implemented frequently. Because of the high ratio of R/X in LV networks, RPA is inefficient to alleviate the overvoltage issues. The less efficiency notwithstanding, proper control of RPA is still able to support the overvoltage alleviation [8]. $Q-V$ droop control and power factor (PF) control are examples of methods that are suggested to perform the RPA of PV inverters. APC emerges as an appropriate solution to overvoltage problems because the active power change has a strong impact on the voltage variations [9]. $P-V$ droop control is known as a commonly used among various methods for the APC [6]. Nevertheless, the curtailment is unprofitable for the PV owners, since it leads to the loss of revenue from selling their surplus power. The combination of APC and RPA of PV inverters becomes attractive solutions to overvoltage mitigation, especially as the share of PV systems in the power network is rapidly growing.

In this paper, the coordinated control of APC and RPA of PV inverters within a physical LV microgrid (MG) is investigated to solve the overvoltage problems. This paper introduces the combination of the sensitivity matrix-based solution and optimisation solution to realise the coordinated control of APC and RPA of the PV inverters. The coordinated control aims at mitigating the overvoltage problems while minimising the curtailed active power. The proposed mechanism is comprised of RPA using $Q-V$ droop control, and APC employing $P-V$ droop control. The rest of the paper is structured as follows. First, the background and the proposed control approach are presented in Section 2. Next, the problem and optimisation formulations are discussed in Section 3. Subsequently, the simulation results of the proposed control approach in comparison with various control methods are examined in Section 4. Finally, concluding remarks are drawn in Section 5.

2 Coordinated control approach

2.1 Background

Conventionally, when the overvoltage problem appears at the POC, i.e. the voltage magnitude surpass 1.1 p.u., the inverters are disconnected from the grid and are reconnected after some delay [3]. In the case the solar irradiance keeps constant or changes insignificantly after the disconnection and reconnection, the inverters remain switching ON and OFF with the power network. The droop-based APC is commonly used to avoid such repeated tripping of the inverters [3]. However, there is one major drawback of the droop-based APC. In a radial LV feeder, droop-based APC leads to unequal contributions of multiple inverters to overvoltage mitigation [3]. Since the voltage rises along the radial feeder, it is likely that the inverters connected towards the end of the feeder will bear a higher share of curtailment. Meanwhile, the inverters connected closer to the transformer may enjoy no power curtailment. As a result, the inverter owners located at the end of the feeder suffer the loss of revenue. This shortcoming warrants other control strategies to tackle overvoltage issues and minimise the loss of revenue.
On the other hand, as the share of PV systems used in the power generation mix has been quickly rising, it is becoming necessary for PV inverters to provide the support for voltage regulation in the network [10]. Recently, there are commercial PV inverters on the market that are capable of operating with setting the PF at ±0.9 [11], thus providing reactive power generation/absorption. Proper control of reactive power of PV inverters can be of benefit to the overvoltage mitigation [8]. Nevertheless, only controlling reactive power is not able to yield the best voltage regulation because the reactive power control does not have a significant effect on voltage regulation [1]. Therefore, a combination of APC and RPA of PV inverters can become a practical solution to overvoltage mitigation.

2.2 Droop-based APC

$P - V$ droop-based APC reduces the active power injection ($P_{\text{injected}}$) of the inverters to the grid in order to support the overvoltage mitigation, as expressed by [9]

$$P_{\text{injected}} = \begin{cases} P_{\text{MPP}} & \text{if } V_{\text{min}} < V_P \leq V_{\text{th}} \vphantom{\frac{1}{\text{th}}} \\ P_{\text{MPP}} - P_{\text{MPP}} \times \frac{V_P - V_{\text{th}}}{V_{\max} - V_{\text{th}}} & \text{if } V_{\text{th}} < V_P < V_{\max} \\ 0 & \text{if } V_P \geq V_{\max} \end{cases}$$

where $[V_{\text{min}}, V_{\max}] = [0.9, 1.1]$ to comply with the standard EN 50160. When the voltage at the POC ($V_P$) varies within the range from $V_{\text{min}}$ to the active curtailment threshold voltage ($V_{\text{th}}$), the inverters operate at the maximum power point ($P_{\text{MPP}}$). If $V_P$ crosses $V_{\text{th}}$, the APC is activated, thus regulating the amount of active power injection as a function of $V_P$.

2.3 Droop-based RPA

The absorbed reactive power ($Q_{\text{absorb}}$) is a function of $V_P$ as shown in the following formula:

$$Q_{\text{absorb}} = \begin{cases} \frac{Q_{\max} \times (V_P - V_{\text{th}})}{V_{\max} - V_{\text{th}}} & \text{if } V_{\text{th}} < V_P \leq V_{\max} \\ 0 & \text{if } V_{\text{th}} \leq V_P \leq V_{\text{th}} \vphantom{\frac{1}{\text{th}}} \end{cases}$$

When $V_P$ exceeds the reactive absorption threshold voltage ($V_{\text{th}}$), the RPA is accordingly triggered. The $Q - V$ droop control then regulates the amount of $Q_{\text{absorb}}$. $Q_{\max}$ represents the maximum RPA of the inverters and is restricted by the inverter's apparent power and active power generating at a given irradiance. Moreover, $Q_{\max}$ is limited due to the PF. The European Standard EN 50438 stipulates that distributed generation units connecting to the LV network are required to operate with PF ranging from 0.9 lagging to 0.9 leading [12]. This PF requirement is applied to the inverters in this work. Fig. 1 shows the operation mode of the PV inverters including the rated capacity and limits of active and reactive power specified by the PF requirement. The reactive power limits are within the dash-line region. The mathematical expression of $Q_{\max}$ is given as follows:

$$Q_{\max, 1} = \sqrt{S^2 - P^2}$$

$$Q_{\max, 2} = \tan(\arccos(PF)) \cdot P$$

$$Q_{\max} = \min(Q_{\max, 1}, Q_{\max, 2})$$

2.4 Proposed control approach

This study investigates the correlation and coordination of a pair of parameters, referred to as an absorption threshold ($V_{\text{th}}$) and curtailment threshold ($V_{\text{th}}$). A set of various $V_{\text{th}}$ and $V_{\text{th}}$ is defined for different PV inverters along the feeder in a coordinated and optimal manner using the hierarchical control. At each control time interval, the slope of each droop is then updated according to redefined $V_{\text{th}}$ and $V_{\text{th}}$.

Fig. 2 shows the proposed coordination of $Q - V$ and $P - V$ droop controls of the inverters to solve the overvoltage problems. Here $Q - V$ droop control is modified that has a higher slope to reach its maximum rate at the voltage value that triggers the APC. The hierarchical control framework is composed of primary control and secondary control that gave the communication capability is available. Employing droop control, the primary control is locally performed at each of the inverters [13], sending measured operational data to the secondary control. Using the data from primary control, the secondary control implemented at the central controller utilises the multiple optimisation methods to determine the new $V_{\text{th}}$ and $V_{\text{th}}$, and update the new droop control slope. These parameters are consequently sent back to primary control as reference values for active and reactive power control. One of the objective functions of the proposed optimisation is to minimise the APC of all inverters in the physical LV MGs.

From Fig. 2 at point (i), $V_P$ surpasses $V_{\text{th}}$ and the RPA is hence activated. The $Q - V$ droop control then regulates the amount of $Q_{\text{absorb}}$. At point (ii), once $V_P$ reaches $V_{\text{th}}$, the reactive power that an inverter can absorb is capped at $-Q_{\max}$. At the same time, the coordination scheme switches from RPA mode to APC mode with $P - V$ droop control after point (iii). It is noticed that RPA is activated before the APC (i.e. $V_{\text{th}} < V_{\text{th}}$).
3 Problem formulation

3.1 Optimisation variables

The optimisation variables consist of the state variables and the control variables. The state variables express the system operational conditions while the control variables are the required values to satisfy the predefined criteria of the problem. In this paper, the bus voltage magnitudes, \( |V_i| \), are used as the state variables; the output active power and reactive power of the PV inverters, \( P_{PV_i}, Q_{PV_i} \), are defined as the control variables, where \( i \in N \) illustrates the bus where the PV inverters are connected to.

In principle, the correlation between \( |V_i| \) and \( P_{PV_i}, Q_{PV_i} \) can be observed by applying the concept of sensitivity matrix. The sensitivity matrix reveals the sensitivity of the bus voltages \( i \) due to the changes in active and reactive power injected into the bus \( m \), where \( i, m \in N \). Starting with the Jacobian matrix, it represents the linearised relation between the changes in active and reactive power, \( \Delta P_i \) and \( \Delta Q_i \), respectively, with the change in the bus voltage magnitude and angle, \( \Delta |V_i| \) and \( \Delta \delta_i \), as expressed in (6) [14]

\[
\begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix} = \begin{bmatrix} J_{P\delta} & J_{PV} \\ J_{Q\delta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta \delta_i \\ \Delta |V_i| \end{bmatrix} \tag{6}
\]

Assuming \( \Delta Q_i = 0 \) and applying in (6), the separate influence of \( \Delta P_i \) on \( \Delta |V_i| \) can be demonstrated as follows:

\[
\frac{\Delta |V_i|}{|V_i|} = [A] \cdot \Delta P_i = \left[ [J_{PV} - J_{P\delta}] \cdot [J_{QV} - J_{Q\delta}] \right]^{-1} \cdot \Delta P_i \tag{7}
\]

From (7), a sensitivity coefficient \( a_i \) between active power and bus voltage is defined as

\[
a_i = A_{ij} \tag{8}
\]

Similarly, the impact of \( \Delta Q_i \) on \( \Delta |V_i| \) can be separately determined as follows:

\[
\frac{\Delta |V_i|}{|V_i|} = [B] \cdot \Delta Q_i = \left[ [J_{QV} - J_{Q\delta}] \cdot [J_{PV} - J_{P\delta}] \right]^{-1} \cdot \Delta Q_i \tag{9}
\]

From (9), a sensitivity coefficient \( \lambda_i \) between reactive power and bus voltage is defined as

\[
\lambda_i = B_{ij} \tag{10}
\]

From (8) and (10), the combined influence of \( \Delta |V_i| \) is defined as follows:

\[
\frac{\Delta |V_i|}{|V_i|} = \sum_{i=1}^{N} \left( a_i \Delta P_i + \lambda_i \Delta Q_i \right) \tag{11}
\]

3.2 Optimisation objectives

The first optimisation objective is the minimisation of voltage magnitude deviation over the network as given by

\[
\text{min} \ (F_1) = \min \ \sum_{i=1}^{N} \left( |V_i| - \frac{1}{N} \sum_{i=1}^{N} |V_i| \right)^2 \tag{12}
\]

Function (12) encourages the flat voltage profiles as it calculates the distance of the vector collecting the bus voltage magnitude \( \{ |V_i| \}_{i \in N} \) from the average value \( \left( 1/N \sum_{i=1}^{N} |V_i| \right) \). The second optimisation objective is the minimisation of the curtailed active power that uses the following expression:

\[
\text{min} \ (F_2) = \min \ \sum_{i=1}^{N} (P_{i, \text{MPP}} - P_{PV_i, \text{opt}}) \tag{13}
\]

where \( P_{i, \text{MPP}} \) is the maximum values according to the MPPT algorithm and \( P_{PV_i, \text{opt}} \) is the optimisation variable of the active power of PV inverter at bus \( i \). This optimisation objective can be described as the common goal for the PV owners.

The third optimisation objective is the maximisation of the absorbed reactive power of the inverters, as given as follows:

\[
\text{min} \ (F_3) = \min \ \sum_{i=1}^{N} (Q_{i, \text{max}} - Q_{PV_i, \text{opt}}) \tag{14}
\]

where \( Q_{i, \text{max}} \) is the maximum value and \( Q_{PV_i, \text{opt}} \) is the optimisation variables of active power absorption of PV inverter at bus \( i \).

3.3 Multi-objective optimisation solution

The objective functions \( F_1 \) and \( F_2 \) are conflicting with each other. Specifically, minimisation of voltage magnitude deviation may need more curtailed active power. The choice of objective functions is preferred by different individuals. For instance, power utilities may prefer the objective function \( F_1 \) and \( F_2 \) for a better voltage profile. While PV owners prefer the objective function \( F_2 \) for better revenue from selling the power produced from the PV systems. Therefore, the satisfaction of a single objective function may provoke the conflict of interest among the relevant parties. Harmonisation of various objectives should be achieved. The Pareto-based optimal approach is utilised to define the solutions for multiple optimisation problems [15]. The weighted sum method is used to combine these three objective functions into a single function [16]. This method involves multiplying each of the objective function with a predefined weighting factor \( \{ w_i \} \). The weighting factors reflect the user preferences for the objective functions regarding its significance. Subsequently, all objective functions are summed up to form the single-objective function, which is formulated by

\[
F = \sum_{i=1}^{3} w_i \cdot F_i(x) \tag{15}
\]

subject to:

\[
\sum_{i=1}^{3} w_i = w_1 + w_2 + w_3 = 1 \tag{16}
\]

\[
V_{\min} \leq |V_i| \leq V_{\max} \tag{17}
\]

\[
0 \leq P_{PV_i} \leq P_{i, \text{MPP}} \tag{18}
\]

\[
- Q_{i, \text{max}} \leq Q_{PV_i} \leq Q_{i, \text{max}} \tag{19}
\]

Fig. 3 shows a flowchart of the implementation of the multiple optimisation methods.

4 Simulation and results

4.1 Simulation setup

The test system for the proposed coordinated control strategy is a simplified radial LV feeder as shown in Fig. 4. The feeder accommodates three households as three-phase balanced variable PQ loads with identical load profile and three equal-sized PV systems with 28.5 kW peak generation. All the lines are the same underground cables A1 185 mm XLPE with parameters \( R(\Omega/km) \) and \( X(\Omega/km) \) of 0.182 and 0.0663, respectively. MATLAB is used to load all input data, such as household loads, irradiation and environment temperature for the PV inverters, and set the other parameters. Simulink is used to simulate the test system with defined parameters. The proposed optimisation problem is solved using the MATLAB optimisation toolbox.
Five cases of different control methods are involved in the simulation as follows: In case 1, no any control actions of active and reactive power are implemented. In case 2, only the APC approach is used to solve overvoltage with the fix $V_{\text{th}P}$ at 1.07 p.u. are equally set to all PV inverters. In case 3, in addition to the equally fixed $V_{\text{th}P}$ at 1.07 p.u., $V_{\text{th}Q}$ at 1.06 p.u. are equally configured to all PV inverters. Case 4 involves utilising the proposed coordinated control of active and reactive power where a set of $w_1$, $w_2$, $w_3$ equals 0.05, 0.475, and 0.475, respectively. Finally, case 5 also apply the proposed coordinated control but different a set of $w_1$, $w_2$, $w_3$ that equal to 0.9, 0.05, and 0.05, respectively. The simulation is running for 20 min.

4.2 Simulation results

The simulation results of voltage magnitude at bus 3 in all cases are illustrated in Fig. 5. It can be observed that in case 1 overvoltage appears at bus 3. In the remaining cases from case 2 to case 5, the overvoltage problem is solved. It is important to note that, for a fair comparison between control cases, the control actions are activated after the first 5 min.

More specifically, in case 2 with only APC ($V_{\text{th}P} = 1.07 \text{ p.u.}$), the voltage at bus 3 remains constant at $V_{\text{th}P}$ over the control time period which implies that APC keeps activated. In case 3 with both APC and RPA, the voltage at bus 3 is regulated at the lower value than $V_{\text{th}P}$ in several last minutes because of RPA control actions. In case 4, the coordinated control of APC and RPA with higher priority of minimising APC and lower priority of minimising voltage deviation introduces different setpoints of $V_{\text{th}P}$ and $V_{\text{th}Q}$ to the PV inverters, particularly $V_{\text{th}P,1} = 1.055$, $V_{\text{th}Q,1} = 1.045$, $V_{\text{th}P,2} = 1.067$, $V_{\text{th}Q,2} = 1.057$, $V_{\text{th}P,3} = 1.075$, and $V_{\text{th}Q,3} = 1.065$. We can see that voltage at bus 3 is properly regulated without any violation of threshold values. In case 5 with higher priority of minimising voltage deviation, lower setpoints of $V_{\text{th}P}$ and $V_{\text{th}Q}$ are provided to the PV inverters, particularly $V_{\text{th}P,1} = 1.052$, $V_{\text{th}Q,1} = 1.042$, $V_{\text{th}P,2} = 1.062$, $V_{\text{th}Q,2} = 1.055$, $V_{\text{th}P,3} = 1.069$, $V_{\text{th}Q,3} = 1.059$. The rippling part of voltage profile at bus 3 during 14:07–14:13 depicts that APC is performing to regulate the voltage at bus 3 at a lower value compared to case 4.

Figs. 6 and 7 show the active power injections and reactive power absorptions, respectively, of the PV inverter at bus 3 in all cases. It is evident that case 2 has the highest amount of curtailed active power and no absorbed reactive power. In case 3, the activation of RPA leads to smaller curtailed active power. In case 4 with high amount of absorbed reactive power, the inverter 3 does not curtail any power, resulting in injecting exact amount of active power compared to case 1. In comparison with case 4, case 5
results demonstrate a smaller amount of both injected active power and absorbed reactive power. It reveals that although APC and RPA controls are coordinated among the inverters to alleviate overvoltage, more preference of flat voltage requires more power curtailment.

Table 1 summarises the numerical results of the simulation. It demonstrates the ability of RPA to support overvoltage mitigation and reduce the curtailed active power. Furthermore, it can be seen from cases 2 and 3 that all amount of curtailed active power is from only PV inverter 3, while the inverters 1 and 2 have zero curtailed active power. This shows the unfairness when the inverter 3 suffers a loss in revenue. Comparing all cases can conclude that coordinated control of APC and RPA is a more effective control for overvoltage mitigation while minimising active power curtailment.

5 Conclusion

This paper investigates the droop-based APC and RPA controls for overvoltage mitigation in LV MGs. Droop-based APC is proven to solve the overvoltage problems but at the expense of active power generation, leading to a loss in revenue of the inverters located towards the end of the feeder. On the other hand, RPA has the capability of supporting overvoltage mitigation while decreasing the curtailed active power. Hence, this paper proposed a coordinated control of APC and RPA, which is capable of providing overvoltage mitigation with minimum curtailed active power by employing hierarchical control and multiple optimisation method. The simulation results of the proposed control strategy are analysed in comparison with different control methods, highlighting the effectiveness of coordinated control of APC and RPA among the PV inverters in LV MGs.

6 Acknowledgments

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7 References


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<th>Table 1</th>
<th>Results for different cases of control methods</th>
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<tr>
<td>$P_{PV2}$, kWh</td>
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<tr>
<td>$P_{PV3}$, kWh</td>
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