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Dynamic performance of Reactive Power Control for Voltage Support in Low-Voltage Distribution networks with Photovoltaic Systems

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Abstract. The coordinated reactive power control among photovoltaic (PV) systems, without communication requirement, is introduced to prevent the over-voltage problems in radial distribution networks. The voltage source inverter in PV system can provide the reactive power control to deal with the dynamic voltage variations. Two reactive power control methods, $Q(P)$ and $Q(V)$, can be employed into each PV system depending on its location. The dynamic voltage control performances are examined on simulation in DIgSILENT *PowerFactory* software. The results showed that the proposed control method can mitigate the rise of voltage level sufficiently.

Introduction

The increase of penetration level of photovoltaic (PV) power generations can cause the overvoltage problems for distribution networks; especially, along the low-voltage radial systems during the light load conditions, as demonstrated in [1]. Additionally, the critical voltage rise occurs at the end of feeder while at the sending end, which is close to the distribution transformer, has a small voltage change. This problem can restrict a number of PV connections.

To prevent the over-voltage from exceeding the statutory standards such as IEEE 1159-2009 and IEC 610000-6-1, the active power (P) curtailment and reactive power (Q) control are applied into PV system [2]. The P curtailment should be operated as a little due to the PV should produce power into the network as much as possible. Hence, the Q control is preference for voltage control. The modern PV's grid-tied inverter, based on the voltage source inverter (VSI), can provide the Q controllability with the fast response (i.e. 1-2 seconds) to deal with the dynamic voltage variations, as can be seen in [3].

This work aims to enhance the use of Q control among the PV systems in the network, by increasing the Q support from the PV systems located near the sending end of the feeder while maintaining the power factor of the network within the statutory limit. The coordinated Q control manner among PV systems is applied by setting the different Q control method and control set-points into the individual PV system. This gives each PV system supporting Q to deal with the local voltage change, at its connected bus, efficiently without requiring the communication infrastructures.

Reactive power control

There are 2 recommended local Q control strategies for implementation in the VSI controller in PV system, which are $Q(P)$ and $Q(V)$ methods [1].

$Q(P)$ method. This Q control method is suitable for the PV system located close to the distribution transformer, which receive the little impact in voltage changes during high PV generation condition. Assuming the potential risk of the overvoltage become higher when the power production from PV is high. Therefore, the Q from VSI is generated proportional to the produced active power, P, from the PV system. Moreover, the threshold values of active power and voltage (P_{th} and V_{th}) are set to ensure that the Q control will operate only when the local voltage change trends to over the limit. The Q control function of this method can be written as;

$$Q=\begin{cases} m\left(P-P_{th}\right) & \text{when} \quad V>V_{th} \text{ and } P>P_{th} \\ 0 & \text{when} \quad else \end{cases} \tag{1}$$

where m is a slope factor which can be determined by using the voltage sensitivity matrix.

$Q(V)$ method. This $Q(V)$ method will adjust the Q support following to the change of local bus voltage, which is a consequence of the PV production and load consumption. This method is suitable for the PV site that can face the critical voltage change during high PV generation, such as at the end of feeder. The $Q(V)$ method will generate Q when PV production and local bus voltage is higher than the threshold values. The PI controller is employed to command the Q output corresponding to the dynamic voltage variations, see (2). In consequent, the VSI controller still supply Q at the minimum power factor value, in case that $V < V_{th}$ but $P > P_{th}$, to avoid the hunting between controllers that use this method. Then, the Q control will be stopped completely when $P < P_{th}$ and $V < V_{th}$.

$$Q=K\left(1+\frac{1}{sT}\right)\left(V-V_{th}\right) \qquad \text{when} \quad P>P_{th} \text{ and } V>V_{th}. \tag{2}$$

where K and T are PI controller's gains

VSI controller with the Q control

The VSI controller of the PV system is based on the dq-synchronous reference frame (adopt from [4]). The Q is controlled on the q-axis and P is controlled on the d-axis. The Q controller, used $Q(P)$ or $Q(V)$ method, is connected to the q – axis to control Q output of VSI with respect to the change of PV generation and the bus voltage, as illustrated in Fig. 1. Additionally, the Q output is limited by the minimum value of power factor ($\mathrm{PF_{min}}$). If the $\mathrm{PF_{min}}$ is constant, the Q limit will be changed proportional to the PV power production. The maximum Q value, Q_{max}, which the VSI can generate calculated from;

$$\pm Q_{max} = \pm P\tan\left(\cos^{-1}\left(\mathrm{PF_{min}}\right)\right) \tag{3}$$

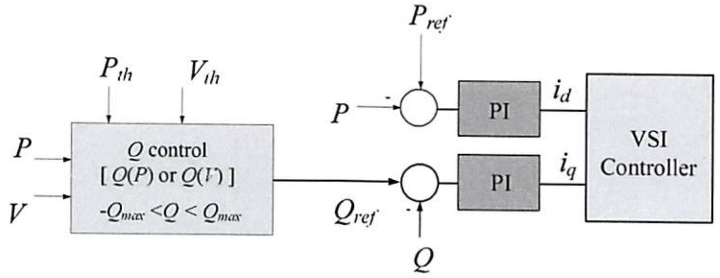


Fig. 1. VSI controller with the Q control.

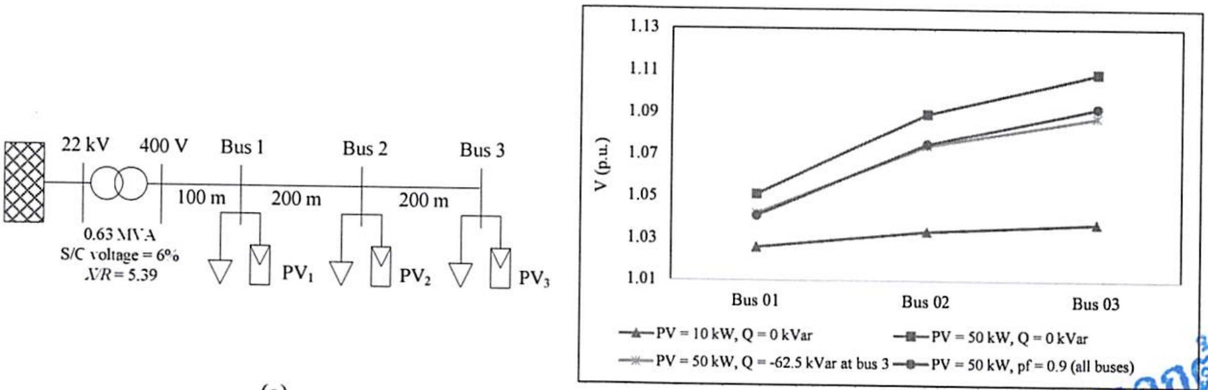
Test system

The test system is a 400 V balanced, three-phase distribution network which has PV systems connect in 3 locations along the feeder, as illustrated in Fig. 2 (a). The line parameter is 0.346+j0.0754 Ω/km. The upstream grid is set as a slack bus with the voltage set-point = 1.02 p.u. During the light load condition, each connected load is 1 kW and power factor (p.f.) = 0.9 lagging. The PV system is based on VSI which has the capacity of 50 kW and can support Q compensation in the range of ±24.22 kVar (p.f. = 0.9 at rated power). Furthermore, the statutory limits in this test are defined as the over-voltage is not over 1.09 p.u. and p.f. > 0.9, both leading and lagging.

The initial condition is assumed as each PV system injects 10 kW into the network. The comparison results from the load flow simulation between PV systems supply 10 kW and 50 kW are shown in Fig. 2 (b). It is found that critical voltage change is at the end of feeder, while the bus that close to the transformer has a small voltage change. Moreover, only voltage level at bus 3 ($V \approx$ 1.11 p.u.) is above the statutory limit when all PV systems supply at rated power. To reduce the voltage level within the limit, the PV_3 is required to absorb the $Q \approx -62.5$ kVar. However, this value of Q absorption causes the p.f. at bus 3 is 0.63, which is below the statutory limit.

To avoid the heavy Q support from only one PV system at bus 3, the associated Q control from another PV systems, along the same feeder, is necessary. Assuming all three PV sites can absorb Q to reach -24.22 kVar, to maintain the p.f. > 0.9 lagging, during at rated PV generation. The result in Fig. 2 (b), shows that the voltage level at all buses can stay within the statutory limit while the power factor at each PV system is still satisfy.

The different Q control methods are applied into individual PV system. At bus 1, the PV_1 using $Q(P)$ control method which has $P_{th,1} = 33.3$ MW, $V_{th,1} = 1.035$ p.u. and $m = 1.65$. On the other hand, the $Q(V)$ control method is assigned to PV systems at bus 2 and 3. The PV_2 has $P_{th,2} = 27.8$ MW , $V_{th,2} = 1.07$ p.u., while the PV_3 bus 3 has $P_{th,3} = 10$ MW , $V_{th,3} = 1.09$ p.u.. The gains of PI controller of PV_2 is $K_2 = 1$ and $T_2 = 0.5$ and PV_3 is $K_3 = 2$ and $T_3 = 0.1$. Moreover, All VSI controller will update the measured data (e.g. P and V) in every 1 second.



(a) (b)

Fig. 2. Test system and results from load flow simulations

Simulation and results

The dynamic performance of the coordinated Q control among PV systems is investigated on DIgSILENT *PowerFactory* software. The voltage variations in the network are implemented by applying a gradual increasing and decreasing of PV generation, as shown in Fig. 3 (a), while the connected loads remain constant. The simulation results show the comparison between PV systems with and without Q control. The changes of Q and power factor of each PV system and bus voltages are demonstrated in Fig. 3 (b) to (f), respectively.

The results show that, without Q control from PV systems, the network starts to meet the over - voltage problem at bus 3 since each PV system supplies more than 39 kW (start at $t \approx 72$ s). On the other hand, it can be seen that the Q control from all PV systems with coordinated controller manner can maintain the voltage level, especially at bus 3, while the power factor within the statutory limits.

It can be seen that PV_1 will start to support the Q compensation before the others, at $t \approx 60$ s, when the production from PV_1 is relatively high (>50% of rated power). The PV_1 will continue absorbing Q, if the PV generation is still over the $P_{th,1}$ and voltage level at bus 1 is higher than $V_{th,1}$, until power factor is 0.9 lagging (Q is -24.22 kVar at rated power).

The Q absorption at PV_2 and PV_3 will start at $t \approx 65$ s and $t \approx 75$ s, respectively. Although PV_2 operate the Q control before PV_3, the control response of PV_3 is faster for dealing with the critical over-voltage at the end of feeder. PV_2 and PV_3 will support Q until reaching the capacity limit to keep control the voltage level at bus 2 and 3 at the values of $V_{th,2}$ and $V_{th,3}$, respectively.

After $t = 223$ s, the active power from PV starts to decrease. PV_1 will reduce the Q absorption rapidly, to follow the change of PV generation. The PV_1 stops the Q control at $t \approx 280$ s, where the power from PV_1 and voltage level at bus 1 are lower than $P_{th,1}$ and $V_{th,1}$, respectively. On the other hand, PV_2 and PV_3 start to decrease the Q support when voltage level at their buses are below the threshold values. Additionally, those PV systems maintain absorbing Q at power factor = 0.9 while the PV generation is decreasing. Then, they stop to operate Q control when the PV generation is less than $P_{th,2}$ and $P_{th,3}$, which are at $t \approx 291$ s and $t \approx 320$ s, respectively.

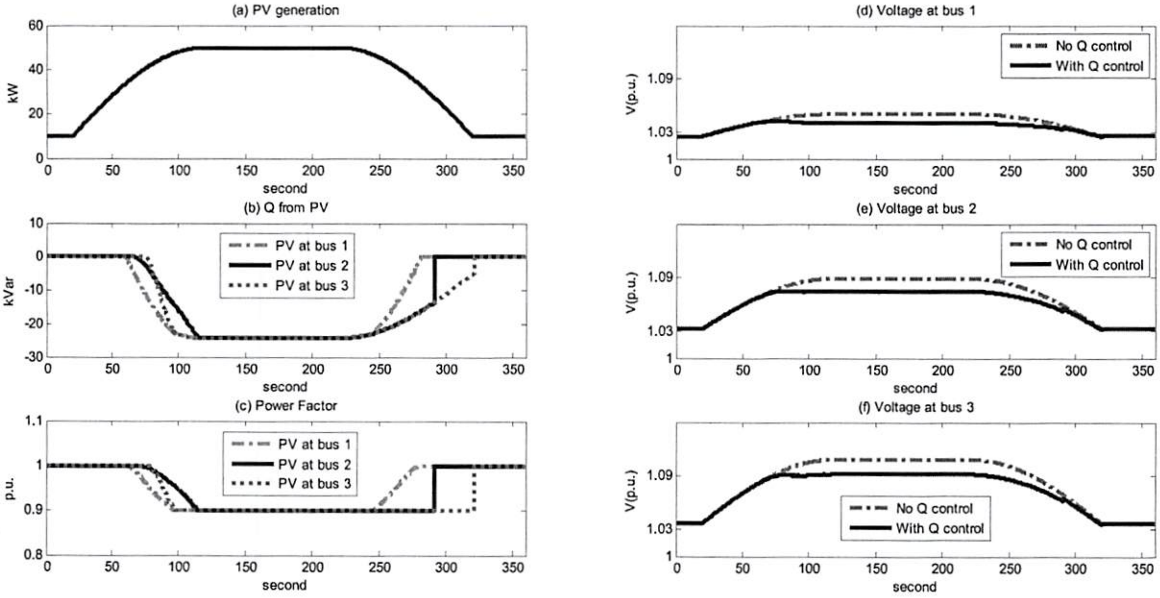


Fig. 3. Simulation results of the proposed test systems

Summary

The over-voltage in distribution networks can be prevented by supporting Q from the VSI in PV systems. The $Q(P)$ method is implemented to encourage the Q supported from the PV system located near the sending end. The $Q(V)$ method is applied to the PV systems at the middle and the end of feeder, to track the change of the voltage level. Using different controller set-points are necessary, to operate Q control among PV systems in the coordinated manner without communication technology. The simulation results showed that the coordinated Q control among VSI controllers in the PV systems can reduce the over-voltage problem in the low-voltage radial feeder, efficiently.

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