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Micro Static Var Compensator for Over-voltage Control in Distribution Networks with High Penetration of Rooftop Photovoltaic Systems

Piyadanai Pachanapan* and Phudit Inthai
Department of Electrical and Computer Engineering
Faculty of Engineering, Naresuan University, Thailand
piyadanip@nu.ac.th* and phuditi56@email.nu.ac.th

สำเนาถูกต้อง

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Abstract. A micro static var compensator (μSVC) is introduced in this work to prevent the over-voltage problems in radial distribution networks with high number of rooftop photovoltaic (PV) connections. The μSVC is aimed to use in the PV system that has the fixed-power factor inverter, which cannot provide the active voltage controllability. The μSVC is a small shunt compensator installed parallel with the PV system and providing the automatic reactive power support to deal with the dynamic voltage variations at the point of common coupling. Two reactive power control methods, $Q(P)$ and $Q(V)$, can be employed into each μSVC depending on the location of PV systems. Moreover, the coordinated reactive power control among μSVCs, without communication system requirement, is presented for enhancing the Volt-Var controllability to the group of PV systems located in the same feeder. 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 number of rooftop photovoltaic (PV) systems connected to low voltage distribution networks has increased dramatically since the year 2000. Although the PV systems give the benefit of raising the power generation capacity, the high penetration of PV systems can cause the over-voltage problem into the networks especially during the light load condition and consequently restrict a number of PV connections, 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.

To prevent the over-voltage to exceed 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 the power into the network as much as possible. Then, the Q control is preference for the voltage control. The modern PV's grid-tied inverter, based on the voltage source inverter, can provide the Q controllability with the fast response to deal with the voltage variations, as shown in [3]. However, the majority of existing PV systems is still using the fixed - power factor inverter which is unable to give the active Q support.

This work aims to use the micro static var compensator (μSVC) to enhance the voltage controllability for the PV system with the fixed-power factor inverter. The μSVC is a shunt compensation device which can reduce the voltage level at the point common coupling (PCC) by absorbing Q from the network into its reactor. The study in [4] showed that the response of Q control using static var compensation in transmission systems is relatively fast. Furthermore, the coordinated Q control manner among PV systems is implemented to increase the Q support among the PV systems across the network, by encouraging 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. This coordinated Q control manner is applied by setting the different Q control method and controller set-points into the individual PV system. This gives each PV system supporting Q to deal with the local voltage change, at its PCC bus, efficiently without requiring the communication infrastructures.

Reactive power control

There are two recommended local Q control strategies for implementation in the 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. Assuming the potential risk of the overvoltage become higher when the power production from PV is high. Therefore, the Q from the PV system is generated proportional to the produced active power, P, from the PV system. Moreover, the threshold values of active power and bus voltage (P_{th} and V_{th}) are introduced to ensure that the Q control will operate only when the local voltage change trends to over the limit due to the increasing of PV generation.

$Q(V)$ method. The $Q(V)$ 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. To use the $Q(V)$ method for the over-voltage control, the PV system will support the Q control when PV production and local bus voltage is higher than the threshold values.

Reactive power control

The μSVC is a small shunt compensation device based on the thyristor controlled reactor (TCR). In addition, the basic TCR consists of two-anti parallel thyristors connected in series with the inductor. This μSVC will be installed parallel with the PV system and providing the over-voltage control at the PCC bus by absorbing the Q from the network, as shown in Fig. 1.

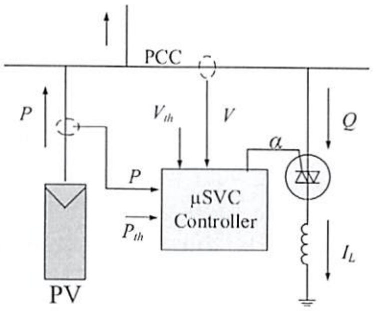


Fig. 1. Micro static var compensator

From Fig. 1, the mathematics related to the μSVC are given by the following [5];

$$v = V_m \sin(\omega t) = L\frac{di_L(t)}{dt} \tag{1}$$

where v is the voltage at the PCC, V_m is the amplitude of voltage at the PCC and ω is the angular velocity. Moreover, L is the inductor and i_L is the inductive current flowing through the μSVC.

Integrating (1), it is found that

$$i_L = -\frac{V_m}{\omega L}\cos(\omega t) + C \qquad \text{where } C \text{ is the constant} \tag{2}$$

Using the initial condition given in (3), the solution of (2) can be solved as in (4)

$$i_L(\alpha) = 0 \tag{3}$$

$$i_L = \frac{V_m}{\omega L}\left(\cos(\alpha) - \cos(\omega t)\right) \tag{4}$$

where α is the thyristor firing angle of TCR which it can operate between 90° and 180°.

From (4), it is found that i_L and Q of μSVC can be controlled by the adjusting of α. Therefore, the Q control methods, which are $Q(P)$ and $Q(V)$, will be re-written in the form of $\alpha(P)$ and $\alpha(V)$

respectively. To use the μSVC for over-voltage control, the decision table is introduced to consider the value of α when the changes of PV generation and voltage at the PCC are above the threshold values (P_{th} and V_{th}). An example of decision tables for $\alpha(P)$ and $\alpha(V)$ control is shown in Table. 1.

Table 1. Decision table for $\alpha(P)$ and $\alpha(V)$ controls

$\alpha(P)$ method		$\alpha(V)$ method		Thyristor firing angle
P from PV	V at the PCC	P from PV	V at the PCC	
All P level	$V < V_{th}$	$P < P_{th}$	All V level	$\alpha = 180^{\circ}$
$P < P_{th}$	$V \geq V_{th}$	$P \geq P_{th}$	$V < V_{th}$	$\alpha = 180^{\circ}$
$P_{th} \leq P < P_1$	$V \geq V_{th}$	$P \geq P_{th}$	$V_{th} \leq V < V_1$	$\alpha = \alpha_1$ where $\alpha_2 < \alpha_1 < 180^{\circ}$
$P_1 \leq P < P_2$	$V \geq V_{th}$	$P \geq P_{th}$	$V_1 \leq V < V_2$	$\alpha = \alpha_2$ where $90^{\circ} < \alpha_2 < \alpha_1$
$P \geq P_2$	$V \geq V_{th}$	$P \geq P_{th}$	$V \geq V_2$	$\alpha = 90^{\circ}$

Test system

The test system is a 400 V balanced, three-phase distribution network which has the PV system connect in three locations along the feeder, as illustrated in Fig. 2 (a). Assuming the PV system in each location is the aggregation of residential rooftop PV systems. The line parameter is $0.346+j0.0754\ \Omega$/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, using the fixed-power factor inverter, has the capacity of 50 kW. The μSVC is used to support Q compensation with the capacity of 24.22 kVar (p.f. = 0.9 lagging, at rated power). Furthermore, the statutory limits in this test are defined as the over-voltage is not over 1.09 p.u.

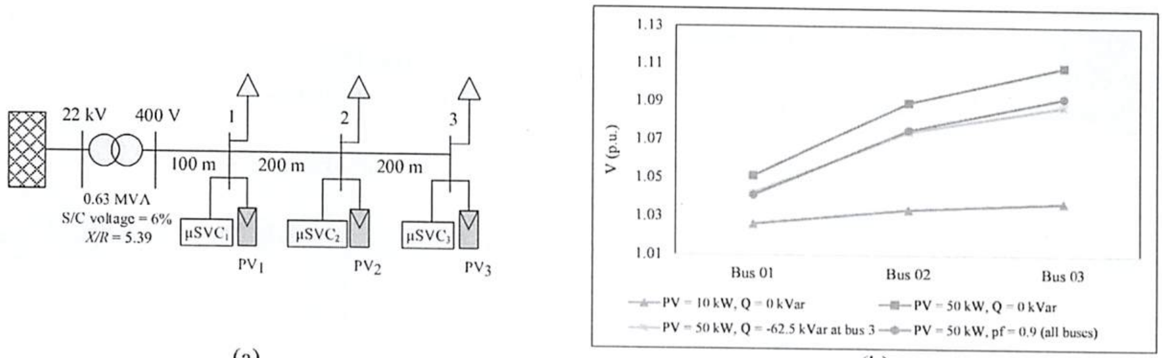
The initial condition is assumed as each PV system injects 10 kW into the network. The comparison results from the load flow simulation between PV systems supply 10 kW and 50 kW are shown in Fig. 2 (b). It is found that critical voltage change is at the end of feeder, while the bus that close to the transformer has a small voltage change. Furthermore, 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 prevent the voltage level over the limit value, 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 lagging, 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 the 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 depending on its location. At bus 1, the μSVC using the $\alpha(P)$ control method. On the other hand, the $\alpha(V)$ control method is assigned to μSVC at bus 2 and bus 3. The decision table for the μSVC control of all three buses is illustrated in Table. 2. It can be seen that the different P_{th} and V_{th} are applied into the individual μSVC to providing the coordinated Q control manner among PV systems, without communication system requirement. Moreover, all μSVC will update the measured data (e.g. P and V) in every 4 s.

Table 2. Decision table for the α control of each μSVC unit

Bus 1 ($\alpha(P)$ method)		Bus 2 ($\alpha(V)$ method)		Bus 3 ($\alpha(V)$ method)		Thyristor firing angle
P of PV (kW)	V at PCC (p.u.)	P of PV (kW)	V at PCC (p.u.)	P of PV (kW)	V at PCC (p.u.)	
All P level	$V < 1.035$	$P < 27.8$	All V level	$P < 11.1$	All V level	$\alpha = 180^{\circ}$
$P < 33.3$	$V \geq 1.035$	$P \geq 27.8$	$V < 1.06$	$P \geq 11.1$	$V < 1.07$	$\alpha = 180^{\circ}$
$33.3 \leq P < 38.9$	$V \geq 1.035$	$P \geq 27.8$	$1.06 \leq V < 1.065$	$P \geq 11.1$	$1.07 \leq V < 1.075$	$\alpha = 157.5^{\circ}$
$38.9 \leq P < 44.5$	$V \geq 1.035$	$P \geq 27.8$	$1.065 \leq V < 1.07$	$P \geq 11.1$	$1.075 \leq V < 1.08$	$\alpha = 135^{\circ}$
$44.5 \leq P < 50$	$V \geq 1.035$	$P \geq 27.8$	$1.07 \leq V < 1.075$	$P \geq 11.1$	$1.08 \leq V < 1.085$	$\alpha = 112.5^{\circ}$
$P \geq 50$	$V \geq 1.035$	$P \geq 27.8$	$V \geq 1.075$	$P \geq 11.1$	$V \geq 1.085$	$\alpha = 90^{\circ}$



(a) (b)

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

Simulations 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, while the connected loads remain constant. The simulation results show the comparison between PV systems with and without the Q control by μSVC. The changes of Q and α of each μSVC, the power factor of each PV system and bus voltages are demonstrated in Fig. 4 (a) to (f), respectively.

The results show that, without the Q control in 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 μSVC units with coordinated controller manner can maintain the voltage level, especially at bus 3, while the power factor within the statutory limits.

The Q absorption at μSVC$_2$ and μSVC$_3$ will start at $t \approx 52$ s and $t \approx 56$ s, respectively. The control setting of these two μSVCs aims to provide the fast Q support for dealing with the critical over-voltage at the end of feeder. μSVC$_2$ and μSVC$_3$ will support Q until reaching the capacity limit to keep control the voltage level at bus 2 and 3 at the values of 1.075 and 1.085 p.u., respectively. Alternatively, the μSVC$_1$ will start to support the Q compensation later the others, at $t \approx 63$ s, when the production from PV$_1$ is relatively high (>50% of rated power). The μSVC$_1$ is mainly operated at 112° to maintain the voltage level at bus 1 to not higher than 1.035 p.u..

After $t = 223$ s, the P from PV system starts to decrease. The μSVC$_1$ will reduce the Q absorption rapidly, to follow the change of PV generation. The μSVC$_1$ stops the Q control at $t \approx 283$ 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, μSVC$_2$ and μSVC$_3$ start to decrease the Q support when voltage level at their buses are below the threshold values, at $t \approx 240$ s and $t \approx 247$ s, respectively. Hence, they stop to operate the Q control when the PV generation is less than 27.8 kW and 11.1 kW, which are at $t \approx 289$ s and $t \approx 291$ s, respectively. It is found that the power factor is slightly below the value of 0.9 (lagging) during the period that PV generation is decreasing, between $t \approx 240$ s and $t \approx 267$ s. This happens due to the response of Q supported by μSVC is a slightly slower than the change of P from the PV systems.

Conclusion

The μSVC is used as a shunt compensation device in the PV system, which has the fixed-power factor inverter. The over-voltage in distribution networks can be prevented by supporting Q from μSVCs in PV systems, which the Q of μSVC can be controlled by adjusting the thyristor firing angle. The $Q(P)$ method is implemented to encourage the Q supported from the μSVC located near the sending end. Whilst, 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. Furthermore, using different controller set-points are necessary, to operate Q control among PV systems in the coordinated manner without communication infrastructures. The simulation results showed that the coordinated Q control among μSVC units in the same feeder can reduce the over-voltage problem in the low-voltage radial feeder efficiently.

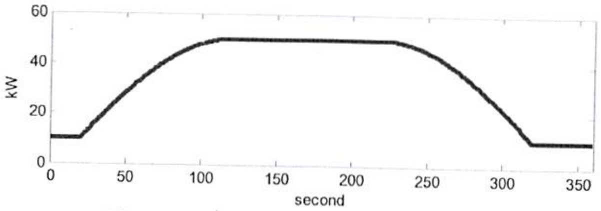


Fig. 3. Change of PV generation

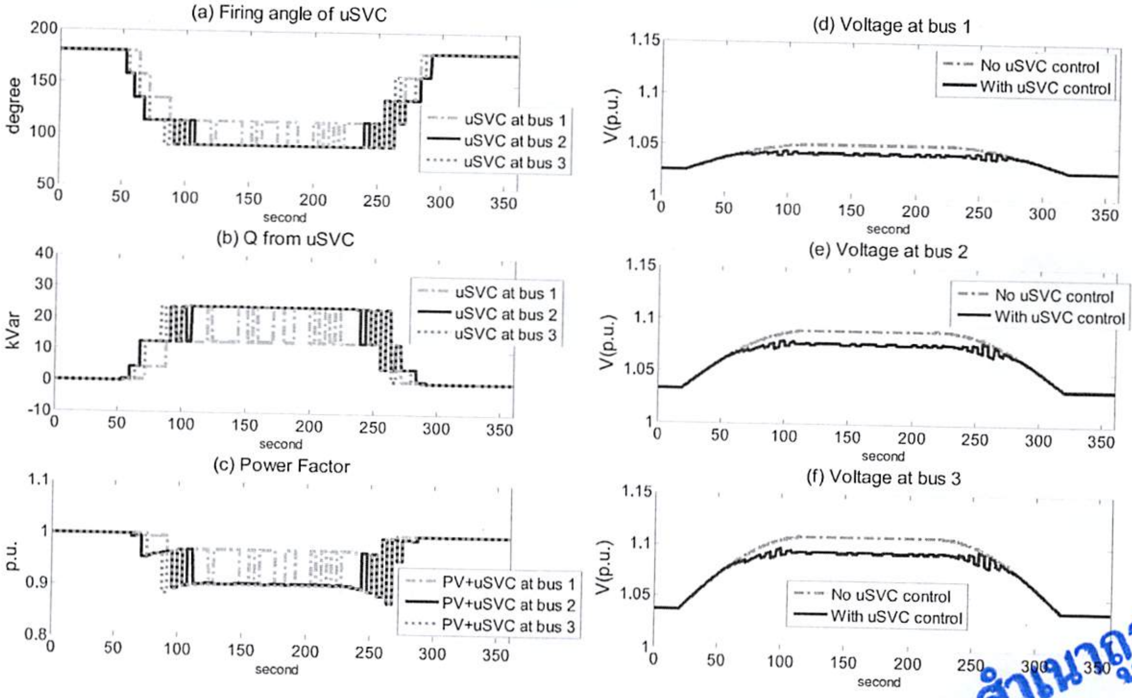


Fig. 4. Simulation results of the proposed test systems

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