COMBINED COMPENSATION STRATEGY OF VOLTAGE SAGS FOR DISTRIBUTION NETWORK WITH DISTRIBUTED GENERATION

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ABSTRACT

Voltage sag is a common power quality problem, coordinated control frame of series and shunt compensation is needed to extend the compensation capability of distribution network with distributed generation. In this paper a combined compensation strategy is proposed. The proposed strategy is intended to reduce the active power generation of series compensator by participation of shunt compensation. Based on the analysis of relation between voltage and power in distribution network, not only in normal condition but also in compensation case, the equation expressing the relation between active power reduction of series compensator and power generation of shunt compensator is presented. According to the equation, the combined compensation strategy is proposed, which reduces the active power generation of series compensation with less constrain on location of shunt compensator. The power flow analysis and simulation study is processed to verify the accuracy and effectiveness of proposed strategy. The proposed strategy is especially suitable for distribution network with distributed generation.

INTRODUCTION

Voltage sag is a common power quality problem. Because the network of distribution network is resistive and low voltage, voltage magnitude is determined by the balance of active more than reactive power. Improved voltage compensation strategies focus on enlarging active generation capacity of compensator have been proposed. Shunt voltage compensation is more feasible to take advantages of distributed generation (DG) in Microgrid. Voltage sag compensation using active power filter (APF) has been studied [1], as well as using static synchronous compensator (STATCOM) [2]. Power requirement of shunt voltage compensation has been studied too [3]. Cost efficiency is the main advantage of shunt voltage sag compensation strategy. Since all of shunt connecting multi-functional components in distribution network, such as DG, STATCOM, and APF can all be used as shunt compensator. However, limited by its small power capacity, severe voltage sag can not been completely compensated by shunt compensator alone. Series compensator is capable to compensate severe voltage sag, but its capability of compensation is depends on active power, i.e. the size of its inner battery [4]. Coordinated voltage sag compensation strategy had been proposed by researchers pursuing the combination of the vantages of series and shunt compensator. Sharing DC bus of DG and series compensator [5] and separately using of series and shunt compensator in light and severe voltage sags respectively [4] had been suggested as the coordinated strategy. The former has overcome the limitation of inner battery size of series compensator, but got limited applicable. Since short distance between DG and series compensator is required. The latter is too complicated in control action to be widely applied.

VOLTAGE COMPENSATION CAPACITY CACULATION

Mathematical Model of Active Power Generation of Series Compensation

The active power determines the severity of voltage sag that can be mitigated by series compensator, or not. The active power required for the fully compensation in example system illustrated in Figure 1, can be expressed as following [4]:

$$P_{\mathrm{sc}} = \left[1-\left(1-U_{\mathrm{sag}}\right)\cos\left(\varphi+\psi\right)\right]P_{\mathrm{load}} \Big/ \cos\varphi \qquad (1)$$

where P_{s} is the active power generation of series compensator to mitigate the voltage sag with dip depth of V_{sag}, P_{l} is total active power of the sensitive load, φ is load angle, and ψ is phase-angle jump of voltage sag. In Figure 1 U_{sc} is the voltage generated by series compensator.

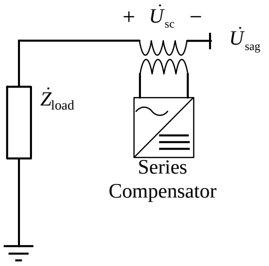

Figure 1. Example System of Series Compensation

Mathematical Model of Power Generation of Shunt Compensation

The example system illustrated in Figure 2 is used to express the relationship between shunt power injection and voltage change. U_{DN} is the voltage of the voltage resource representing distribution network (DN), Z_{load} and Z_{line} representing the impedance of feeder and load respectively, and Z_{DN} is the impedance representing the short circuit capacity of DN. The voltage change caused by power injection of the shunt compensator depends on both short-circuit capacity of the distribution network and power output of shunt compensator. The relation can be expressed in following equation [6]:

$$\left|\Delta\dot{U}_{\mathrm{l}}\right|/U_{\mathrm{l}} = \left|\dot{S}_{\mathrm{nc}}\right|/\left|\dot{S}_{\mathrm{DN}}\right| \tag{2}$$

where $\Delta\dot{U}_{\mathrm{l}}$ is the voltage change caused by shunt compensator generation of $\dot{S}_{\mathrm{scr}}$, U_{l} is the voltage magnitude at the shunt compensator connection node before compensation, $\dot{S}_{\mathrm{DN}}$ is the short circuit capacity of the distribution network.

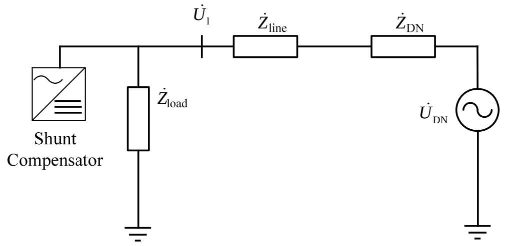

Figure 2. Example System of Shunt Compensation

Combined Compensation Strategy

Series voltage sag compensation is efficiency but limited method caused by the limited size of inner battery. Sharing DC bus with DG brings increased capacity of active power but decreased places of compensator installation [5]. If shunt compensators with enough capacity of active power injecting currents to enhance the voltage profile of network, the burden of series compensator can be released without adding new stress on the its location.

Electric vehicle can be used as shunt compensator which has enough active power in distribution network. Because it has larger battery size, and is insensitive to temporarily releasing active power back to Distribution network [7]. For only one vehicle, communication and control devices needed to complete a shunt voltage sag compensator may be too expensive. But it won't be worthless for a group of the vehicles connecting at electric vehicle charging station (EVCS) [8].

The example system for demonstration of proposed combined compensation strategy is illustrated in Figure 3. $Z_{\mathrm{DN+line}}$ is the impedance of line connecting distribution network at public coupling connection (PCC). U_{l} is the voltage at the load node, U_{ln} is the voltage at the feeder end node L, U_{pcc} is the voltage at the PCC, and U_{DN} is the source voltage of the distribution network.

The normal voltage is U'_{ln}, when voltage sag with dip depth of U'_{sag} happened the voltage at node L is (3).

$$U_{\mathrm{ln}} = U'_{\mathrm{ln}}\left(1-U'_{\mathrm{sag}}\right) \tag{3}$$

Thus the active power generation P'_{sc} of series compensator working in in-phase compensation mode can be expressed in (4) according to (1):

$$P'_{\mathrm{sc}} = P_{\mathrm{load}}\left(\frac{1-\cos\varphi}{\cos\varphi}\right) + P_{\mathrm{load}}U'_{\mathrm{sag}} \tag{4}$$

After the shunt compensation the voltage change at node L can be expressed in (5):

$$\Delta U = \frac{\left|S_{\mathrm{nc}}\right|}{\left|S_{\mathrm{DN}}\right|}\left(1-U'_{\mathrm{sag}}\right)U'_{\mathrm{ln}} \tag{5}$$

Where S_{nc} is the apparent power produced by shunt compensator, and S_{DN} is the short circuit capacity of the distribution network. Thus U_{sag}, the dip depth after shunt compensation participation is:

$$U_{sag} = \frac{U'_{\mathrm{ln}} - \left(U_{\mathrm{ln}} + \Delta U\right)}{U'_{\mathrm{ln}}} \tag{6}$$

According to (3) and (5), (6) can be deduced to (7)

$$U_{sag} = 1-\left(1-U'_{sag}\right)\left(1+\frac{\left|\dot{S}_{\mathrm{nc}}\right|}{\left|\dot{S}_{\mathrm{DN}}\right|}d\right) \tag{7}$$

where d is the effect coefficient of shunt compensation on node L. It equals to dividing the voltage change on node L by the voltage change on connection of shunt compensation, when shunt compensation is applied only. The equation of active power generation of series compensator with assistance of shunt compensation can be obtained as following:

$$P_{\mathrm{sc}} = P_{\mathrm{load}}\left(\frac{1-\cos\varphi}{\cos\varphi}\right) + P_{\mathrm{load}}\left[1-\left(1-U'_{\mathrm{sag}}\right)\left(1+\frac{\left|\dot{S}_{\mathrm{nc}}\right|}{\left|\dot{S}_{\mathrm{DN}}\right|}d\right)\right] \tag{8}$$

Thus the change of P_{sc} during shunt compensation can be obtained by subtract (4) from (8):

$$\Delta P_{\mathrm{sc}} = P_{\mathrm{sc}} - P'_{\mathrm{sc}} = -P_{\mathrm{load}}\left(1-U'_{\mathrm{sag}}\right)\frac{\left|S_{\mathrm{nc}}\right|}{\left|S_{\mathrm{DN}}\right|}d \tag{9}$$

ΔP_{sc} is the active power generation of series compensator reduced by assistance of shunt compensation. According to (9), the reduction effect of active power generation caused by series compensator is depends on variables of load power P_{load}, dip depth of voltage sag U'_{sag}, the location of shunt compensator d, and the ratio of capacity of shunt compensator to short circuit capacity of distribution network $|S_{\mathrm{nc}}|/|S_{\mathrm{DN}}|$. In case of distribution network, the effect of active power reduction mainly depends on the ratio of the capacities.

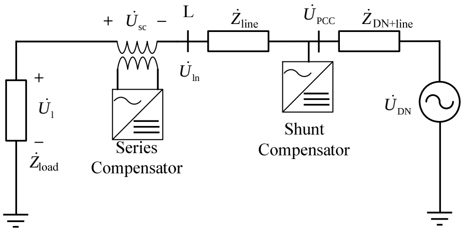

Figure 3. Combined Compensation Strategy

SIMULATION

Studied Urban Residential Distribution Network

The studied system illustrated in Figure 4 is abstracted form power supply network of typical north Chinese resident sub-district. The distribution network is consisted by a voltage resource representing main power system, a transformer connecting between PCC and cable. Additionally there are an EVCS, a dynamic voltage restorer (DVR) as series compensator to prevent sensitive load from voltage problem, and cables connecting each components together.

Table 1. The Impedance of Components in Distribution network

Line 1	Line 2	Total Impedance of Upstream Grid
0.7725+j0.0093 Ω	0.3117+j0.024 Ω	0.1069+j0.0893 Ω

The impedances of cables (Z_{line1} and Z_{line2}) and transformer (Z_T) are listed in Tab. 1 along with the impedance ($Z_{\text{ND+line}}$) representing short circuit capacity of distribution network (201.3kVA) and transmission line, and all impedance has been converted to voltage level of 380V. "Total Impedance of Upstream Grid" in Table 1 is the sum impedance of $Z_{\text{ND+line}}$ and Z_T. The EVCS is operating in charging mode with power of 5kW in normal condition, and in voltage compensation mode with max output power of 70kVA in voltage sag. The converting of two different operation mode is triggered by voltage magnitude at PCC. If voltage depth is larger than 20% then the compensation mode will be triggered and EVCS turns to generate power to enhance the voltage at PCC. The EVCS and DVR installed at the load end of the feeder line2 are considered as ideal voltage source, which means ignoring the dynamic process of its power converting parts.

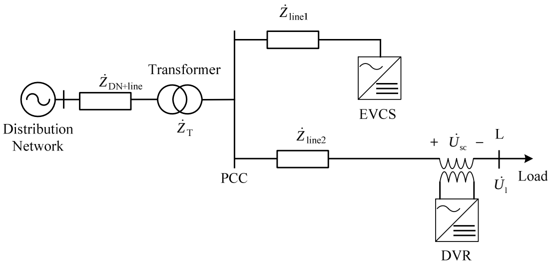

Figure 4. Study System

Active Power Reduction on Series Compensation

The equivalent source voltage of distribution network is 402.8V (106%) in normal condition, and 190V (50%) in sag condition. The active power generated by DVR is calculated by power flow program to reveal the effects of power generation of EVCS. DVR works in in-phase boosting technique [9] mode and maintaining the voltage of sensitive load unchanged during simulation. The result is illustrated in Figure 5. According to the curves, the active power generated by DVR is reduced form 2.6kW to about 2.37kW, when the EVCS generating power increased to 10kVA.

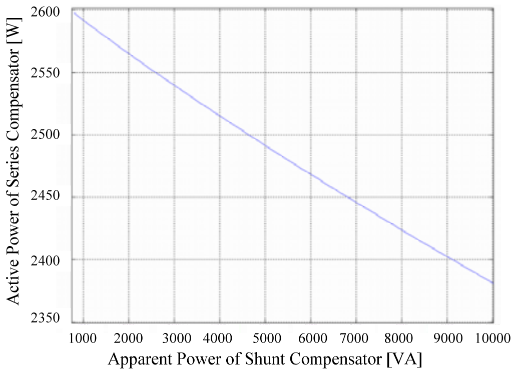

Figure 5. Active Power Decrease of Series Compensator vs. Apparent Power Increase of Shunt Compensator

Case Study

Study system is established in *MATLAB/Simulation* environment to verify the proposed method in a case study. Assumption is the system voltage dip to 50% at 0.15s until 0.27s. DVR and EVCS turn to work when sag began. The control method of EVCS in compensation mode is proposed in [10], and method of DVR is proposed in [9]. The system voltage and compensated voltage on sensitive load is illustrated in Figure7 and Figure8 respectively, and power generated by DVR and EVCS is expressed respectively in Figure 8 and Figure 9.

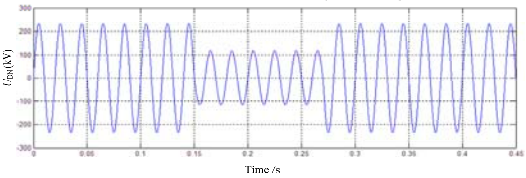

Figure 6. The curve of the system voltage

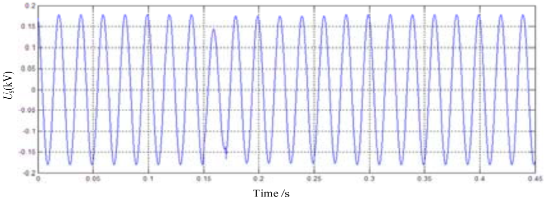

Figure 7. The curve of the load voltage

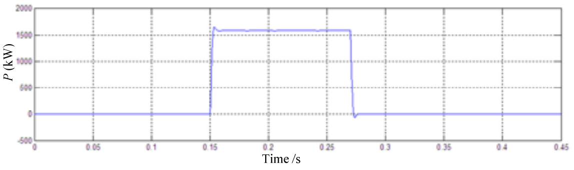

Figure 8. The active generation of DVR

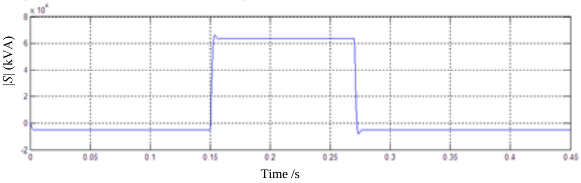

Figure 9. The apparent power generated by EVCS

Figure 6 shows the phase voltage of system that drop to 50% in 6 cycles and Figure 7 shows the voltage on load side of DVR. Figure 8 shows the active power of DVR during voltage sag, and Figure 9 shows how the EVCS power changes form charging mode to compensation mode and back.

Assisted by the EVCS, active power of DVR reduced to only 1380W to maintain the load voltage undisturbed. It is a significant reduction contrasted with 2210W of power DVR generated in the same case without EVCS in previous section.

CONCLUSION

This paper has proposed a combined strategy for voltage sag compensation in distribution network, which needs no physical connection on DC bus for establishing coordination between shunt and series compensators. The theoretical analysis has been processed to reveals the relation between the active power reduction on series compensation and the power injection of assistive shunt compensator. The equation describing the relation has been proposed based on which the combined strategy is also proposed. The power flow analysis and simulation test in studied Distribution network had been processed, and the accuracy and effectiveness of proposed strategy has been verified by the results. The demonstrated voltage curves have shown the high performance of proposed strategy.

The proposed strategy is simple and brings significantly reduction to the active power requirement of series compensator without sharing DC bus with other components, which means less constrain on compensator location.

Acknowledgments

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