DYNAMIC VOLTAGE REGULATION USING DISTRIBUTED ENERGY RESOURCES

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ABSTRACT

Many distributed energy (DE) resources are near load centers and equipped with power electronics converters to interface with the grid, therefore it is feasible for DE to provide ancillary services such as voltage regulation, nonactive power compensation, and power factor correction. A synchronous condenser and a microturbine with an inverter interface are implemented in parallel in a distribution system to regulate the local voltage. Voltage control schemes of the inverter and the synchronous condenser are developed. The experimental results show that both the inverter and the synchronous condenser can regulate the local voltage instantaneously, while the dynamic response of the inverter is faster than the synchronous condenser. Also, integrated voltage regulation (multiple DE perform voltage regulation) can increase the voltage regulation capability and reduce the capital and operation costs.

INTRODUCTION

There are a wide range of ancillary services in the distribution level that can be supplied by distributed energy (DE) resources [1], among which voltage regulation has drawn much interest because of the nonactive power shortage in power systems. Previously, others have reported that the power electronics interface between the DE and the utility can provide several nonactive power services [2]-[3]. The installation of DE and the provision of voltage regulation from DE can have a beneficial impact on transmission stability by supplying nonactive power at the distribution level [4]. The total installed DE capacity for installations smaller than 5 MW in the U.S. is 195,251 MW, among which the nonactive-power-capable DE is estimated at 10% of the total installations [5]. Therefore, there is a large amount of DE resources potentially available for voltage regulation.

SYSTEM CONFIGURATION

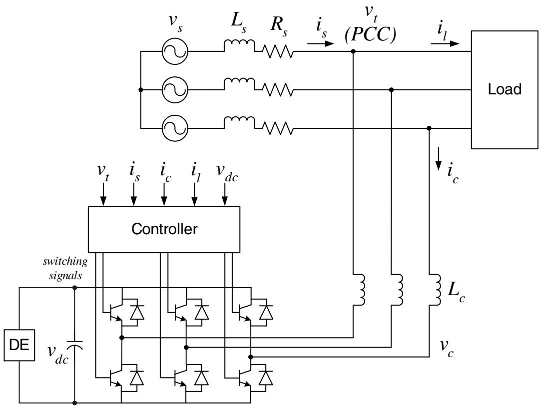


Fig. 1. Parallel connection of a DE with power electronics converter interface.

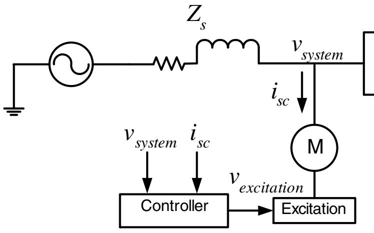


Fig. 2. System configuration of a synchronous condenser.

A parallel-connected DE with power electronics inverter interface is shown in Fig. 1. The interface, including the inverter, the DC side capacitor v_{dc}, and the coupling inductor L_c, is referred to as the compensator because voltage regulation from DE is the main topic in this paper. The compensator is connected in parallel with the utility at the point of common coupling (PCC) v_t. By generating or consuming nonactive power, the compensator regulates the PCC voltage v_t. The compensator current i_c only contains the nonactive power component.

The system configuration of a parallel-connected synchronous condenser is shown in Fig. 2. The synchronous condenser generates nonactive power at over-excitation, and consumes nonactive power at under-excitation. By controlling the excitation voltage $v_{excitation}$, the synchronous condenser regulates the voltage v_{system} by changing the nonactive power it provides or consumes. The synchronous condenser current i_{sc} only contains the nonactive power component.

Two system configurations of the compensator and the synchronous condenser are studied in this paper, which are shown in Figs. 3 and 4. In Fig. 3, the two devices are connected on two different circuits from a 2.4 kV substation. The synchronous condenser is connected to the 480 V Panel A with some other loads through transformer 1,

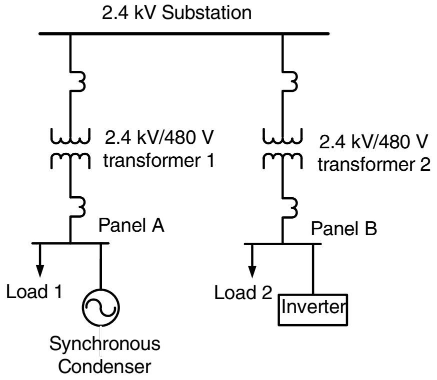


Fig. 3. Parallel connection of the two DE on different panels.

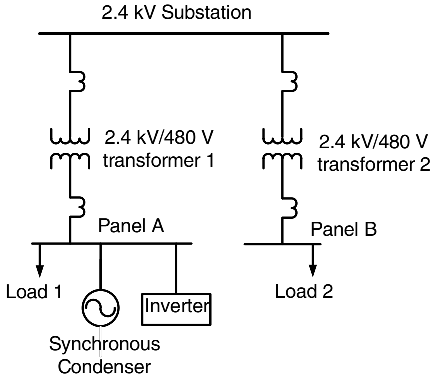


Fig. 4. Parallel connection of the two DE on the same panel.

and the compensator is connected to the 480 V Panel B with some loads through transformer 2. In Fig. 4, both the synchronous condenser and the compensator are connected to Panel A. The electrical distance between the compensator and the synchronous condenser in Fig. 4 is less than the case in Fig. 3, and therefore different voltage regulation methods are used.

CONTROL METHODS

Most of the voltage fluctuation in the power system is because of a shortage or surplus of nonactive power. Capacitor banks are widely used in power systems for voltage regulation. However, capacitor banks are switched on or off, which are not a continuous variable real-time source of nonactive power. Moreover, the nonactive power from capacitor banks decreases as the system voltage decreases (by voltage squared) when nonactive power is most needed. Therefore, capacitor banks cannot provide sufficient nonactive power when they are most needed.

DE with a power electronics converter can provide continuous real-time voltage regulation service. A voltage regulation method is developed based on the system configuration in Fig. 1. The control diagram is shown in Fig. 5. The PCC voltage is measured and the rms value is calculated. The rms value is compared to the voltage reference V_t^*, and the error is fed to a PI controller. The reference compensator output voltage vc* is the reference to generate PWM signals to drive the inverter. The output voltage of the compensator is controlled so that it is in phase with the PCC voltage and the magnitude of the compensator output voltage is controlled so that the PCC voltage is regulated at a given level V_t^*. The control scheme is shown in (1).

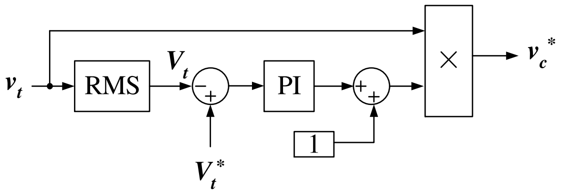


Fig. 5. Control diagram for compensator voltage regulation.

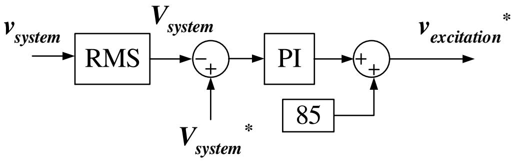


Fig. 6. Control diagram for synchronous condenser voltage regulation.

$$v_c^*(t) = v_t(t)[1 + K_{P1}(V_t^*(t) - V_t(t)) + K_{I1}\int_0^t (V_t^*(t) - V_t(t))dt] \qquad (1)$$

In a three-phase system, a voltage or a current is balanced if the magnitudes of all phases are equal, and the phase-angles between consecutive phases are also equal. Most of the voltage unbalance in power systems is because of the magnitude inequalities, and only this case is considered in this paper. In this control method, the rms value of voltage in each phase is controlled independently; therefore the unbalance in the PCC voltage can be compensated by the compensator.

The voltage regulation method of the synchronous condenser is designed based on the configuration in Fig. 2 and the control diagram is shown in Fig. 6. For the synchronous condenser which is used in the experiments, the synchronous condenser does not generate or consume any nonactive power when the excitation voltage is 85 V. Controlling the excitation voltage to be higher or lower than 85 V generates or consumes nonactive power, and therefore the system voltage v_s is regulated. The control scheme is shown in (2).

$$v_{excitation}^*(t) =$$

$$K_{P2}(V_{system}^*(t) - V_{system}(t)) + K_{I2}\int_0^t (V_{system}^*(t) - V_{system}(t))dt + 85 \qquad (2)$$

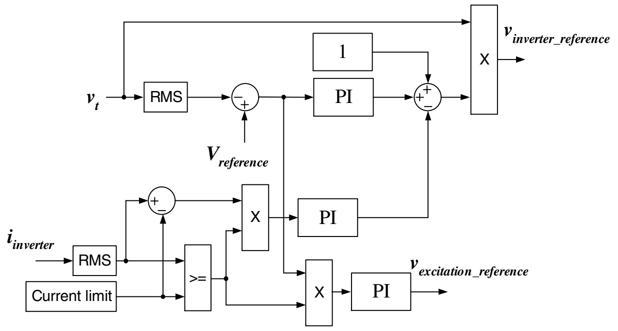


Fig. 7. Integrated control of the compensator and the synchronous condenser.

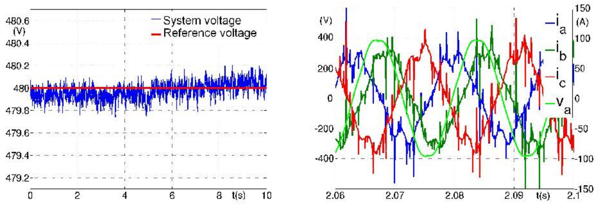
When the compensator and the synchronous condenser are connected to different panels as shown in Fig. 3, the electrical distance of the two devices are large so that the controls of the two devices are independent, as shown in Figs. 5 and 6. However, when they are connected to the same panel as shown in Fig. 4, they are close to each other and control the same voltage so that they must be controlled together. The integrated control diagram is shown in Fig. 7 for this case.

The compensator response time is shorter than the synchronous condenser, therefore when the two devices are operating together to control a voltage, the compensator is responsible for the fast and small changes in the voltage, and the synchronous condenser is responsible for the long-term changes. The reference voltage for the synchronous condenser ($v_{excitation\_reference}$ in Fig. 7) is only changed if the required compensator current exceeds the pre-set current limit.

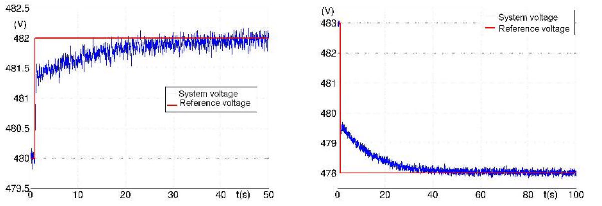
VOLTAGE REGULATION

The parallel voltage regulation system is implemented in a distributed system at Oak Ridge National Laboratory. The simplified system diagram is shown in Fig. 3. The synchronous condenser and the compensator are operated simultaneously to regulate Panel A voltage (referred to as system voltage in Fig. 8) and Panel B voltage (referred to as PCC voltage in Fig. 9).

In the synchronous condenser voltage regulation, the system voltage was 478.2 V before the regulation. The reference voltage is set to be 480 V (the red line in Fig. 8a), and the regulated voltage is shown as the blue waveform in Fig. 8a, which tracks the reference voltage with the error within 0.2 V. The three-phase synchronous condenser current waveforms are shown in Fig. 8b together with the phase *a* voltage to show the phase angle between the voltage and the current. The phase *a* current leads the phase *a* voltage by about 90°, which shows that the synchronous condenser is generating nonactive power. The spikes in the current waveforms are because of the electromagnetic interference (EMI) in the current measurement. The dynamic response of the synchronous condenser is shown in Figs. 8c and 8d. The reference voltage increases from 480 V to 482 V (the red waveform in Fig. 8c), and decreases from 483 V to 478 V (the red waveform in Fig. 8d), respectively. The corresponding system voltage waveforms are the blue waveforms in Figs. 8c and 8d, respectively. The synchronous condenser can regulate the system voltage to a reference level at steady state and dynamically by controlling the amount of nonactive power generated or consumed by the synchronous condenser.

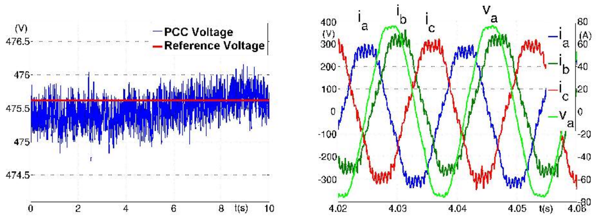


(a) rms line-to-line voltage (b) Synchronous condenser current

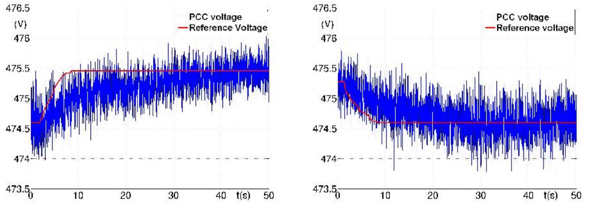


(c) Voltage increase control (d) Voltage decrease control

Fig. 8. Experimental results of synchronous condenser voltage control.



(a) rms line-to-line voltage (b) Compensator current



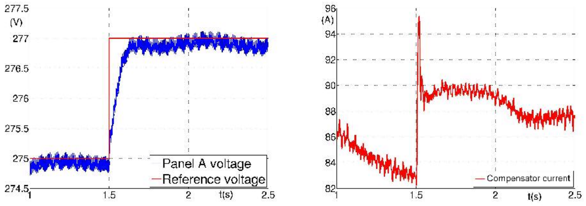
(c) Voltage increase control (d) Voltage decrease control

Fig. 9. Experimental results of compensator voltage control.

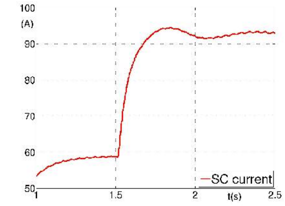
In the compensator voltage regulation, the PCC voltage was 473.7 V before regulation. The reference voltage is set at 475.6 V (the red line in Fig. 9a) instead of the rated value 480 V, which is because of the current limit of the inverter, and a smaller range of voltage regulation is performed. The regulated voltage is shown as the blue waveform in Fig. 9a. The three-phase compensator current waveforms are shown in Fig. 9b together with the phase a voltage to show the phase angle between the voltage and the current. The phase a current leads the phase a voltage by about 90°, which shows that the compensator is generating nonactive power. The ripple in the compensator output current is partly filtered by the coupling inductor (L_c in Fig. 1), so that the current waveforms are fundamental sinusoids with some harmonics. Larger coupling inductors could reduce the ripple to a lower level, but this would require a higher DC link voltage on the inverter. The dynamic response of the compensator is shown in Figs. 9c and 9d. The reference voltage increases from 474.4 V to 475.5 V (the red waveform in Fig. 9c), and decreases from 475.3 V to 474.4 V (the red waveform in Fig. 9d), respectively. The corresponding PCC voltage waveforms are the blue waveforms in Figs. 9c and 9d, respectively. The compensator can regulate the system voltage to a reference level at steady state and dynamically by controlling the amount of nonactive power generated or consumed by the compensator.

The parallel operation of the synchronous condenser and the inverter on the same panel (Fig. 4) is simulated, and the simulation results are shown in Fig. 10. The reference voltage of the rms line-to-neutral voltage is set at 275 V from $t = 1$ s to $t = 1.5$ s, and then at 277 V from $t = 1.5$ s to t = 2.5 s, as shown by the red waveform in Fig. 10a. The blue waveform is the Panel A voltage. At steady state, it follows the reference voltage, and at transient state, the dynamic response is less than 0.2 s. The compensator current limit is set at 90 A according to the current rating of the inverter. If the compensator current is below 90 A, the reference voltage for the synchronous condenser remains the same value, and the compensator responds to all the changes in the voltage. If the required compensator current is above 90 A, as shown in Fig. 10b because of the sudden voltage reference change at t = 1.5 s, a short period of current over 90 A is allowed for the compensator so that the system can have a faster dynamic response. After this short current overshoot, the compensator current is controlled below 90 A. At the same time, the synchronous condenser increases the nonactive power output which is required by the system to increase the panel A voltage according to the increased reference voltage.

There are two advantages to controlling the synchronous condenser and the compensator on the same voltage panel. 1) The two devices share the nonactive power requirement for voltage regulation; therefore the voltage regulation capability is improved. 2) Devices of different characteristics are operated in parallel together, and these characteristics are combined together to achieve faster system dynamic response, and to reduce the capital and operation costs at the same time.



(a) rms line-to-neutral voltage (b) Compensator current



(c) Synchronous condenser current

Fig. 10. Simulation results of parallel operation on the same panel.

CONCLUSIONS

Based on the analysis of simulation and experimental results, the following conclusions can be drawn. 1) DE can perform real-time local voltage regulation. 2) The voltage regulation is instantaneous. 3) Voltage regulation can be performed locally. 4) Power electronic converters have fast dynamic response, which can effectively compensate voltage sags and other sudden changes in the system. 5) Power electronic converters can correct voltage unbalance. 6) Integrated voltage regulation (multiple DE performing voltage regulation) can increase the voltage regulation capability and reduce the capital and operation costs.

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