

# *International Review of Electrical Engineering (IREE)*

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# Using Distributed Energy Resources to Supply Reactive Power for Dynamic Voltage Regulation

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**Abstract** – Distributed energy (DE) resources are power sources located near load centers and equipped with power electronics converters to interface with the grid, therefore it is feasible for DE to provide reactive power (along with active power) locally for dynamic voltage regulation. In this paper, a synchronous condenser and a DE source with an inverter interface are implemented in parallel in a distribution system to regulate the local voltage. Developed voltage control schemes for the inverter and the synchronous condenser are presented. Experimental results show that both the inverter and the synchronous condenser can regulate the local voltage instantaneously although the dynamic response of the inverter is much faster than the synchronous condenser. In a system with multiple DEs performing local voltage regulation, the interaction of multiple DE at different locations under different load levels may have an impact to the control parameter setting for each individual DE control system. Future research is needed to find out the interaction of DEs to identify the optimal control parameter settings with the consideration of many factors such as system configuration, load variation, and so on. **Copyright © 2008 Praise Worthy Prize S.r.l. - All rights reserved.**

**Keywords:** Distributed Energy Resources, Instantaneous Power Theory, PI Control, Power Electronic Interface, Voltage Regulation

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## I. Introduction

There are a wide range of ancillary services in the distribution system that can be supplied by distributed energy (DE) resources [1]-[9], among which voltage regulation has drawn much interest because of the reactive power shortage and transport problems in power systems [5]-[9]. Previously, others have reported that the power electronics interface between the DE and the utility can provide several reactive power services [10]-[12]. The installation of DE and the provision of voltage regulation from DE can have a beneficial impact on transmission capacity and stability by supplying reactive power at the distribution level [13],[14]. The total installed DE capacity for installations smaller than 5 MW in the U.S. is 195,251 MW, among which the reactive-power-capable DE is presently estimated at around 10% of the total installations [15]. If DE resources were designed to provide reactive power when they were purchased, this amount could easily be 90% of the total installations. In order to be a reactive power supplier, a fuel cell or photovoltaic installation would need an inverter capable of operating at non-unity power factor, and an engine generator would need a clutch between the engine and generator. The generators are typically capable of operating at 0.8 to 0.9 power factor.

200,000 MW of DE thus equipped could provide nearly 100,000 to 150,000 MVar of reactive power.

This amount of dynamic reactive power installed near loads would have a dramatic effect in reducing distribution losses, increasing circuit capacity, improving power quality, and expanding the margin to voltage collapse.

The power and current ratings of the power electronics interface are required to be larger to provide both active power and reactive power instead of only active power, while the DE ratings remain the same. If the power factor is 0.9, 0.48 MVar reactive power is provided from a 1 MW DE, i.e., the reactive power is 48% of the active power. The power and current ratings (i.e., capital costs) of the power electronics interface is only required to be 11.1% larger than the no reactive power service case. If the DE can run at 0.8 power factor, 0.75 MVar reactive power can be supplied from a 1 MW DE, and the power and current ratings is only increased by 25%.

The reactive power capability is significant comparing to the additional costs.

## II. System Configuration

Some DE requires a power electronics inverter interface to connect to the utility, while others do not. A typical DE with a power electronics inverter interface is connected in parallel with respect to the load to provide voltage regulation, as shown in Fig. 1.

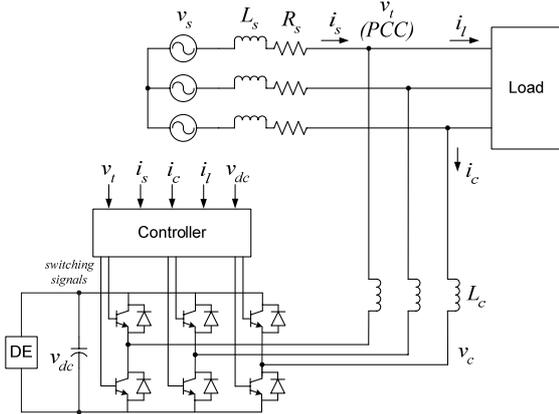


Fig. 1. Parallel connection of a DE with power electronics inverter interface

The interface, including the inverter, the DC link capacitor with a voltage  $V_{dc}$ , and the coupling inductor  $L_c$ , is referred to as the compensator because voltage regulation from DE is the main topic of this paper. The compensator is connected in parallel at the point of common coupling (PCC), and the PCC voltage is denoted as  $v_r$ . By generating or consuming reactive power, the compensator regulates the PCC voltage  $v_r$ . The compensator current  $i_c$  only contains reactive power component.

A synchronous condenser does not need any power electronics interface to connect to the utility. The synchronous condenser supplies reactive power during over-excitation to boost voltage, and absorbs reactive power during under-excitation to lower voltage. By controlling the excitation voltage, and consequently changing the reactive power it provides or consumes, the synchronous condenser regulates the system voltage.

The Distributed Energy and Communication Center (DECC) at Oak Ridge National Laboratory (ORNL) is conducting research and testing on dynamic voltage regulation using DE and multiple DE control schemes. Fig. 2 shows the configuration of DECC with interconnected external primary distribution feeders and transmission systems. With the installation of multiple DE in the distribution system, the control and operation of DE is different depending on the system configuration. Two system configurations of the compensator (inverter) 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 local loads through transformer 1, and the compensator is connected to the 480 V Panel B with local loads through transformer 2. In Fig. 4, both the synchronous condenser and the compensator are connected to Panel A.

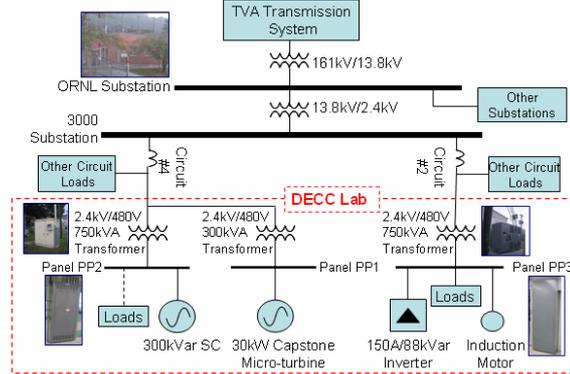


Fig. 2. Configuration of DECC laboratory at ORNL

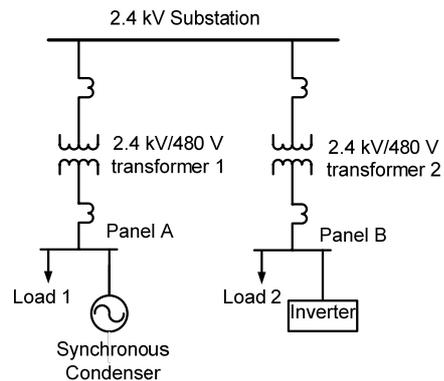


Fig. 3. Parallel connection of the two DE on different panels

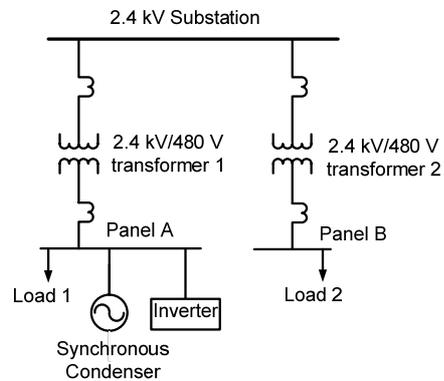


Fig. 4. Parallel connection of the two DE on the same panel

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.

### III. Instantaneous Power Theory

An instantaneous nonactive (i.e., reactive) power theory [16] is adopted in this paper for the real-time calculation and control of DE voltage regulation. In the theory, definitions of instantaneous active current, instantaneous reactive current, average active power, average reactive power, apparent active power, and

apparent reactive power are defined. Only the definitions that are related to the calculation and control in this paper are presented in this section. The full description of the theory is presented in [16]. In all the following equations, the lower case  $t$  indicates time. All the definitions are functions of time. For a three-phase voltage vector  $\mathbf{v}(t)$  and current vector  $\mathbf{i}(t)$  (vectors for voltage and current will be denoted in bold):

$$\mathbf{v}(t) = [v_a(t), v_b(t), v_c(t)]^T \quad (1)$$

$$\mathbf{i}(t) = [i_a(t), i_b(t), i_c(t)]^T \quad (2)$$

The instantaneous power  $p(t)$  and the average power  $P(t)$  over the averaging interval  $[t-T_c, t]$  are defined by (3) and (4):

$$p(t) = \mathbf{v}^T(t) \mathbf{i}(t) = \sum_{k=1}^3 v_k(t) i_k(t) \quad (3)$$

$$P(t) = \frac{1}{T_c} \int_{t-T_c}^t p(\tau) d\tau \quad (4)$$

The averaging interval  $T_c$  can be chosen arbitrarily from zero to infinity, and for different  $T_c$  values, the resulting active current and reactive current will have different characteristics. In a periodic system with period  $T$ ,  $T_c$  is normally chosen as integral multiples of  $T/2$  to eliminate current harmonics.

The instantaneous active current  $\mathbf{i}_a(t)$  and instantaneous reactive current  $\mathbf{i}_n(t)$  are defined by, respectively:

$$\mathbf{i}_a(t) = \frac{P(t)}{V_p^2(t)} \mathbf{v}_p(t) \quad (5)$$

$$\mathbf{i}_n(t) = \mathbf{i}(t) - \mathbf{i}_a(t) \quad (6)$$

The voltage  $\mathbf{v}_p(t)$  is the reference voltage, which is chosen based on the characteristics of the system and the desired compensation results.  $V_p(t)$  is the root-mean-square (rms) value of the reference voltage  $\mathbf{v}_p(t)$ , i.e.:

$$V_p(t) = \sqrt{\frac{1}{T_c} \int_{t-T_c}^t \mathbf{v}_p^T(\tau) \mathbf{v}_p(\tau) d\tau} \quad (7)$$

The rms values of the voltage  $\mathbf{v}(t)$  and the current  $\mathbf{i}(t)$  are:

$$V(t) = \sqrt{\frac{1}{T_c} \int_{t-T_c}^t \mathbf{v}^T(\tau) \mathbf{v}(\tau) d\tau} \quad (8)$$

$$I(t) = \sqrt{\frac{1}{T_c} \int_{t-T_c}^t \mathbf{i}^T(\tau) \mathbf{i}(\tau) d\tau} \quad (9)$$

As pointed out in [16], the above generalized definition from (1) to (9) extends the traditional definition of instantaneous nonactive power from three-phase, balanced, and sinusoidal systems to other cases. This unique feature makes it easy to be applied in modern distribution systems in which there are challenges like single-phase, non-sinusoidal, unbalanced, and non-periodic waveforms. Therefore, it is suitable for real-time control in a real-world system and provides advantages for the design of control schemes, which will be discussed in the next section.

#### IV. Control Methods

Most of the voltage fluctuations in the power system are because of a shortage or surplus of reactive power. Capacitor banks are widely used in power systems for voltage regulation. However, capacitor banks are switched on or off, and are not a continuously variable real-time source of reactive power. Moreover, the reactive power supplied by capacitor banks decreases as the system voltage decreases (by voltage squared) when reactive power is most needed. Therefore, capacitor banks fail to provide sufficient reactive power when it is most needed during severe voltage excursions.

DE with a power electronics converter can provide dynamic voltage regulation service. The voltage is controlled according to a voltage schedule that could be supplied and updated by the local utility to coordinate with the needed utility support and to change in configuration and conditions. Under this voltage schedule method, the local voltage would be better regulated, i.e., supported during low voltage, such as a sag due to a fault or motor start, and reduced during an overvoltage, such as excessive fixed capacitance during light load. The concerns of feeding excessive current to a fault or exceeding the rating of a circuit breaker or confusing protective relaying will be addressed by selecting the appropriate control settings for the DE based on the distribution system type and protective relaying configuration. Development of the engineering guidelines for the selecting the settings would ensure trouble free, reliable DE installations.

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 proportional-integral (PI) controller. The reference compensator output voltage  $v_c^*$  is the reference to generate pulse-width modulation (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 value of  $V_t^*$  could be supplied by the local utility's voltage schedule. The control scheme is shown in (10):

$$v_c^*(t) = v_t(t) \left[ \begin{array}{l} 1 + K_{P1} (V_t^*(t) - V_t(t)) + \\ K_{I1} \int_0^t (V_t^*(t) - V_t(t)) dt \end{array} \right] \quad (10)$$

In a three-phase system, a voltage or a current is balanced if the magnitudes of the three 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 the 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 corrected 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. The synchronous condenser, which is used in the experiments, does not generate or consume any reactive power when the excitation voltage is 85 V. Reactive power is generated or consumed by controlling the excitation voltage to be higher or lower than 85 V, and therefore the system voltage  $v_s$  is regulated to follow the utility's voltage schedule. The control scheme is shown in (11):

$$v_{excitation}^*(t) = K_{P2} (V_{system}^*(t) - V_{system}(t)) + K_{I2} \int_0^t (V_{system}^*(t) - V_{system}(t)) dt + 85 \quad (11)$$

In the ORNL DECC laboratory, the compensator and the synchronous condenser are currently connected to different panels and subsequently different distribution circuits as shown in Fig. 3. Thus, the electrical distance of the two devices is 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 panel 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 much shorter than the synchronous condenser, therefore when the two devices are operating together, the compensator is responsible for the fast and small changes in the voltage while the synchronous condenser is responsible for the slower and larger changes.

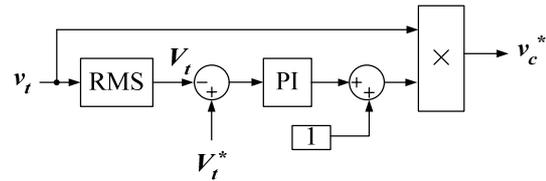


Fig. 5. Control diagram for compensator voltage regulation

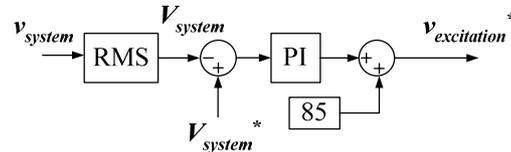


Fig. 6. Control diagram for synchronous condenser voltage regulation

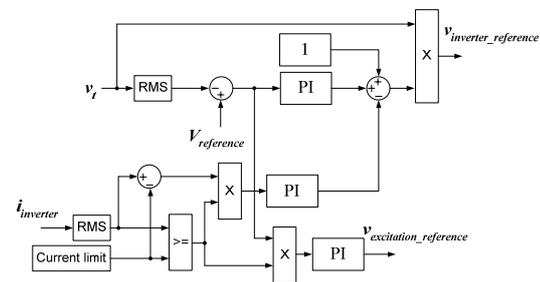


Fig. 7. Integrated control of the compensator and the synchronous condenser

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 and thus reaches the limit of its capability.

## V. Dynamic Voltage Regulation

The parallel voltage regulation system is implemented in a DE system on the local distribution 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). The synchronous condenser can supply around 300 kVar of maximum reactive power, while the compensator can provide about 45 kVar maximum.

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. 8(a)), and the regulated voltage is shown as the blue waveform in Fig. 8(a), which tracks the reference voltage with an error within  $\pm 0.1$  V. The three-phase synchronous condenser current waveforms are shown in Fig. 8(b) together with the phase *a* voltage to show the phase angle between the voltage and the current. The phase *a* current is leading the phase *a* voltage by about  $90^\circ$ , which shows that the synchronous condenser is

supplying reactive 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. 8(c) and 8(d). The reference voltage is increased from 480 V to 482 V (the red waveform in Fig. 8(c)), and decreased from 483 V to 478 V (the red waveform in Fig. 8(d)), respectively. The corresponding system voltage waveforms are the blue waveforms in Figs. 8(c) and 8(d), respectively. The synchronous condenser can regulate the system voltage to a reference level at steady state and dynamically by controlling the amount of reactive power generated (to raise voltage) or consumed (to lower voltage) by the synchronous condenser.

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. 9(a)) instead of the rated value 480 V, which is because of the current limit of the inverter which permits a smaller range of voltage regulation. The regulated voltage is shown as the blue waveform in Fig. 9(a). The three-phase compensator current waveforms are shown in Fig. 9(b) together with the phase *a* voltage to show the phase angle between the voltage and the current. The phase *a* current is leading the phase *a* voltage by about 90°, which shows that the compensator is generating reactive 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 higher DC link voltage to the inverter. The dynamic response of the compensator is shown in Figs. 9(c) and 9(d). The reference voltage is increased from 474.4 V to 475.5 V (the red waveform in Fig. 9(c)), and decreased from 475.3 V to 474.4 V (the red waveform in Fig. 9(d)), respectively. The corresponding PCC voltage waveforms are the blue waveforms in Figs. 9(c) and 9(d), respectively. The compensator can regulate the system voltage to a reference level at steady state and dynamically by controlling the amount of reactive power generated or consumed by the compensator.

The parallel operation of the synchronous condenser and the inverter on the same panel (Fig. 4) was simulated, and the results are shown in Fig. 10. The reference 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. 10(a). 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. 10(b) 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.

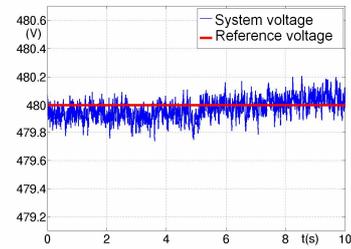


Fig. 8(a)

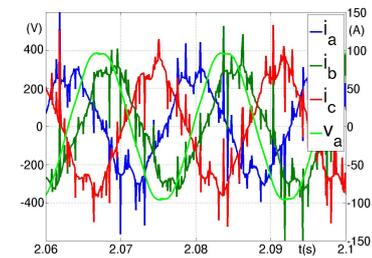


Fig. 8(b)

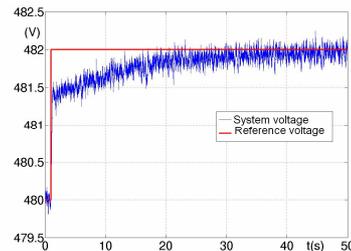


Fig. 8(c)

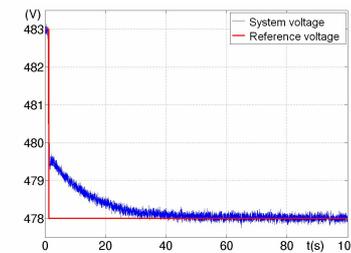


Fig. 8(d)

Figs. 8. Experimental results of synchronous condenser voltage control: (a) Rms line-to-line voltage, (b) Synchronous condenser current, (c) Voltage increase control, (d) Voltage decrease control

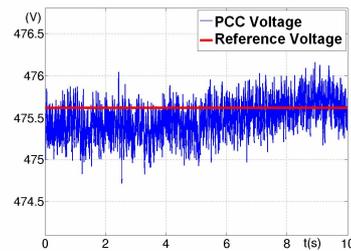


Fig. 9(a)

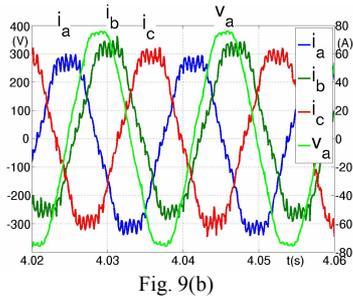


Fig. 9(b)

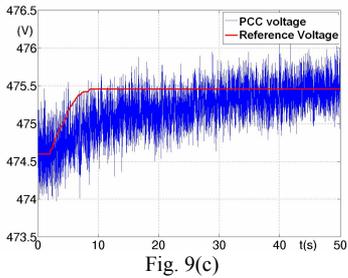


Fig. 9(c)

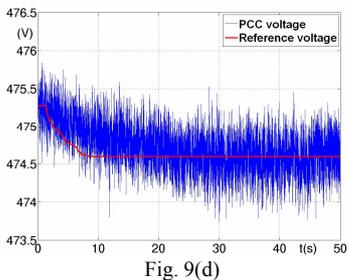


Fig. 9(d)

Figs. 9. Experimental results of compensator voltage control: (a) rms line-to-line voltage, (b) Compensator current, (c) Voltage increase control, (d) Voltage decrease control

After this short current overshoot, the compensator current is controlled below 90 A. At the same time, the synchronous condenser increases the reactive power output which is required by the system to increase the panel A voltage according to the increased reference voltage.

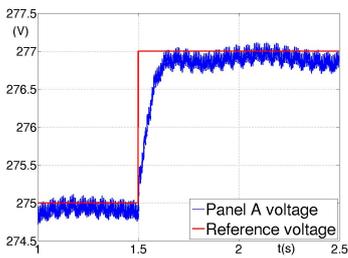


Fig. 10(a)

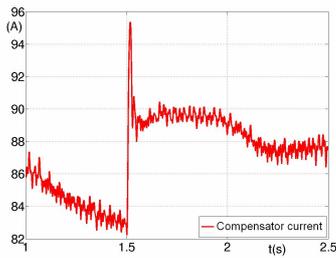


Fig. 10(b)

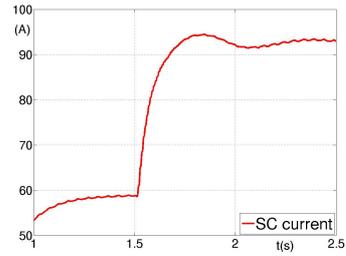


Fig. 10(c)

Figs. 10. Results of parallel operation on the same panel: (a) rms line-to-neutral voltage, (b) Compensator current, (c) Synchronous condenser current

There are two advantages to controlling the synchronous condenser and the compensator on the same voltage panel:

- The two devices share the reactive power requirement for voltage regulation; therefore the voltage regulation capability is improved;
- The devices of different characteristics are operated in parallel together, and these characteristics are combined together to achieve faster overall system dynamic response, and to reduce the capital and operating costs at the same time.

## VI. Interaction of Multiple DEs

The future distribution system should have multiple DEs connected [17]. It is still unclear about the exact interaction of multiple DEs regarding different locations, load levels, control parameters, etc. To explore the interaction of multiple DEs, a series of simulation has been performed as an initial attempt to explore this interesting area. Two DEs, DE1 and DE2 are placed at Bus 2 and 5, respectively, in a test system shown in Fig. 11, which is more complicated than the field experiment configuration at DECC. Here, Bus 5 is away from the source (substation), so it is subject to the biggest voltage drop and identified as the weak bus.

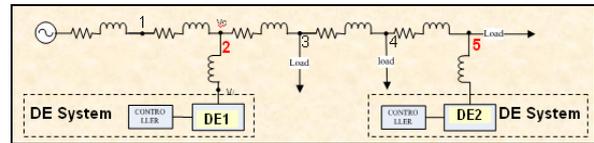


Fig. 11. The one-line diagram of a sample distribution system with two DEs connected

Fig. 12 shows the voltage at Bus 5 under two different scenarios: DE1 placed at different buses (Bus 2 and Bus 1, respectively) while DE2 is always placed at Bus 5. It should be noted that the voltage references are raised to mimic the situation that a voltage regulation is needed to boost the voltage under a sudden disturbance. From Fig. 12, it is apparent that the voltage regulation speed is faster when DE1 is closer to the weak bus than the case that DE1 is placed far away from the load.

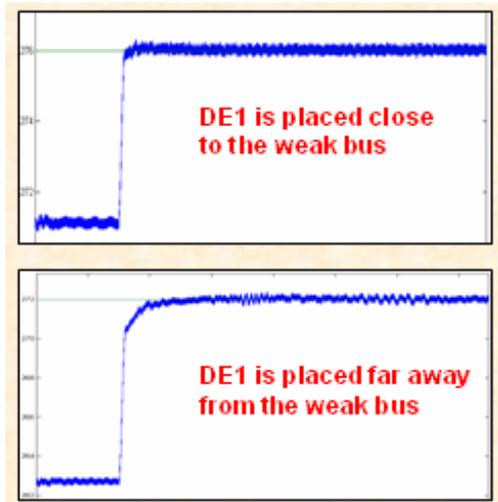


Fig. 12. Voltages at the weak bus (Bus 5) with two DEs installed (DE2 is always at the weak bus)

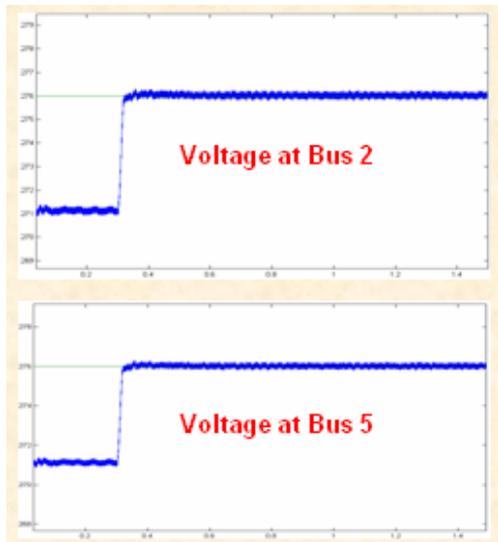


Fig. 13(a)

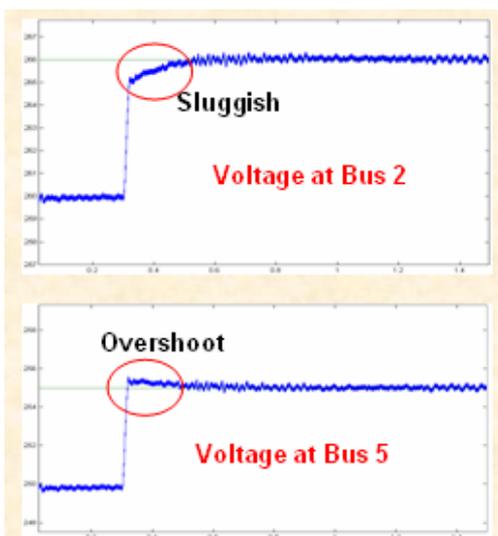


Fig. 13(b)

Figs. 13. Voltages at Buses 2 and 5 under low load and high load at Bus 3: (a) Low Load at Bus 3; (b) High Load at Bus 3

Fig. 13 shows the impact of different load levels to voltage regulating DEs.

In Fig. 13(a), local voltage regulation at Bus 2 and 5 are shown when the load at Bus 3 is low. As shown in the figures, even if the same control parameters and the final voltage references are maintained, it will be sluggish for DE1 to bring its local voltage to the desired reference value while it is interesting to observe a slight overshoot for DE2 to bring its local voltage to the reference value.

Future research is needed to find out the interaction of DEs to identify the optimal control parameter settings with the consideration of many factors such as system configuration, load variation, and so on.

## VII. Conclusions and Future Works

This paper presents the recent research, development and demonstration through simulation and experiment about the possible utilization of the dynamic Var capability from DE to regulate local voltage at the customer side. It applies a generalized definition, extended from traditional definitions, of instantaneous nonactive power such that it works in a real-world distribution system that may have single-phase, non-sinusoidal, unbalanced, and non-periodic waveforms. DE, if equipped with the proposed PI control based on the instantaneous nonactive power theory and the new power electronic converters, has fast dynamic response to effectively compensate voltage sags and other sudden changes in the system. This is shown with simulation and experiment results.

Simulation result also shows the interaction of multiple DE at different locations or under different load levels may have an impact to the control parameter setting for each individual DE control system. This leads to possible further research directions. It will be also necessary to investigate the correlation of voltage changes with respect to the electrical distance between different DE in a larger system. Also, it needs further study to identify an approach to utilize multiple DE to regulate voltage in a decentralized approach with minimum communication to achieve the best transient performance in voltage regulation.

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