Nonactive-Power-Related Ancillary Services Provided by Distributed Energy Resources

Yan Xu, *Member, IEEE*, Leon M. Tolbert, *Senior Member, IEEE*,
D. Tom Rizy, *Senior Member, IEEE*, John D. Kueck, *Senior Member, IEEE*

***Abstract*-- The nonactive-power-related ancillary services provided by distributed energy (DE) resources are categorized by voltage regulation, reactive power compensation, power factor correction, voltage and/or current unbalance compensation, and harmonics compensation. An instantaneous nonactive power theory is adopted to control the DE system to provide these ancillary services. Three control schemes, including nonactive current compensation, power factor correction, and voltage regulation, are developed which can perform one or more of the ancillary services. The control schemes are implemented in a DE system in simulation and experiments. The simulation and the experimental results show that DE is feasible for providing nonactive-power-related ancillary services.**

***Index Terms*-- ancillary services, distributed energy resources, harmonics, nonactive power, reactive power, unbalance, voltage regulation.**

I. INTRODUCTION

THERE are a wide range of ancillary services in the distribution level that can be supplied by distributed energy (DE) resources, including voltage control, regulation, load following, spinning reserve, supplemental reserve (non-spinning), backup supply, harmonic compensation, network stability, seamless transfer, and peak shaving [1]. Previously, others have reported that the power electronics interface between the DE and the utility can provide several ancillary services [2]-[3]. The installation of DE and the provision of ancillary services from DE can have a beneficial impact on transmission stability by supplying reactive power at the distribution level [4]. Research on the following ancillary services is found in the literature: load following [5] and voltage dip compensation in a system with short-circuit fault [6].

These ancillary services can be divided into two major categories: active-power-related ancillary services and nonactive-power-related ancillary services. The nonactive-power-related ancillary services include voltage regulation, reactive power compensation, power factor correction, voltage and/or current unbalance compensation, and harmonics compensation. For DE providing only nonactive-power-related ancillary services, there are usually no extra rating requirements on DE itself for these services, while the power-electronics-based converter interface is required to have higher power and/or current ratings because both active current and nonactive current flow through the interface.

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 [7]. Therefore, there is a large amount of DE resources potentially available for nonactive-power-related ancillary services.

A method to implement the aforementioned nonactive-power-related ancillary services is proposed in this paper. An instantaneous nonactive power theory that is applicable for these ancillary service tasks is used for real-time calculation and control. Three control schemes, nonactive current compensation, power factor correction, and voltage regulation, are developed and implemented in a parallel-connected DE system. The simulation and experimental results are discussed after the theory and control schemes are presented.

II. INSTANTANEOUS NONACTIVE POWER DEFINITION

A new instantaneous nonactive power theory was presented in [8]. In the theory, definitions of instantaneous active current, instantaneous nonactive current, average active power, average nonactive power, apparent active power, and apparent nonactive power are defined. The theory is adopted for the calculation and control of DE ancillary services in this paper. In all the following equations, the lower case t indicates time. All the definitions are functions of time. For a voltage vector $\boldsymbol{v}(t)$ and a current vector $\boldsymbol{i}(t)$ (vectors for voltage and current will be denoted in bold),

$$\boldsymbol{v}(t) = [v_1(t), v_2(t), \ldots, v_m(t)]^T, \quad (1)$$

$$\boldsymbol{i}(t) = [i_1(t), i_2(t), \ldots, i_m(t)]^T, \quad (2)$$

Y. Xu, L. M. Tolbert, D. T. Rizy, and J. D. Kueck are with Oak Ridge National Laboratory, Oak Ridge, TN 37831 (e-mail: xuy3@ornl.gov, tolbertlm@ornl.gov, rizydt@ornl.gov, kueckjd@ornl.gov).

L. M. Tolbert is with The University of Tennessee, Knoxville, TN 37996-2100 (e-mail: tolbert@utk.edu).

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where m is the number of phases. The instantaneous power $p(t)$ is defined by

$$p(t) = \boldsymbol{v}^T(t)\boldsymbol{i}(t) = \sum_{k=1}^{m} v_k(t) i_k(t) \,. \tag{3}$$

The average power $P(t)$ is defined as the average value of $p(t)$ over the averaging interval $[t\text{-}T_c, t]$,

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

$P(t)$ is an instantaneous value, i.e., a function of time. And all the other definitions in the theory are also instantaneous values. τ is the integral variable. The integral is from time $t\text{-}T_c$ to the present time t. The averaging interval T_c can be chosen from zero to infinity depending on the compensation objectives, and for different T_c, the resulting active current and nonactive current will have different characteristics as shown in Table I. The choice of T_c was discussed in detail in [8].

The instantaneous active current $i_a(t)$ and instantaneous nonactive current $i_n(t)$, are defined by, respectively,

$$\boldsymbol{i}_{\boldsymbol{a}}(t) = \frac{P(t)}{V_p^2(t)} \boldsymbol{v}_{\boldsymbol{p}}(t) \,, \tag{5}$$

$$\boldsymbol{i}_{\boldsymbol{n}}(t) = \boldsymbol{i}(t) - \boldsymbol{i}_{\boldsymbol{a}}(t) \,. \tag{6}$$

The voltage $\boldsymbol{v}_{\boldsymbol{p}}(t)$ is the reference voltage, which is chosen based on the characteristics of the system and the desired compensation results as shown in Table I [10]. $V_p(t)$ is the rms value of the reference voltage $\boldsymbol{v}_{\boldsymbol{p}}(t)$, i.e.,

$$V_p(t) = \sqrt{\frac{1}{T_c} \int_{t-T_c}^{t} \boldsymbol{v}_{\boldsymbol{p}}^T(\tau) \boldsymbol{v}_{\boldsymbol{p}}(\tau) d\tau} \cdot \tag{7}$$

Based on the above definitions for $\boldsymbol{i}_{\boldsymbol{a}}(t)$ and $\boldsymbol{i}_{\boldsymbol{n}}(t)$, the instantaneous active power $p_a(t)$ and instantaneous nonactive power $p_n(t)$ are defined by, respectively,

$$p_a(t) = \boldsymbol{v}^T(t)\boldsymbol{i}_{\boldsymbol{a}}(t) = \sum_{k=1}^{m} v_k(t) i_{ak}(t) \,, \tag{8}$$

$$p_n(t) = \boldsymbol{v}^T(t)\boldsymbol{i}_{\boldsymbol{n}}(t) = \sum_{k=1}^{m} v_k(t) i_{nk}(t) \,. \tag{9}$$

The average active power $P_a(t)$ is defined as the average value of $p_a(t)$ over the averaging interval $[t\text{-}T_c, t]$,

$$P_a(t) = \frac{1}{T_c} \int_{t-T_c}^{t} p_a(\tau) d\tau \cdot \tag{10}$$

The average nonactive power $P_n(t)$ is defined as the average value of $p_n(t)$ over $[t\text{-}T_c, t]$,

$$P_n(t) = \frac{1}{T_c} \int_{t-T_c}^{t} p_n(\tau) d\tau \cdot \tag{11}$$

TABLE I. SUMMARY OF THE PARAMETERS IN THE NONACTIVE POWER THEORY

Load Current $i(t)$	$\boldsymbol{v_p}$	$\boldsymbol{T_c}$	**Active Current $i_a(t)$**
Three-phase fundamental nonactive current	$\boldsymbol{v}$	0	Unity *pf* and pure fundamental sine wave
		$T/2$	
Single-phase or multi-phase fundamental nonactive current and harmonic current	$\boldsymbol{v}$	$T/2$	Unity *pf* and same shape of $\boldsymbol{v}$
	$\boldsymbol{v}_f$	$T/2$	Pure sine wave and in phase with $\boldsymbol{v}_{f+}$.
	$\boldsymbol{v}$	0	Instantaneous current
Sub-harmonic current	$\boldsymbol{v}_f$	nT	Pure fundamental sine wave or smoothed sine wave
Non-periodic current	$\boldsymbol{v}_f$	nT	Smoothed and near sine wave
Non-periodic current	$\boldsymbol{v}$	$T_c \to \infty$	In phase with $\boldsymbol{v}$ with unity *pf*
Unbalanced voltage	$\boldsymbol{v}_{f+}$	$T/2$	Balanced and sinusoidal current

Notes: Both $\boldsymbol{v}(t)$ and $\boldsymbol{i}(t)$ are distorted except in Case 1.
$\boldsymbol{v}_f$ is the fundamental component of $\boldsymbol{v}$.
$\boldsymbol{v}_{f+}$ is the positive sequence of the fundamental component of $\boldsymbol{v}$.

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

$$V(t) = \sqrt{\frac{1}{T_c} \int_{t-T_c}^{t} \boldsymbol{v}^T(\tau) \boldsymbol{v}(\tau) d\tau} \,, \tag{12}$$

$$I(t) = \sqrt{\frac{1}{T_c} \int_{t-T_c}^{t} \boldsymbol{i}^T(\tau) \boldsymbol{i}(\tau) d\tau} \cdot \tag{13}$$

The rms values of the instantaneous active current $\boldsymbol{i}_{\boldsymbol{a}}(t)$ and the instantaneous nonactive current $\boldsymbol{i}_{\boldsymbol{n}}(t)$ are

$$I_a(t) = \sqrt{\frac{1}{T_c} \int_{t-T_c}^{t} \boldsymbol{i}_{\boldsymbol{a}}^T(\tau) \boldsymbol{i}_{\boldsymbol{a}}(\tau) d\tau} \,, \tag{14}$$

$$I_n(t) = \sqrt{\frac{1}{T_c} \int_{t-T_c}^{t} \boldsymbol{i}_{\boldsymbol{n}}^T(\tau) \boldsymbol{i}_{\boldsymbol{n}}(\tau) d\tau} \cdot \tag{15}$$

The apparent power $S(t)$, the apparent active power $P_p(t)$, and the apparent nonactive power $Q(t)$ are defined by

$$S(t) = V(t) I(t) \,, \tag{16}$$

$$P_p(t) = V(t) I_a(t) \,, \tag{17}$$

$$Q(t) = V(t) I_n(t) \,. \tag{18}$$

Table 1 shows the different combinations of $\boldsymbol{v_p}$ and T_c for different loads, and the corresponding compensation results are shown in the last column. The choice of the reference voltage influences the active current. A pure fundamental sinusoidal active current can be achieved by choosing the positive sequence component of the fundamental voltage. For a system with fundamental component and/or harmonics, the

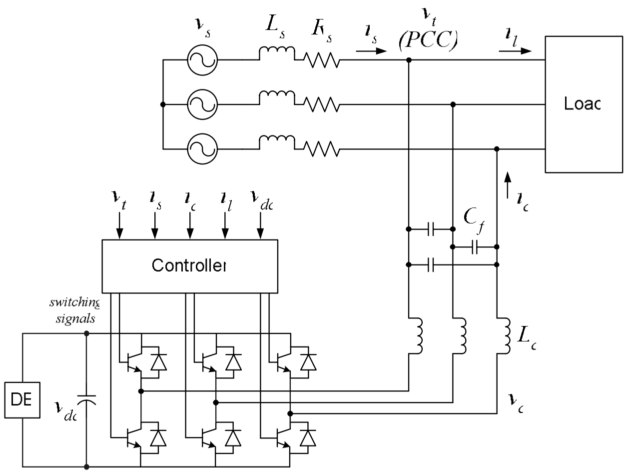


Fig. 1. Parallel connection of a DE with power electronics converter interface.

nonactive current component can be completely eliminated by choosing the averaging interval to be $T/2$.

The definitions in this instantaneous nonactive power theory are all consistent with the standard definitions for three-phase fundamental sinusoidal systems [9] and are valid in various cases, such as single-phase systems, non-sinusoidal systems, and non-periodic systems as well, by changing the averaging interval T_c and the reference voltage $\boldsymbol{v}_p(t)$. In this theory, all the definitions are instantaneous values; therefore, they are suitable for real-time control and provide advantages for the design of control schemes, which will be discussed in the next section. The compensation-based definition proposed in this paper is a generalized one that can be made applicable to most any parallel-connected compensator and improves on some earlier definitions such as the one found in [11].

III. NONACTIVE-POWER-RELATED ANCILLARY SERVICES AND CONTROL SCHEMES

The nonactive-power-related ancillary services from DE include nonactive power compensation, power factor correction, voltage and/or current unbalance compensation, harmonics compensation, and voltage regulation. The system configuration and control schemes for providing these ancillary services are discussed in this section.

A parallel-connected DE with power electronics converter interface is shown in Fig. 1. This parallel configuration will be referred to as a compensator, because nonactive power services from DE are the main topic in this paper, and DE will be operated as a nonactive power compensator. For each different task, the required variables are measured and fed to the controller for calculation and control purposes.

A significant advantage of this configuration is that it is applicable to all the nonactive-power-related ancillary services from DE, which decreases the capital costs. By using different software (calculation and control), the compensator can perform different tasks.

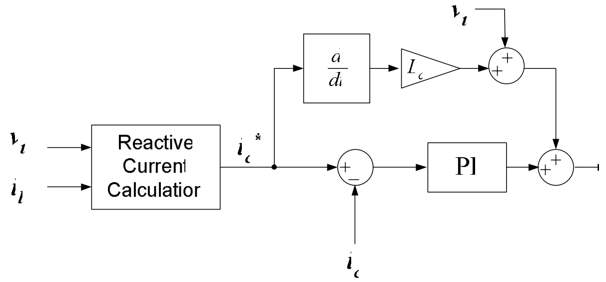


Fig. 2. Control diagram for nonactive current compensation.

A. Nonactive Current Compensation

Three of the ancillary services (nonactive power compensation, current harmonics compensation, and the current unbalance) are achieved by controlling the current of the compensator. The compensator current is controlled so that the current from the utility (source current) is fundamental sinusoidal, unity power factor (in phase with the point of common coupling (PCC) voltage), and balanced. Therefore in control design, they can all be implemented as a single category termed nonactive current compensation.

The load current may contain fundamental nonactive power components and/or harmonics. In a three-phase system, the currents of the three phases may be unbalanced. The goal of the nonactive current compensation is to let the compensator provide the nonactive current component, harmonics, and the unbalance component in the load current so that the utility current is fundamental sinusoidal, unity power factor, and balanced.

The point of common coupling (PCC) voltage $\boldsymbol{v}_t(t)$, the load current $\boldsymbol{i}_l(t)$, and the compensator current $\boldsymbol{i}_c(t)$ are measured. The reference current of the compensator $\boldsymbol{i}_c^*(t)$ is calculated using the instantaneous nonactive power theory in the previous section. A feedforward controller is designed in (19), where K_P and K_I are the proportional and integral gains of the PI controller. PWM switching signals are generated from the reference of the compensator $\boldsymbol{v}_c^*(t)$ and drive the switches in the converter. The control diagram is shown in Fig. 2.

$$\boldsymbol{v}_c^*(t) = \boldsymbol{v}_t(t) + L_c\frac{d\boldsymbol{i}_c^*(t)}{dt} + K_P(\boldsymbol{i}_c^*(t) - \boldsymbol{i}_c(t)) + K_I\int_0^t (\boldsymbol{i}_c^*(t) - \boldsymbol{i}_c(t))dt \tag{19}$$

Because the DE is connected on the DC side of the inverter, the DC link voltage is maintained by the DE, and no DC link voltage control is required.

B. Power Factor Correction

Some utilities penalize customers with low power factors, which urges the customers to install power factor correction devices to improve their power factor within the required limits.

In this compensation mode, the PCC voltage $\boldsymbol{v}_t(t)$ and the source current $\boldsymbol{i}_s(t)$ are measured, and the power factor pf is

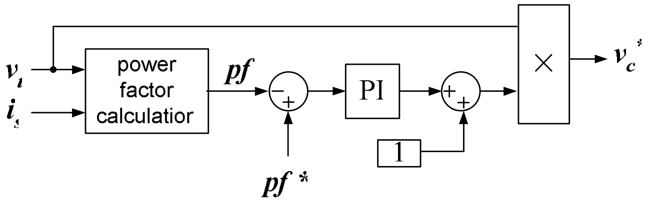


Fig. 3. Control diagram for power factor compensation.

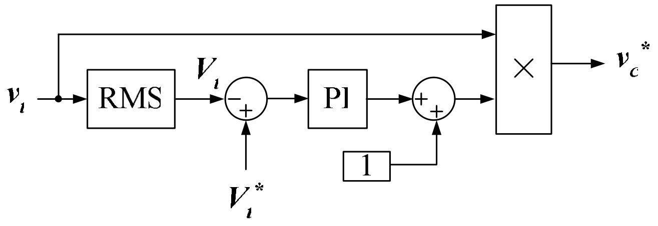


Fig. 4. Control diagram for voltage regulation.

calculated, which is compared to the reference power factor pf^*.

The compensator is controlled so that only nonactive power is generated or consumed by the compensator. The output voltage of the compensator $\boldsymbol{v}_c(t)$ is in phase with the PCC voltage and the magnitude is controlled. If the magnitude of the compensator voltage is larger than the PCC voltage, nonactive power is generated by the compensator and supplied to the power system. If the magnitude of the compensator voltage is smaller than the PCC voltage, the nonactive power is consumed by the compensator. This is utilized in the control of power factor correction and the voltage regulation in the next subsection.

The error between the actual power factor and the reference power factor is fed to a PI controller, and the output of the PI controller modifies the magnitude of the compensator output voltage reference $\boldsymbol{v}_c^*$. Since $\boldsymbol{v}_c^*$ is in phase with the PCC voltage, there is only nonactive power exchange between the compensator and the system. The power factor correction control is shown in (20), and the control diagram is illustrated in Fig. 3.

$$\boldsymbol{v}_c^*(t) = \boldsymbol{v}_t(t)[1 + K_P(pf^*(t) - pf(t)) + K_I\int_0^t (pf^*(t) - pf(t))dt] \tag{20}$$

C. Voltage Regulation

Most of the voltage fluctuation in the power system is because of 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 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. As shown in Fig. 4, 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. Similar to the control strategy in the previous subsection, the magnitude of the compensator output voltage is controlled so that the PCC voltage is kept at a given level. The control scheme is shown in (21).

$$\boldsymbol{v}_c^*(t) = \boldsymbol{v}_t(t)[1 + K_P(V_t^*(t) - V_t(t)) + K_I\int_0^t (V_t^*(t) - V_t(t))dt] \tag{21}$$

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 this paper.

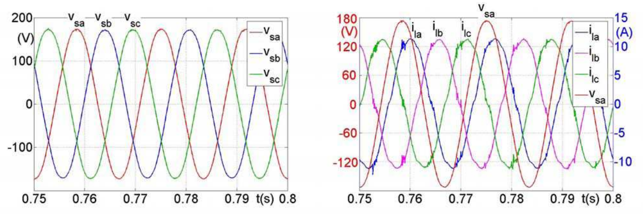
The voltage unbalance compensation is to provide nonactive power to the system to regulate the voltage. The rms value of each phase is controlled independently so that the three-phase rms values will be controlled to an equal value, i.e., balanced. Therefore, neither the nonactive power provided by the compensator nor the compensator current is equal in each phase.

IV. EXPERIMENTAL AND SIMULATION RESULTS

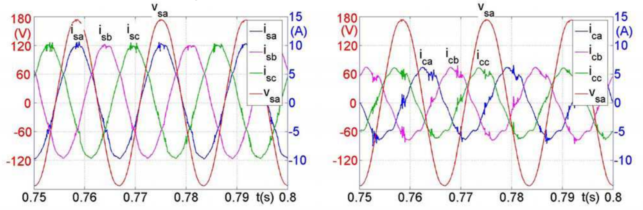
Both experimental and simulation results of the nonactive-power-related ancillary services are presented.

A. Nonactive Current Compensation

As indicated above, the goal of nonactive current compensation is to control the compensator current so that the source current is fundamental sinusoidal with a unity power factor. This goal can be achieved despite the PCC voltage, i.e., the PCC voltage can have harmonics and/or can be unbalanced. If the PCC voltage is not pure fundamental

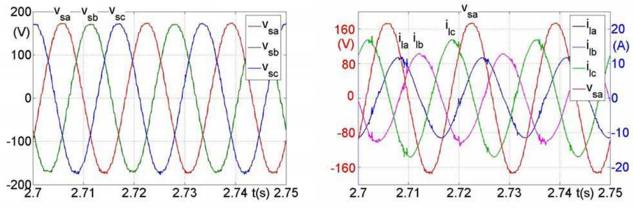


(a) PCC voltage (b) Load current

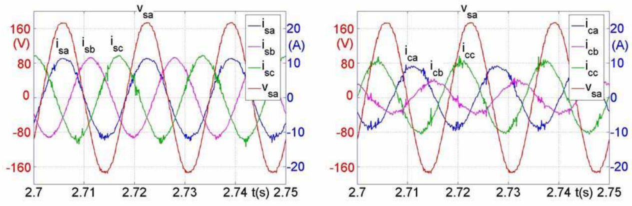


(c) Source current (d) Compensator current

Fig. 5. Experimental results of fundamental nonactive power compensation.

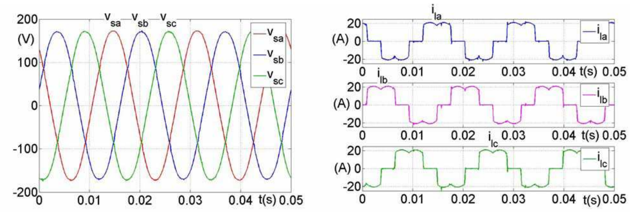


(a) PCC voltage (b) Load current

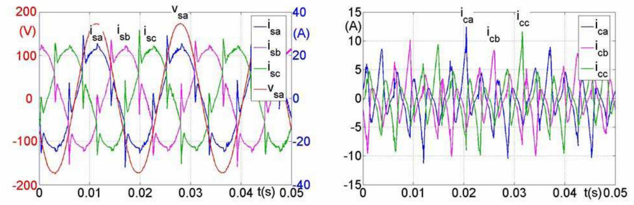


(c) Source current (d) Compensator current

Fig. 6. Experimental results of unbalanced current compensation.



(a) PCC voltage (b) Load current



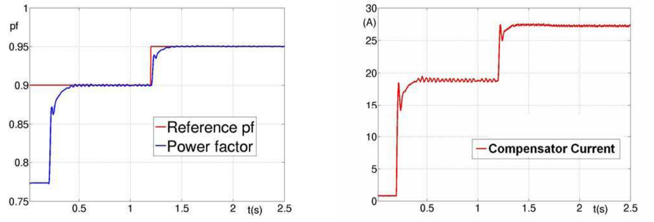
(c) Source current (d) Compensator current

Fig. 7. Experimental results of diode rectifier load compensation.

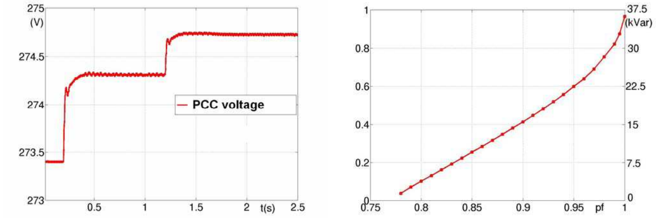
sinusoidal and balanced, the reference voltage $\boldsymbol{v}_p(t)$ in the instantaneous nonactive power theory (5) is chosen as the fundamental positive sequence of the PCC voltage, which results in the desired source current. Different load cases, i.e., fundamental nonactive power load, unbalanced load, and diode-rectifier load (harmonics load), are tested in the experiments.

The experiments in this section are performed in a three-phase system with a line-to-neutral rms voltage of 120 V. A diode rectifier, a balanced *RL* load, and an unbalanced *RL* load are used as loads in different testes. A Powerex POW-R-PAK$^{\text{TM}}$ configurable IGBT based three-phase inverter is used as the interface between the DE and the utility in the experiment. Danfysik ULTRASTAB$^{®}$ 866 current transducers are used for measuring the load current and the compensator current. LEM CV 3-500 voltage transducers are used for measuring the PCC voltage and the inverter DC link voltage. dSPACE, a real-time control platform, is used to implement the Simulink controller on hardware to perform the real-time control of the compensator.

The experimental results of fundamental nonactive power load current compensation are shown in Fig. 5. The three-phase PCC voltage is sinusoidal and balanced as shown in Fig. 5a. The load is a balanced *RL* load. The three-phase load current is shown in Fig. 5b together with the phase *a* PCC voltage. The load current is inductive and lagging the voltage. The source current after compensation is shown in Fig. 5c; it is in phase with the voltage, so unity power factor is achieved. The compensator current is also illustrated in Fig. 5d with the phase *a* voltage to demonstrate that the compensator current is about 90º out of phase with the voltage.



(a) Power factor (b) Compensator current



(c) Source current (d) Power factor vs. nonactive power

Fig. 8. Power factor correction (simulation).

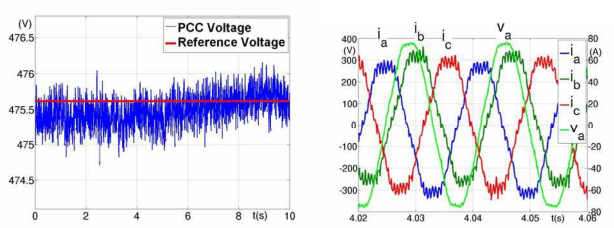
The experimental results of unbalanced load compensation are shown Fig. 6. The voltage is sinusoidal and balanced as shown in Fig. 6a. The load in this case is an unbalanced *RL* load. The load current shown in Fig. 6b is unbalanced and lagging the voltage. After compensation, as shown in Fig. 6c, the source current is balanced and in phase with the voltage. The unbalanced and out of phase compensator currents are shown in Fig. 6d.

Fig. 7 shows the experimental results of the diode-rectifier load compensation. Again the voltage is sinusoidal and balanced as shown in Fig. 7a. In Fig. 7b, there are harmonics in the load current. After compensation, as shown in Fig. 7c, the source current is nearly sinusoidal. The spikes in the source current is because of the high *di/dt* in the load current which requires high DC link voltage for the complete compensation. The source current is also balanced and near-unity power factor. In Fig. 7d, the compensator current contains most of the nonactive component of the load current.

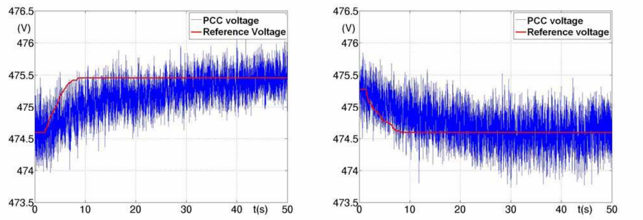
B. Power Factor Correction

An *RL* load is used in this case to show the power factor correction. The power factor of the load is 0.77, and the load nonactive power is 37.5 kvar.

The compensator provides some or part of the load nonactive power so that the source current power factor is increased. Fig. 8a shows the source current power factor before and after compensation. The red waveform is the reference power factor, and the blue waveform is the actual power factor. There is no compensation from t = 0 s to 0.2 s;



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



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

Fig. 9. Experimental results of voltage control.

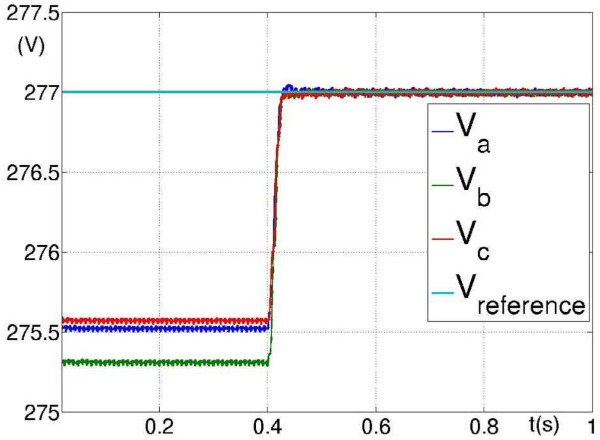


Fig. 10. Voltage unbalance compensation (simulation).

so the source current power factor is 0.77 as shown in Fig. 8a; the rms value of the compensator current is nearly zero as shown in Fig. 8b, and the rms value of PCC voltage is 273.4 V as shown in Fig. 8c. From $t = 0.2$ s to 1.2 s, the source current power factor is controlled at 0.9. The actual power factor, the rms value of the compensator current, and the rms value of the PCC voltage are shown in Figs. 8a, 8b, and 8c, respectively. From $t = 1.2$ s to 2.5 s, the source current power factor is controlled at 0.95. More compensator current is injected into the system, and the PCC voltage is increased correspondingly.

Fig. 8d shows the curve of the source current power factor versus the compensator nonactive power (with the load nonactive power as per unit). The power factor is controlled at different values, from 0.77 to 1.0, and the required nonactive power from the compensator varies correspondingly. The plot shows that the relationship between the power factor (horizontal axis) and the nonactive power (vertical axis) is nearly linear when the source current power is controlled lower than 0.95. However, the nonactive power required from the compensator increases dramatically if the source current power factor is controlled above 0.95. If the source current power factor is controlled at 0.95, 22.5 kvar nonactive power is required from the compensator, which is 60% of the total load nonactive power, while if the source current power factor is controlled at 1.0, 37.5 kvar (i.e., 100% of the load nonactive power) is required. To increase the power factor from 0.77 to 0.95, the compensator needs to provide 60% of the load nonactive power, while to increase the power factor from 0.95 to 1.0, the compensator needs to provide 67.5% more nonactive power, i.e., 67.5% higher current rating for the compensator than the 0.95 power factor case.

C. Voltage Regulation

By generating or consuming nonactive power, the compensator can regulate the PCC voltage. If the load is heavy, and the voltage is lower than the rated voltage, the compensator generates nonactive power so that the voltage is boosted. If the load is light, and the voltage is higher than the rated voltage, nonactive power is consumed by the compensator so that the voltage is decreased.

The voltage unbalance can be a result of load unbalance or a voltage source unbalance. From the standpoint of the compensator, the voltage source unbalance can be caused by other loads in the system or the voltage source itself. If the voltage unbalance is caused by the unbalanced load, the voltage will be balanced if the nonactive current compensation presented in subsection IV.A is performed. In this case, the source current is balanced after the nonactive current compensation, therefore from the standpoint of the utility, a balanced current is drawn and the PCC voltage is balanced.

If the voltage unbalance is caused by some other devices in the system, a voltage regulation method must be used to balance the voltage and control the magnitude of the voltage.

The experimental setup of voltage regulation in this section is similar to the one in the previous section, with the difference of the system voltage. The experiments are performed in a three-phase system with a line-to-neutral rms voltage of 277 V. The experimental results of the voltage regulation are illustrated in Fig. 9. The rms value of the line-to-line voltage is 473.7 V before compensation. In Fig. 9a, the red waveform is the reference voltage, which is 475.6 V, and the blue waveform is the actual voltage. The instantaneous compensator current is shown in Fig. 9b together with the phase *a* voltage. The compensator current is about 90º leading the voltage, i.e., the nonactive power is flowing from the compensator to the system. Because of the current rating limit of the inverter, the voltage regulation range in this case is about 2 V.

Figs. 9c and 9d show the dynamic response of the voltage regulation control. The reference voltage is increased (Fig. 9c) and decreased (Fig. 9d) about 1 V, and the blue waveforms show the actual voltage tracking the reference voltage.

The voltage unbalance compensation is simulated, and the simulation results are shown in Fig. 10. The rms values of the three phase voltages and the reference voltage waveforms are shown in Fig 10. There is no voltage regulation from $t = 0$ s to $t = 0.4$ s. The three phase voltages are unbalanced and lower than the rating (line-to-neutral rms value 277 V). From $t = 0.4$ s to $t = 1$ s, the voltage regulation is performed. The three phase voltages are balanced and the magnitudes are boosted to 277 V.

V. CONCLUSIONS

The nonactive-power-related ancillary services provided by distributed energy resources (DE) are categorized, which are voltage regulation, reactive power compensation, power factor correction, voltage and/or current unbalance compensation, and harmonics compensation. An instantaneous nonactive power theory is adopted into the DE system for these ancillary services. Three control schemes, including nonactive current compensation, power factor correction, and voltage regulation, are developed which can perform one or more of the ancillary services. The control schemes are implemented in a DE system in simulation and experiments. The simulation and the experimental results show that DE is feasible for nonactive-power-related ancillary services.

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VII. BIOGRAPHIES

Yan Xu (S 2002 – M 2007) received the B.E. in 1995 from Shanghai Jiaotong University, Shanghai, China, majoring in Electric Power Engineering, M.S. in 2001 from North China Electric Power University, Beijing, China, majoring in Electric Power Engineering, and Ph.D. in 2006 from The University of Tennessee, Knoxville, Tennessee, majoring in Electrical Engineering.

She worked in Anhui Electric Power Company Ma'anshan Branch, China from 1995 to 1998. She was an engineer in the Power Dispatch Department. She worked on the SCADA system and contributed to several SCADA projects in the distributions and dispatch center. She also worked at Beijing Pengfa Xingguang Power Electronics Co. Ltd. from August 2001 to December 2001 as a research and development engineer. She presently is a postdoctoral researcher at Oak Ridge National Laboratory.

Leon M. Tolbert (S 1989 – M 1991 – SM 1998) received the B.E.E., M.S., and Ph.D. in Electrical Engineering from the Georgia Institute of Technology, Atlanta, Georgia.

Since 1991, he worked on several electrical distribution projects at the three U.S. Department of Energy plants in Oak Ridge, Tennessee. In 1999, he joined the Department of Electrical and Computer Engineering at the University of Tennessee, Knoxville, where he is presently an associate professor. He is an adjunct participant at the Oak Ridge National Laboratory. He does research in the areas of electric power conversion for distributed energy sources, reactive power compensation, multilevel converters, hybrid electric vehicles, and application of SiC power electronics.

Dr. Tolbert is a registered Professional Engineer in the state of Tennessee. He was the chair of the Education Activities Committee of the IEEE Power Electronics Society from 2003-2006. He is the recipient of a National Science Foundation CAREER Award and the 2001 IEEE Industry Applications Society Outstanding Young Member Award.

D. Tom Rizy (SM – 87) is a senior research power systems engineer at Oak Ridge National Laboratory and a reviewer for the IEEE Transactions on Power Systems. He has over 28 years experience in power systems R&D and received his MSEE and BSEE from Virginia Tech and the University of Virginia, respectively. He is the coauthor of the book entitled "Automating Electric Utility Distribution Systems: The Athens Automation and Control Experiment" published by Prentice Hall. He is a co-recipient of the IEEE Prize Paper Award for the IEEE Transactions paper entitled "Adaptive Transmission Relaying Concepts for Improved Performance".

John D. Kueck (SM – 98) has a BS in Physics and an MS in Electrical Engineering. He has been an electrical engineer with Sargent and Lundy Engineers, Combustion Engineering, and Carolina Power and Light Co. From 1992 to present, he has been a researcher at the Oak Ridge National Laboratory in issues regarding grid reliability, restructuring, and distributed energy.