Active Power and Nonactive Power Control of Distributed Energy Resources

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***Abstract* -- Distributed energy resources (DE) have been widely used in the power systems to supply active power, and most of the present DE resources are operated with limited or without nonactive power capability. This paper shows that with a slight modification in hardware configuration and a small boost in the power ratings, as well as proper implementation of control strategies, a DE system with a power electronics converter interface can provide active power and nonactive power simultaneously and independently. A DE can provide dynamic voltage regulation to the local bus because of its nonactive power capability. Furthermore, the proposed DE control method in this paper can effectively compensate the unbalance in the local voltage. The system requirements such as the inverter current rating and the dc voltage rating are discussed. The analysis of the system requirements to provide nonactive power shows that it is cost-effective to have DE provide voltage regulation.**

***Index Terms* – active power, distributed energy resources, dynamic voltage regulation, nonactive power, unbalance compensation.**

I. Introduction

VOLTAGES are regulated at certain levels throughout the power systems, and such voltage regulation is closely related to nonactive (reactive) power generation and nonactive power flow. STATCOM is one of the FACTS devices that can provide dynamic nonactive power to regulate voltage and to improve power quality, such as mitigation of voltage flicker and fluctuation and improvement in transient voltage stability. Furthermore, its functions can be enhanced with some energy storage. For example, the installation of a STATCOM with energy storage near or at wind power generation can reduce voltage flicker and remove the wind speed fluctuations [1]. Another example is mitigation of the voltage fluctuation generated by arc furnaces using a STATCOM enhanced with energy storage [2]. When grid connected, distributed energy resources (DE) can provide nonactive power in the power systems to provide local voltage regulation near the load. With their power electronics interfaces, they are basically equipment-ready to provide nonactive power services such as local voltage regulation and power quality improvement. The system configuration and the control strategies are very similar to a STATCOM with energy storage.

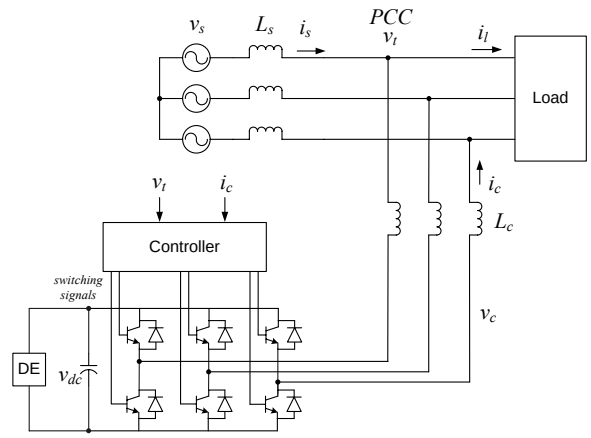

Fig. 1. Parallel connection of a DE with power electronics converter

Both the active power and the nonactive power flow are controlled in a STATCOM with energy storage and a DE with voltage regulation capability. A widely-used control scheme is to convert the three-phase ac system to a two-phase system using the Park Transformation and then convert to a two-phase dc system [3-5]. After the conversions, the active and nonactive components are dc and are decoupled; therefore, the active power and the nonactive power can be controlled separately. Another control method is to use genetic and evolutionary algorithms [6].

Instantaneous definitions of active power, nonactive power, active current, nonactive current, voltage rms value, and current rms value are presented in this paper, which provides the basis of real-time control of DE. A new control scheme is proposed in this paper to control the active power and nonactive power of the DE independently. The control of each phase is also independent of each other so that the control can be used to compensate for unbalance due to the system and/or load.

II. Active and Nonactive Power Control Scheme

Most of the distributed energy resources are dc power sources, such as photovoltaic, some wind turbines, and fuel cells. An interface between the DE and the power grid is needed to connect it to the grid, which converts dc power from the DE to ac power with appropriate waveform, frequency, magnitude, and phase angle. Furthermore, the interface maintains the DE in operation, and controls its power output. A typical DE system with a power electronics interface is shown in Fig. 1. The inverter converts the dc power from the

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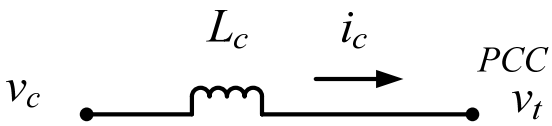


Fig. 2. Simplified circuit diagram of a parallel connected DE.

DE to ac power, and is connected in parallel with the load through a coupling conductor L_c. The rest of the system is simplified as an infinite utility voltage source with a system impedance of $j\omega L_s$, neglecting the resistance. The inverter is connected at the point of common coupling (PCC), and the PCC voltage is denoted as v_t. The PCC voltage v_t and the inverter current i_c are measured and provided to the controller. The output active power and nonactive power of the DE can be controlled independently. The active power can be controlled in active power mode (the DE output active power is controlled at a reference level), active current mode (the DE output active current is controlled at a reference level), and power factor mode (the DE power factor is controlled at a reference level). The nonactive power can be controlled in nonactive power mode (the DE output nonactive power is controlled at a reference level), voltage regulation mode (the PCC voltage is controlled at a reference level), and power factor mode (the DE power factor is controlled at a reference level). After calculation, the PWM switching signals are given to the inverter gate drive to turn on or off the power electronics switches.

An instantaneous nonactive power theory has been proposed in [7], which provides the basis of real-time control of the active power and nonactive power in various systems. The DE system shown in Fig. 1 can be simplified as the single-phase equivalent circuit in Fig. 2, assuming that the three-phase system is balanced. Let

$$v_t(t) = \sqrt{2}V_t \cos(\omega t) \tag{1}$$

denote the instantaneous PCC voltage, and

$$v_c(t) = \sqrt{2}V_c \cos(\omega t + \alpha) \tag{2}$$

denote the instantaneous inverter output voltage (harmonics are neglected) respectively where α is the phase angle of $v_c(t)$ relative to the PCC voltage. The rms values of $v_t(t)$ and $v_c(t)$ are shown in (3) and (4), respectively.

$$V_t(t) = \sqrt{\frac{2}{T}\int_{t-\frac{T}{2}}^{t} v_t^2(\tau)d\tau} = V_t \tag{3}$$

$$V_c(t) = \sqrt{\frac{2}{T}\int_{t-\frac{T}{2}}^{t} v_c^2(\tau)d\tau} = V_c \tag{4}$$

where $T/2$ is one half of the period of the voltage. It is the averaging interval used in this paper. In the instantaneous nonactive power theory [7], the averaging interval can be different values depending on the system characteristics. In a sinusoidal system with period T, the averaging interval is usually chosen as $kT/2$, where k is a positive integer. In this paper, k is chosen as 1, which is the shortest averaging interval so that a fast transient response can be achieved.

The current from the DE to the utility is denoted as $i_c(t)$:

$$i_c(t) = \frac{\sqrt{2}}{\omega L_c}[V_c \sin(\omega t + \alpha) - V_t \sin(\omega t)] \tag{5}$$

where α is the phase angle between the PCC voltage $v_t(t)$ and the inverter current $i_c(t)$.

The rms value of $i_c(t)$ is

$$I_c(t) = \sqrt{\frac{2}{T}\int_{t-\frac{T}{2}}^{t} i_c^2(\tau)d\tau} = \frac{1}{\omega L_c}\sqrt{V_t^2 + V_c^2 - 2V_tV_c\cos\alpha} \tag{6}$$

The average power of DE is denoted as $P(t)$:

$$P(t) = \frac{2}{T}\int_{t-\frac{T}{2}}^{t} v_t(\tau)i_c(\tau)d\tau = \frac{V_tV_c}{\omega L_c}\sin\alpha \tag{7}$$

The instantaneous active current component of the inverter current $i_c(t)$ is defined as,

$$i_{ca}(t) = \frac{P(t)}{V_t^2(t)} i_c(t) \tag{8}$$

The instantaneous nonactive power is defined as,

$$i_{cn}(t) = i_c(t) - i_{ca}(t) \tag{9}$$

The $i_{ca}(t)$ and $i_{cn}(t)$ are the active component and the nonactive component of the inverter current $i_c(t)$. By controlling these two current components, the active power and the nonactive power of the DE can be controlled independently.

The rms values of $i_{ca}(t)$ and $i_{cn}(t)$ are defined as $I_{ca}(t)$ and $I_{cn}(t)$, respectively.

$$I_{ca}(t) = \sqrt{\frac{2}{T}\int_{t-\frac{T}{2}}^{t} i_{ca}^2(\tau)d\tau} \tag{10}$$

$$I_{cn}(t) = \sqrt{\frac{2}{T}\int_{t-\frac{T}{2}}^{t} i_{cn}^2(\tau)d\tau} \tag{11}$$

The apparent power $S(t)$ and the average nonactive power $Q(t)$ of the DE are:

$$S(t) = V_t(t)I_c(t) = \frac{V_t}{\omega L_c}\sqrt{V_t^2 + V_c^2 - 2V_tV_c\cos\alpha} \tag{12}$$

$$\begin{aligned} Q(t) = V_t(t)I_{cn}(t) &= \sqrt{S^2(t) - P^2(t)} \\ &= \frac{V_t}{\omega L_c}(V_c\cos\alpha - V_t) \end{aligned} \tag{13}$$

where $Q(t)$ is defined as positive if the inverter injects nonactive power to the utility, and negative if the inverter absorbs nonactive power from the utility. $P(t)$ and $Q(t)$ in (12) and (13) can be approximated by the first terms of the Taylor series if the angle α is small, as shown in (14) and (15),

$$P(t) \approx \frac{V_tV_c}{\omega L_c}\alpha \tag{14}$$

$$Q(t) \approx \frac{V_t}{\omega L_c}(V_t - V_c) \tag{15}$$

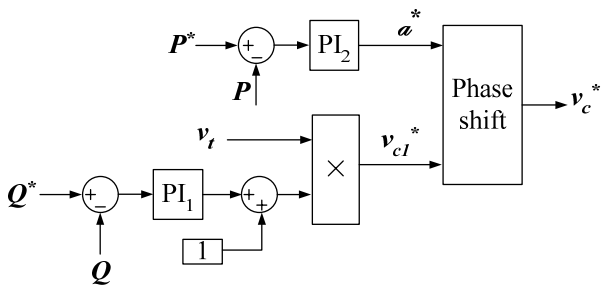


Fig. 3. Active power and nonactive power control diagram.

TABLE 1 ACTIVE POWER AND NONACTIVE POWER CONTROL VARIABLES

Outer Loop / Inner Loop	Active power P	Active current I_a	Power factor pf
Nonactive power Q	Yes	Yes	Yes
Nonactive current I_n	Yes	Yes	Yes
Power factor pf	Yes	Yes	No
PCC voltage V_t	Yes	Yes	Yes

Assuming the variation of V_t can be neglected, i.e., V_t is constant, then the average nonactive power $Q(t)$ is inversely proportional to the magnitude of the inverter output voltage $v_c(t)$. However, the average active power $P(t)$ is dependent on both the amplitude V_c and the phase angle α of $v_c(t)$. A control scheme is developed accordingly. There are two control loops, as shown in Fig. 3. The inner loop (lower loop shown in Fig. 3) is the control of nonactive power $Q(t)$. Because nonactive power is only dependent on the amplitude of V_c, as shown in (15), the instantaneous inverter output voltage $v_c(t)$ is controlled to be in phase with the PCC voltage $v_t(t)$, and the amplitude is controlled by the PI controller PI_1:

$$v_{c1}^* = \left[1 + K_{P1}(Q^* - Q) + K_{I1}\int_0^t (Q^* - Q)dt\right] v_t(t) \tag{16}$$

where Q^* is the reference, Q is the actual value, and K_{P1} and K_{I1} are the proportional gain and integral gain of the PI controller PI_1. The result of this control loop is $v^*_{c1}(t)$, which is in phase with PCC voltage $v_t(t)$. The outer loop (the upper loop shown in Fig. 3) is the control of active power $P(t)$ by controlling the phase angle α of $v_c(t)$. In this control loop, the phase angle of v^*_{c1} is shifted by α^*, which is decided by the PI controller PI_2. K_{P2} and K_{I2} are the proportional and integral gains of the PI controller PI_2.

$$\alpha^* = K_{P2}(P^* - P) + K_{I2}\int_0^t (P^* - P)dt \tag{17}$$

where P^* is the reference, and P is the actual value.

Fig. 3 shows that the average active power $P(t)$ and average nonactive power $Q(t)$ are the control objectives. Different control variables can be used for the control loops according to different objectives. In Table 1, the inner control loop variable can be the inverter average active power P, the rms active current I_a, or the power factor pf, and the outer loop can be the inverter average nonactive power Q, the rms nonactive current I_n, the power factor pf, or the rms PCC voltage V_t. The yes means that the inner loop control variable and the outer loop control variable can be chosen at the same time in this row and column, while a no means that the choice of this row and column is not valid. The choices for the inner loop and the outer loop are independent of each other, except that they cannot both choose the power factor as the control variables.

This control method can also be applied to unbalanced systems with either unbalanced currents or unbalanced voltages, because the definition and control of each phase is independent. A voltage unbalance case is simulated and studied in the following section.

III. System Implementation and Simulation Results

Most DE systems are installed at the end of distribution systems; therefore, a low voltage level (480 V line-to-line rms) DE system as shown in Fig. 1 is simulated in Matlab. The inverter dc side voltage is 1000 V, which enhances the DE system's capability of fast transient response and unbalance compensation.

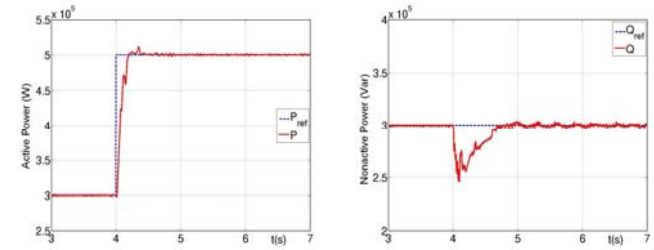
Among the possible control situations shown in Table 1, the simulation results of two cases are presented in the paper below, and the voltage unbalance compensation is illustrated as well.

A. Active Power and Nonactive Power Control

The control of the active power and the nonactive power of the DE is decoupled. Not only the steady-state operation is simulated, but also the transient responses of the active power and the nonactive power control are studied. The dynamic response of the control is tested by applying a sudden change to the active power reference and/or the nonactive power reference.

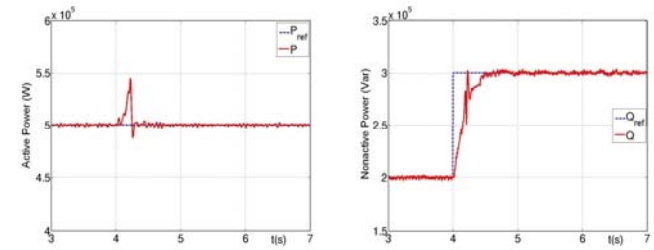
Figs. 4a and 4b show that there is a step change in the active power reference while the nonactive power reference remains constant. The active power and the nonactive power are controlled at 300 kW and 300 kVar respectively before t = 4s. The active power reference is changed to 500 kW at t = 4s, while the nonactive power reference remains 300 kVar. The dashed-line waveforms are the references and the solid-line waveforms are the actual active power and nonactive power outputs. The transient process lasts less than 1 second, and both the active power and the nonactive power reach their new references after the transient.

Figs. 4c and 4d show a step change in the nonactive power reference while the active power reference remains constant. The active power and nonactive power are controlled at 500 kW and 200 kVar before t = 4s. The nonactive power reference is increased to 300 kVar at t = 4s, while the active



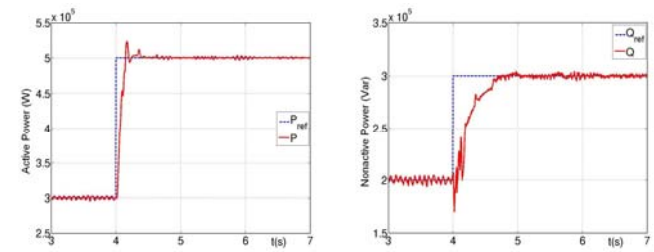
Active power dynamic response:

(a) Active power (b) Nonactive power



Nonactive power dynamic response:

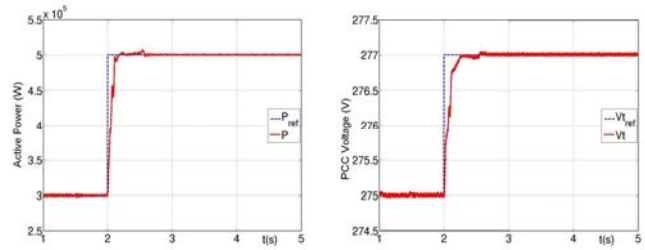
(c) Active power (d) Nonactive power



Active and nonactive power dynamic response:

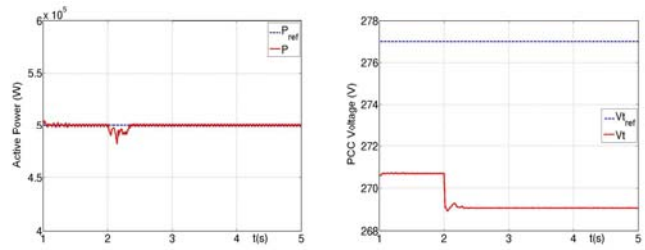
(e) Active power (f) Nonactive power

Fig. 4. Simulation of active power and nonactive power control.



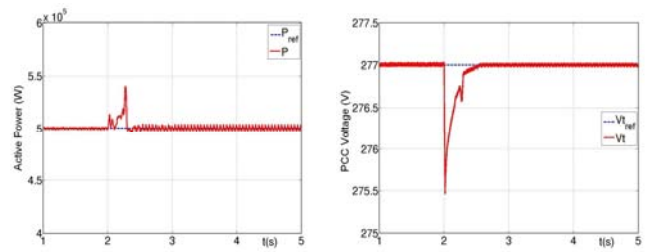
(a) Active power (b) PCC voltage

Fig. 5. DE Voltage regulation.



No Without voltage regulation:

(a) Active power (b) PCC voltage



With voltage regulation:

(c) Active power (d) PCC voltage

Fig. 6. DE Voltage regulation at a sudden load change.

power reference remains constant. Similar to the previous case, during the transient process there is a variation in the active power while the nonactive power is undergoing a step change of 50% increase. Both the active power and the nonactive power are maintained at their new references after the transient.

The third situation is when both the active power and nonactive power references are changed. In Figs. 4e and 4f, the active power and nonactive power are controlled at 300 kW and 200 kVar respectively before t = 4s. The active power reference is increased to 500 kW, and the nonactive power reference is increased to 300 kVar at t = 4s. The simulations show that the active power and nonactive power outputs of the DE are controlled independently.

B. Voltage Regulation

By supplying nonactive power to or consuming nonactive power from the power system, a DE can effectively control the local voltage. In the system shown in Fig. 1, the magnitude of the PCC voltage V_t is controlled by the DE. Because of the real-time control, DE can provide dynamic nonactive power which provides a solution to transient voltage events, such as voltage flicker, voltage dip, and induction motor starts, which can cause system and load problems and are beyond the dynamic capability of capacity banks as well as line and substation regulators that are too slow and do not have the variability to react. At the same time, DE active power output can also be controlled at a desired and acceptable range.

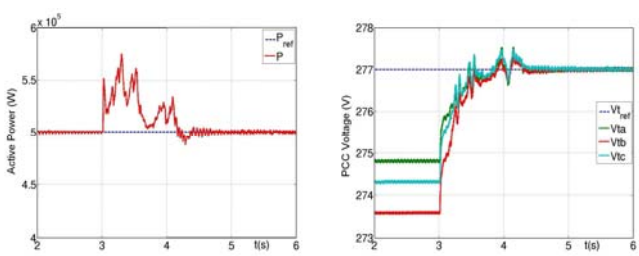
The simulation results of the voltage regulation with active power output control of the DE are shown in Figs. 5 and 6. Fig. 5 shows the steady state and dynamic responses by applying a sudden reference change in both the voltage regulation and the active power control. In Fig. 5a, the active power is controlled at 300 kW before t = 2s, and at 500 kW after t = 2s. In Fig. 5b, the PCC voltage is controlled at 275 V before t = 2s, and at 277 V after t = 2s. As shown in Figs. 5a and 5b, initially the active power and the PCC voltage are at steady state 300 kW and 275 V, respectively. After the reference changes, a new steady state of the active power and the PCC voltage of 500 kW and 277 V is reached in 0.5 second.

Fig. 6 is the comparison of the PCC voltage with and without voltage regulation when a sudden load change occurs. Figs. 6a and 6b show the active power and the PCC voltage when there is no voltage regulation. The active power is controlled at 500 kW, and the nonactive power output is zero which results in the PCC voltage not being regulated at the reference level of 277 V. A sudden load change occurs at t = 2s, and the PCC voltage drops 2 V because there is no nonactive power support. Figs. 6c and 6d are the active power and the PCC voltage with the same load change at the same moment but with DE performing the voltage regulation. The voltage is always regulated at the reference level at different load levels except for the transient period. The maximum voltage drop is decreased to 1.5 V, while the voltage drop at the load change without voltage regulation is 2 V. The transient state duration of the voltage is 0.5 second.

C. Voltage Unbalance Compensation

The definitions in Section II are independent of the number of phases of the power system, and each phase is independent of each other, therefore it is possible to compensate the unbalance components in the power system using a DE system. Either a voltage unbalance or a current unbalance can be compensated, and in this section, simulation results of voltage unbalance compensation due to an unbalanced load are shown.

Fig. 7 shows the voltage unbalance regulation. Fig. 7a is the active power output while voltage regulation is being performed at the same time. The dashed line is the reference active power, which is 500 kW, and the solid line is the actual average active power. Fig. 7b is the three-phase PCC rms voltages. The dashed line is the reference voltage, and the solid lines are the three-phase rms voltages. There is no voltage regulation before t = 3s, and the three-phase voltages are unbalanced and unregulated. The voltage is regulated to the reference level (277 V) and balanced after t = 3s. The transient state duration is 1.5 seconds.



(a) Active power (b) PCC voltage

Fig. 7. Voltage unbalance compensation.

TABLE II RMS VALUES OF THE VOLTAGE UNBALANCE COMPENSATION

	V_t before compensation (V)	V_t after compensation (V)
Phase *a*	274.81	277.05
Phase *b*	273.59	276.98
Phase *c*	274.31	277.01
$V_{unbalance}$	0.24%	0.01%

The voltage unbalance index defined in IEEE Standard 1159 is used to better analyze the unbalance compensation results. The average value of the three-phase voltages is the average of the rms value of the three-phase voltages.

$$Avg(V_a, V_b, V_c) = \frac{V_a+V_b+V_c}{3}. \tag{18}$$

The voltage unbalance index is defined as the maximum deviation from the average of the three-phase voltages divided by the average of the three-phase voltages, expressed in percent.

$$V_{unbalance} = \frac{\max\{|V_a - Avg(V_a,V_b,V_c)|, |V_b - Avg(V_a,V_b,V_c)|, |V_c - Avg(V_a,V_b,V_c)|\}}{Avg(V_a,V_b,V_c)}. \tag{19}$$

The rms values of the three phase PCC voltages before and after compensation are listed in Table II. The unbalance index of the PCC voltage is also listed in the table. The unbalance of the PCC voltage is 0.24% before compensation, and it is improved to 0.01% after the voltage regulation from the DE system.

IV. Discussion

A. DE System Requirements

In the sinusoidal power systems, the voltage, current, and power can be denoted as complex numbers. In this section, the voltage and current variables in the system shown in Fig. 1 are denoted as complex numbers. The PCC voltage is used as the reference voltage, and its rms is given as V_t.

$$\dot{V}_t = V_{tr} + jV_{ti} = V_t e^{j0} = V_t \tag{20}$$

The system voltage is

$$\dot{V}_s = V_{sr} + jV_{si} = V_s e^{j\gamma}, \tag{21}$$

where the amplitude V_s is constant, and the phase angle γ is changing with respect to the PCC voltage.

The system current is

$$\dot{I}_s = I_{sr} + jI_{si}, \tag{22}$$

where I_{sr} and I_{si} are the real part and the imaginary part, respectively.

The load is modeled as a constant current model with load current known as

$$\dot{I}_l = I_{lr} + jI_{li} \tag{23}$$

The DE system provides all or part of the load active power and regulates the PCC voltage, and the DE current is

$$\dot{I}_c = I_{cr} + jI_{ci}, \quad (24)$$

where I_{cr} is a known variable which is part of the load active power. The system current is

$$\dot{I}_s = \frac{\dot{V}_s - \dot{V}_t}{\omega L_s e^{j90°}} \quad (25)$$

Calculating the real part and imaginary part separately, and combining with the circuit KCL, gives

$$\dot{I}_l = \dot{I}_s + \dot{I}_c. \quad (26)$$

The DE current is

$$\dot{I}_c = I_{cr} + j\left(I_{li} + \frac{\sqrt{V_s^2 - \omega^2 L_s^2 (I_{lr} - I_{cr})^2} - V_t}{\omega L_s}\right) = I_c e^{j\beta}, \quad (27)$$

where $\beta = \tan^{-1} \frac{\omega L_s I_{li} - V_t + \sqrt{V_s^2 - \omega^2 L_s^2 (I_{lr} - I_{cr})^2}}{\omega L_s I_{cr}}$.

The increased current rating requirement for the inverter to provide both active and nonactive power is due to the imaginary part of the DE current in (27). There is also an increased voltage rating requirement of the inverter output voltage V_c and the dc side voltage V_{dc}. The inverter output voltage is:

$$\dot{V}_c = V_t + \omega L_c e^{j90°} I_c e^{j\beta} = V_t + \omega L_c I_c e^{j(\beta + 90°)} \quad (28)$$

The amplitude of the inverter output voltage is:

$$V_c = \sqrt{V_t^2 + \omega^2 L_c^2 I_c^2 + 2\omega L_c I_c V_t \sin\beta} \quad (29)$$

If $\beta = 0$, the DE provides only active power, and the required V_c is

$$V_c = \sqrt{V_t^2 + \omega^2 L_c^2 I_c^2} \quad (30)$$

The voltage amplitude in (29) is the increased voltage amplitude if both active power and nonactive power are provided ($\beta \neq 0$).

In a balanced power system, the minimum dc side voltage V_{dc} is [8]:

$$V_{dc} = 2\sqrt{2} V_c \quad (31)$$

Based on the equivalent circuit Fig. 2, the inverter current $i_c(t)$, the inverter output voltage $v_c(t)$, and the PCC voltage $v_t(t)$ satisfy

$$L_c \frac{di_c(t)}{dt} = v_c(t) - v_t(t) \quad (32)$$

In steady state, the rms values of the variables in (32) satisfy

$$V_c = \omega L_c I_c + V_t \quad (33)$$

where ω is the system frequency. This is the required rms value of the inverter output voltage. Combining (31) and (33), the required dc link voltage, V_{dc} is

$$V_{dc} = 2\sqrt{2} V_c = 2\sqrt{2}(\omega L_c I_c + V_s) \quad (34)$$

TABLE III NONACTIVE POWER CAPABILITY VS. POWER RATING REQUIREMENTS

Power factor (pf^*)	Nominal active power (P)	Nominal nonactive power (Q)	Nominal apparent power (S)
1.0	1.0	0	1.0
0.9	1.0	0.48	1.11
0.8	1.0	0.75	1.25
0.7	1.0	1.02	1.43

*Lagging or leading.

B. *Cost-Effective Analysis*

A DE with its power electronics interface can provide nonactive power with the necessary controls as described above along with a higher current rating for the inverter and a higher dc side voltage to provide both active power and nonactive power instead of only active power. Because the active and the nonactive currents are orthogonal, the nonactive power provided by DE is cost-effective.

A comparison of the nonactive power capability of a DE system versus the additional inverter power rating requirements is shown in Table III. Given that the DE active power capability is 1.0 as shown in the second column of the table, four values of power factor, i.e., 1.0, 0.9, 0.8, and 0.7 are listed, and the corresponding nonactive power values are shown in the third column of the table. Finally, the apparent power values are listed in the fourth column, which are the inverter power ratings with nonactive power capability. For example in the fourth row of the table, where the power factor is 0.8, the nonactive power that the DE system can provide is 75% of the active power, while the inverter power rating is only increased by 25%. Therefore, a small increase in the inverter power rating (i.e., costs) gives the DE a significant amount of nonactive power supply.

V. CONCLUSION

The paper shows that distributed energy resources connected to distribution systems can generate both active power and nonactive power. By slight modification of the DE power electronics converter interface configuration and proper control methods, the output active power and nonactive power of the DE system can be controlled simultaneously and independently. Furthermore, because each phase is controlled independently in the proposed control scheme, it can compensate for the unbalance in the three-phase voltages or currents.

In the control of the active power, different control objectives can be achieved by choosing different control variables such as the DE output average active power, the DE

output rms active current, and the DE power factor. Similarly in the control of nonactive power, different control variables can be chosen, such as the DE output average nonactive power, the DE output rms nonactive current, the DE power factor, and the PCC rms voltage. By choosing different variables, DE can perform different tasks, such as local voltage regulation, load following, power factor correction, nonactive power compensation, and unbalance compensation.

The system requirements, such as the inverter current rating and the dc side voltage rating to provide the voltage regulation are discussed. The analysis also shows that it is more cost-effective to use DE systems providing both active power and nonactive power services than to use a separate STATCOM.

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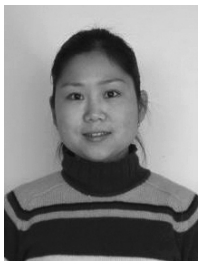
VII. Biographies



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John D. Kueck (M'75, SM'00) earned a BS in Physics from Purdue University in 1971 and an MS in Electrical Engineering - Power Systems, from Ohio State University in 1972. Over the first 20 years of his career, Mr. Kueck worked in the design and operation of fossil fuel and nuclear generating stations. From 1992 to present, Mr. Kueck has been a researcher at the Oak Ridge National Laboratory. His major interest is the local supply of reactive power from distributed energy resources as a reliability service.