Utility-Side Voltage and PQ Control with Inverter-based Photovoltaic Systems

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Abstract: Distributed energy resources (DER) are relatively small-scale generators or energy storage units that are located in close proximity to load centers. The DERs that are integrated to the grid with the power electronic converter interfaces are capable of providing nonactive power in addition to active power. Hence, they are capable of regulating the voltages of weak electrical buses in distribution systems. This paper discusses voltage control capability of photovoltaic (PV) systems as compared to the traditional capacitor banks. The simulation results prove the effectiveness of dynamic voltage control capability of inverter-based PVs. With proper control algorithms, active and nonactive power supplied from DERs (e.g., solar PVs or micro-turbines) can be controlled independently. This paper also presents the scenario of controlling active and nonactive power supplied from a PV array to track and supply the local load.

1. INTRODUCTION

Due to concerns over the depletion of fossil fuels and related environmental issues and rising threats to energy security and power system stability in the recent years, the deployment of distributed energy resources (DER) in modern power systems is gaining popularity. DERs are generating units or energy storage units located close to the load centers with a capacity range of 10 kW–50 MW (Morrison et al., 2007).

Distributed resources, like solar photovoltaics (PVs) and wind, are clean technologies and are capable of providing ancillary services in the form of reactive power through power electronics interface, in addition to the active power. Nonactive power provided by DER can be used to control the voltage at weak electrical buses in distribution systems. Current practice utilizes capacitor banks installed in distribution systems as a cost-effective approach for voltage support.

The control of voltage, active and non-active power from the inverter based DERs to improve the distribution system performance is an emerging area of research. Many research related to this study has been conducted in the past. The combined integration of DER and capacitor banks for voltage support is described by Kai Zou et al. (2009). The application of proportional-integral-derivative (PID)-based controllers in developing the dynamic voltage control models of DER with power electronics interfaces is discussed in papers by S. Ko et al. (2006) and J. Morren et al. (2004). A dynamic voltage control method using adaptive proportional-integral (PI) control to achieve the “plug-and-play” functionality with minimum involvement by users is proposed by H. Li et al. (2009, 2010). A modified Newton Raphson algorithm to control the active and nonactive power injected by the DER through its power electronics interface is proposed by S. Iyer et al. (2006). Similarly, a method to control the active and nonactive power flow in both grid-connected and islanded modes using back- to-back converters is discussed by R. Majumder et al. (2010). Control of inverters using the voltage frequency droop characteristics is discussed by H. Wu et al. (2010) which also uses the widely accepted method of Park’s transformation. It is a method which converts the three-phase rotating reference frame to two-phase stationary reference frame and then to a two-phase dc system (Arunlampalam et al., 2003).

This paper uses dynamic voltage control methods proposed previously (Li et al., 2009; Li et al., 2010) in combination with solar PV-based DER, instead of an ideal voltage source, to further investigate voltage regulation. Through an effective control algorithm, the active and reactive power generated by DER can be controlled to match system reference values. The proper control of active and reactive power from the solar PV to match the local load is presented in this paper. Also, the instantaneous active power and nonactive power theory proposed by Y. Xu et al. (2010) was adopted to perform real-time calculation and control. Instantaneous definitions of active power, nonactive power, active current, nonactive current, voltage root-mean-square (rms) value, and current rms value are given, which provide the basis of real-time control of DER.

The rest of the paper is organized as follows. Section 2 briefly describes the voltage control and active (P) and nonactive (Q) power control algorithms used in this study. Section 3 presents the method of modelling solar array. Section 4 shows the simulation results of voltage control and PQ control, including a comparison of different cases. Section 5 summarizes the major contributions of this study.

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2. DESCRIPTION OF THE CONTROL METHODS

2.1 DER System Configurations

A system configuration of DER with an inverter interface considered in this paper is shown in Fig. 1. An instantaneous active power and nonactive power theory (Xu et al., 2010) was implemented to develop the control algorithm.

The DER system is connected in parallel with the grid through a coupling inductor \( L_c \). The coupling inductor can mitigate the ripples in the DER output current. The connection point is referred to as the point of common coupling (PCC), and the PCC voltage is denoted as \( v_t \).

The equivalent local load is also connected at the PCC. The rest of the system is simplified as an infinite voltage source with a system impedance of \( j \omega L_c \), with resistance neglected. The DER energy source is connected to the DC link of the inverter with a capacitor \( C_d \). The DER energy source is the active power source, and the capacitor is the nonactive power source of the DER system. The inverter current \( i_c \) is controlled so that the desired amount of active power and nonactive power is provided from the DER system. The instantaneous values of the PCC voltage and the inverter current are measured and provided to the controller.

2.2 Voltage Control Algorithm

A voltage regulation method was developed based on the DER configuration shown in Fig. 1 (Li et al., 2009).

The feedback PI controller is used here. As shown in the control diagram in Fig. 2, the PCC voltage is measured and the rms value of \( v_t(t) \) is calculated. Then, the rms value \( V_i(t) \) is compared to a voltage reference \( V_{i}^*(t) \) (which could be a voltage specified by the utility) and the error is fed to a PI controller. The inverter output voltage \( V_i(t) \) is the reference to generate pulse width modulation (PWM) signals to drive the inverter. The output voltage of the inverter is controlled so that it is in phase with the PCC voltage, and the magnitude of the inverter output voltage is controlled so that the PCC voltage is regulated at a given level \( V_i(t) \). The control scheme can be specifically expressed as (1).

\[
v_i(t) = v_i(t) \left[ 1 + K_p \left( V_{i}^*(t) - V_i(t) \right) + K_i \int_0^t \left( V_{i}^*(\tau) - V_i(\tau) \right) d\tau \right],
\]

(1)

where \( K_p, K_i \) are the gain parameters of the PI controller 1.

In (1), 1 has been added to the left-hand side of the expression so that when there is no injection from the DER, the DER output voltage is exactly the same as the terminal voltage.

2.3 Review of Instantaneous Power Theory

The instantaneous power definitions are extensions of the standard steady-state power definitions. They are instantaneous active current, instantaneous nonactive current, instantaneous active power, and instantaneous nonactive power. Similarly, the rms values of voltages and currents are also defined as instantaneous values.

The power system in this study is considered to be a three-phase balanced system; hence, the instantaneous power theory can be simplified, as shown in the following derivations.

The DER system shown in Fig. 1 can also be simplified as the single-phase equivalent circuit in Fig. 3, assuming that the three-phase system is balanced. Let \( v_i(t) \) and \( v_r(t) \) denote the instantaneous PCC voltage and the inverter output voltage (harmonics are neglected), respectively, where \( \alpha \) is the phase angle of \( v_i(t) \) relative to the PCC voltage.

\[
v_i(t) = \sqrt{2} V_i \cos(\omega t) \quad \text{and} \quad v_r(t) = \sqrt{2} V_r \cos(\omega t + \alpha).
\]

(3)

The rms values of \( v_i(t) \) and \( v_r(t) \) are given in (4) and (5), respectively.

\[
V_i(t) = \sqrt{\frac{2}{\pi}} \int_0^t v_i^2(\tau) d\tau \quad \text{and} \quad V_r(t) = \sqrt{\frac{2}{\pi}} \int_0^t v_r^2(\tau) d\tau.
\]

(4)

(5)

where \( T/2 \) is one-half of the period of the voltage and is the average interval used here. \( V_i(t) \) and \( V_r(t) \) are instantaneous variables as a function of time \( t \). All other rms and power definitions are also functions of time; therefore, they are valid in both steady state and transients.

Fig. 3. Simplified circuit diagram of a parallel connected DER.
The current from the DER to the utility is denoted as $i_c(t)$:

$$i_c(t) = \frac{\sqrt{2}}{\omega_L} \left[ V_c \sin(\omega t + \alpha) - V_t \sin(\omega t) \right].$$  

(6)

where $\alpha$ is the phase angle between the PCC voltage $v(t)$ and the inverter current $i_c(t)$. The average power of the DER is denoted as $P(t)$:

$$P(t) = \frac{2}{T} \int_{t-rac{T}{2}}^{t+rac{T}{2}} i_c(r) v_c(r) dr = \frac{V_t V_c}{\omega_L} \sin \alpha.$$  

(7)

The instantaneous active current component of the inverter current $i_a(t)$ is defined as:

$$i_{ca}(t) = \frac{P(t)}{V_c^2(t)} v_t(t).$$  

(8)

The instantaneous nonactive current component of the inverter current is defined as:

$$i_{cn}(t) = i_c(t) - i_{ca}(t).$$  

(9)

The $i_{ca}(t)$ and $i_{cn}(t)$ are the active component and the nonactive component of the inverter current $i_c(t)$, respectively. By controlling these two current components, the active power and the nonactive power of the DER 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:

$$I_{ca}(t) = \frac{2}{T} \int_{t-rac{T}{2}}^{t+rac{T}{2}} i_{ca}^2(r) dr$$  

(10)

$$I_{cn}(t) = \frac{2}{T} \int_{t-rac{T}{2}}^{t+rac{T}{2}} i_{cn}^2(r) dr.$$  

(11)

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

$$S(t) = V_t(t) I_c(t) = \frac{V_t}{\omega_L} \sqrt{V_t^2 + V_c^2 - 2V_t V_c \cos \alpha}$$  

and

(12)

$$Q(t) = V_t(t) I_{ca}(t) = \sqrt{S^2(t) - P^2(t)} = \frac{V_t}{\omega_L} (V_c \cos \alpha - V_t),$$  

(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 (7) and (13) can be approximated by the first terms of the Taylor series if the angle $\alpha$ is small, as shown in (14) and (15):

$$P(t) \approx \frac{V_t V_c}{\omega_L} \alpha$$  

and

$$Q(t) \approx \frac{V_t}{\omega_L} (V_t - V_c).$$  

(14)

(15)

### 2.4 Active and Nonactive Power (PQ) Control Algorithm

In (14) and (15), with the assumption that the variation of $V_t$ can be neglected, that is, $V_t$ is constant, then the average nonactive power $Q(t)$ is proportional to the magnitude of the inverter output voltage $v(t)$. However, the average active power $P(t)$ is dependent on both the amplitude $V_t$ and the phase angle $\alpha$ of $v(t)$.

The phasors in Fig. 4 show the relationships between the respective voltages and currents. The voltage and current variables are vectors, which are indicated by a dot on top of the variables in the figures. The phasors of the PCC voltage, inverter output voltage, the inverter current, the active power and nonactive power, are illustrated as well as the relationships between them. The PCC voltage vector $\hat{V}_t$ is the reference. Figures 4a–4c are diagrams that show only active power, only nonactive power, and both active and nonactive power, respectively.

In Fig. 4a, the diagram on the left side shows that $\hat{V}_t$ and $\hat{V}_c$ have the same magnitude, and the phase angle is $\alpha$. If $\alpha$ is small, the nonactive power $Q$ can be neglected, as shown in the diagram on the right side of Fig. 4a. In Fig. 4b, $\hat{V}_c$ is in phase with $\hat{V}_t$. The amount of nonactive power generated from the inverter is determined by the magnitude of $\hat{V}_c$. As shown in the diagram on the right side of Fig. 4b, the output of the inverter is purely nonactive power. Furthermore, the inverter generates nonactive power if the magnitude of $\hat{V}_c$ is greater than $\hat{V}_t$, and absorbs nonactive power if the magnitude of $\hat{V}_c$ is less than $\hat{V}_t$. In Fig. 4c, $\hat{V}_c$ is not in phase with $\hat{V}_t$; nor of the same magnitude as $\hat{V}_t$; and there are both active power and nonactive power in the inverter output.

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Fig. 4. Phasor diagrams of the voltage, current, and active power and nonactive power.

A control scheme is developed accordingly with two feedback control loops. The inner loop controls the nonactive power $Q(t)$ by controlling the amplitude of $v(t)$, while the outer loop controls the active power $P(t)$ by controlling the phase angle of $v(t)$. If the active power and nonactive power are the variables to be controlled, the inverter current is not a controllable variable. However, the inverter is very sensitive to the current; therefore, to ensure that the inverter is not overloaded, a current limiter is developed in the controller.
Instead of the active power and the nonactive power of the inverter, the inverter current is the direct control variable.

The active current \( I_{a}(t) \) and the nonactive current \( I_{n}(t) \) are control variables instead of \( P(t) \) and \( Q(t) \). At steady state, the relationships of \( I_{a}(t) \), \( I_{n}(t) \), \( P(t) \), and \( Q(t) \) are as follows:

\[
P(t) = V_P(t)I_{ca}(t) \quad \text{(16)}
\]
\[
Q(t) = V_Q(t)I_{ca}(t). \quad \text{(17)}
\]

The active power \( P(t) \) and nonactive power \( Q(t) \) in (14) and (15) can be controlled by directly controlling the active current \( I_{a}(t) \) and nonactive current \( I_{n}(t) \) in (16) and (17).

The decoupled feedback control diagram is shown in Fig. 5. In the nonactive power control loop, the amplitude of the instantaneous inverter output voltage \( v_i(t) \) is controlled by the PI controller \( \text{PI}_1 \), where \( I_{n}^* \) is the reference, \( I_n \) is the actual value, and \( K_p1 \) and \( K_i1 \) are the proportional gain and integral gain of the PI controller \( \text{PI}_1 \). Using the PCC voltage as its reference, the amplitude of the inverter output voltage is modified based on the amount of the nonactive power. The result of this control loop is \( v_{r1}(t) \), which is in phase with the PCC voltage \( v_{pc}(t) \), as shown in (18). Here, 1 is added to the expression for the same reason described in Section 2.2.

\[
v_{r1}(t) = \left[ 1 + K_p1(I_{n}^* - I_{n}) + K_i1 \int_{t_0}^{t} (I_{n}^* - I_{n}) dt \right] v_{i}(t). \quad \text{(18)}
\]

The inverter active power control is realized by controlling the phase angle of the inverter output voltage. Equation (19) describes the active power control loop. The phase angle of \( \alpha^* \) is controlled by the PI controller \( \text{PI}_2 \); where \( I_{a} \) is the reference, and \( I_{a} \) is the actual value.

\[
\alpha^* = K_p2(I_{a}^* - I_{a}) + K_i2 \int_{t_0}^{t}(I_{a}^* - I_{a}) dt. \quad \text{(19)}
\]

\[
\begin{align*}
\text{PI}_1 \quad & \alpha^* \quad I_{ca}^* \quad I_{ca} \\
\text{PI}_2 \quad & \alpha \quad I_{n}^* \quad I_{n} \\
\text{Phase shift} \quad & v_{r1}^* \\
& v_i \\
& v_{pc} \\
\end{align*}
\]

Fig. 5. Active power and nonactive power control diagram.

3. MODELING OF SOLAR PHOTOVOLTAIC ARRAY

The commonly accepted solar cell model is a one diode model (Villalva et al., 2009). This work uses the single diode model of the solar cell to model the Kyocera KC200GT solar array, which is shown in Fig. 6. This solar module is chosen in particular in order to easily validate the simulated I-V curve with the experimentally available curve from the datasheet.

The practical PV array is composed of a certain number of solar cells in series. The I-V characteristics of a solar array, as shown in Fig. 7, are represented by the following mathematical equation:

\[
I = I_{pv} - I_o \left[ \exp \left( \frac{V + R_s I}{V_{term}} \right) - 1 \right] - \frac{V + R_s I}{R_{sh}}, \quad \text{(20)}
\]

where \( I_{pv} \) and \( I_o \) are the photo current and the diode saturation currents, respectively. \( V_{term} = N_e kT/q \) is the thermal voltage of the array, \( N_e \) being the cells connected in series for greater output voltage, \( k \) is the Boltzmann constant (1.3806503 \times 10^{-23} \text{J/K}) \), \( T \) (Kelvin) is the temperature of the p-n junction of the diode, and \( q \) (1.60217646 \times 10^{-19} \text{C}) is the electron charge. Also, \( R_s \) and \( R_{sh} \) are the equivalent series and shunt resistances of the array, respectively, and \( a \) is the ideality factor usually chosen in the range 1 ≤ \( a \) ≤ 1.5. Here \( a \) is taken as 1.

Equation (20) gives the I-V characteristic of the solar array as shown in Fig. 7 in which the significant operating points such as short circuit (0, \( I_s \)), Maximum Power Point (MPP) (\( V_{mpp} \), \( I_{mpp} \)), and open circuit (\( V_{oc} \), 0) are marked clearly.

The photocurrent of the PV array depends linearly on the solar irradiation and the cell temperature, as shown by (21) (Villalva et al., 2009).

\[
I_{pv} = (I_{pv,n} + K_i \Delta T) \frac{a}{G_n}. \quad \text{(21)}
\]

\( I_{pv,n} \) can be calculated based on (22).

\[
I_{pv,n} = \frac{R_{sh} + R_s}{R_{sh}} I_{sc}. \quad \text{(22)}
\]

Using these fundamental equations and parameters from the data sheet, the PV model is developed and verified with the panel datasheet. The I-V characteristics of KC200GT for different irradiance levels at the cell temperature of 25°C as obtained from the simulation and the datasheet are shown in Figs. 8a and 8b, respectively.

The maximum power point obtained from the simulation is 199.99 W, which is close to the value of 200 W mentioned in the datasheet.
4. SYSTEM CONFIGURATION AND SIMULATION RESULTS

Figure 9 shows the simplified system diagram of an active power distribution system located in Catalina Island, California, USA. The Catalina Island power system consists of 61 buses, 3 generators, 66 lines, and 22 loads and is managed by Southern California Edison. Only the buses that are connected to the generators or were part of the study are shown in Fig. 9. The rated voltages of all the buses are 12 kV (line-to-line rms). Buses 1014, 2043, and 3028 have the lowest voltages of each sub-circuit; therefore, these three buses are chosen for examination. For the voltage regulation study, aggregated PV-based DER are installed at Buses 1014, 2043, and 3028, respectively, whereas for the PQ control study, a single aggregated PV is installed at Bus 3051.

Fig. 9. Simplified system diagram of Catalina system.

4.1 Voltage Control

For the study of voltage control with PV, the loads of a few buses are increased from base load values to peak load values at time t = 0.6 s, as shown in Table 1. Figure 10 shows the nonactive power profile, which includes total nonactive power generated from the central generators, the total nonactive power consumed by the load, and voltage profiles of Buses 1014, 2043, and 3028. Table 2 summarizes these results. It can be observed that Bus 3028 has the lowest voltage magnitude of 0.911 pu at peak load among all the buses. PV generators are installed at these buses for voltage regulation. The performance of PV generators is compared with the capacitor banks installed at the same locations. Two cases with low (Case1: around 30%) and high (Case2: around 80%) capacitor/PV nonactive power penetration are considered for study.

Figures 11a and 11b show the nonactive power of the source, the load, and the capacitors, and the voltage profiles of the buses, respectively, in Case 1. Figure 12 shows similar pattern for Case 2. Table 3 summarizes the results of voltage control from capacitors for both cases. It is seen that the nonactive power from the central generators, Q_{source} decreases as capacitors are supplying a portion of nonactive power. It can be observed from Figs. 11b and 12b that voltage profile of Bus 3028 has been boosted beyond 1 pu at the base load case, but at the peak load, the voltage is improved only slightly to 0.936 pu in Case 1 and 0.947 pu in Case 2. It can also be observed that the nonactive power injection from the capacitors decreases at the peak load. This is a major problem of using capacitors to provide voltage support: when the voltage is low and more nonactive power is needed to boost the voltage, the capacitor’s nonactive power injection decreases since reactive power output from a capacitor is related to voltage square.

Table 1. Load increase in Catalina system

<table>
<thead>
<tr>
<th>Base load</th>
<th>Peak load</th>
</tr>
</thead>
<tbody>
<tr>
<td>P(MW)</td>
<td>Q(MVVar)</td>
</tr>
<tr>
<td>Bus 1014</td>
<td>0.6</td>
</tr>
<tr>
<td>Bus 2043</td>
<td>0.14</td>
</tr>
<tr>
<td>Bus 3051</td>
<td>0.02</td>
</tr>
<tr>
<td>Bus 3053</td>
<td>0.088</td>
</tr>
</tbody>
</table>

Table 2. Power and voltage at base and peak load

<table>
<thead>
<tr>
<th>Base load</th>
<th>Peak load</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{load}(MW)</td>
<td>6.73</td>
</tr>
<tr>
<td>P_{source}(MW)</td>
<td>7.43</td>
</tr>
<tr>
<td>Q_{load}(MVAr)</td>
<td>4.29</td>
</tr>
<tr>
<td>Q_{source}(MVAr)</td>
<td>4.624</td>
</tr>
<tr>
<td>V_{1014}(pu)</td>
<td>0.95</td>
</tr>
<tr>
<td>V_{2043}(pu)</td>
<td>0.976</td>
</tr>
<tr>
<td>V_{3028}(pu)</td>
<td>0.9801</td>
</tr>
</tbody>
</table>

Fig. 10. Nonactive power and voltage profiles of the buses without compensation.

Fig. 11. Case 1: nonactive power and voltage profiles of the buses with capacitors (penetration: 27.35%).
bus voltages can be maintained at the same value in both power from the source decreases with the increase in loading levels. As shown in Figs. 13a and 14a, the nonactive peak load level as compared to the base load level so that the magnitudes of these buses can be maintained at 0.96 pu, installed, the nonactive power injection is increased at the peak load level as compared to the base load level so that the bus voltages can be maintained at the same value in both loading levels. As shown in Figs. 13a and 14a, the nonactive power from the source decreases with the increase in nonactive power injection from PV. Figures 13b through 13d show that voltage magnitudes of bus 1014, bus 2043, and bus 3028 are maintained at 0.95 pu, 0.98 pu, and 0.93 pu, respectively, for Case 1 irrespective of the load increase at 0.6 s. Similarly, Figs. 14b through 14d show that the voltage magnitudes of these buses can be maintained at 0.96 pu, 0.99 pu, and 0.94 pu, respectively, for Case 2. Table 4 shows that for Case 1, the PVs absorb 0.6 MVAR at the base load and inject 1.44 MVAR at the peak load so as to maintain the constant voltage profile at different loading levels. The dynamic nonactive power generation capability of inverter-based PV systems is a great advantage over the traditional capacitor banks, which are static devices.

Figure 13 shows the nonactive power and voltage profiles of different buses with the PV installed for Case 1. Figure 14 shows similar results for Case 2. Table 4 summarizes the results of voltage regulation using PV generators. With PV installed, the nonactive power injection is increased at the peak load level as compared to the base load level so that the bus voltages can be maintained at the same value in both loading levels. As shown in Figs. 13a and 14a, the nonactive power from the source decreases with the increase in nonactive power injection from PV. Figures 13b through 13d show that voltage magnitudes of bus 1014, bus 2043, and bus 3028 are maintained at 0.95 pu, 0.98 pu, and 0.93 pu, respectively, for Case 1 irrespective of the load increase at 0.6 s. Similarly, Figs. 14b through 14d show that the voltage magnitudes of these buses can be maintained at 0.96 pu, 0.99 pu, and 0.94 pu, respectively, for Case 2. Table 4 shows that for Case 1, the PVs absorb 0.6 MVAR at the base load and inject 1.44 MVAR at the peak load so as to maintain the constant voltage profile at different loading levels. The dynamic nonactive power generation capability of inverter-based PV systems is a great advantage over the traditional capacitor banks, which are static devices.
limitation of the simulation tool used in this study, the gains of the PI controllers are set at high values so that the simulation can be completed in a few seconds. It causes the high ripples during the transients. Further work needs to be done in setting optimal values of the gains so that the system can achieve both faster responding speed and fewer ripples during transients.

Fig. 15. Case 1: Active power and nonactive power at Bus 3051.

Fig. 16. Case 2: Active power and nonactive power at Bus 3051.

5. CONCLUSIONS

The paper presents the application of PV-based DER systems for voltage control and the active and nonactive power control in a practical utility system. It is shown that the dynamic behaviour of PV in providing controlled amount of nonactive power is more effective than the traditional static capacitor banks. Similarly, the dynamic response of the PV in following the local load pattern is discussed. The ability of the DERs to provide nonactive power in addition to active power is very beneficial in maintaining the voltage stability and power flow control in the future power systems.

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