# Adaptive Voltage Control With Distributed Energy Resources: Algorithm, Theoretical Analysis, Simulation, and Field Test Verification

Huijuan Li, *Student Member, IEEE*, Fangxing Li, *Senior Member, IEEE*, Yan Xu, *Member, IEEE*, D. Tom Rizy, *Senior Member, IEEE*, and John D. Kueck, *Senior Member, IEEE*

***Abstract*—Distributed energy resources (DE) or distributed generators (DG) with power electronics interfaces and logic control using local measurements are capable of providing reactive power related ancillary system services. In particular, local voltage regulation has drawn much attention in regards to power system reliability and voltage stability, especially from past major cascading outages. This paper addresses the challenges of controlling DEs to regulate local voltage in distribution systems. An adaptive voltage control method has been proposed to dynamically modify control parameters to respond to system changes. Theoretical analysis shows that there exists a corresponding formulation of the dynamic control parameters; hence the adaptive control method is theoretically solid. Both simulation and field experiment test results at the Distributed Energy Communications and Controls (DECC) Laboratory confirm that this method is capable of satisfying the fast response requirement for operational use without causing oscillation, inefficiency, or system equipment interference. Since this method has a high tolerance to real-time data shortage and is widely adaptive to variable power system operational situations, it is quite suitable for broad utility application.**

***Index Terms*—Ancillary services, distributed energy resources, distributed generators, inverter control, PI control, reactive power, voltage control.**

## I. Introduction

THE concern for reliability and security of the electric power system and for the environment with deregulation has contributed to the development and growth of distributed energy resources (DE) or what is sometimes called distributed generators (DG). The total installed U.S. DE capacity, for those smaller than 5 MW, is estimated to be 195 GW [1]. DE interconnection with distribution systems can have significant impacts on traditional system operation and protection [2]. The ability to provide local voltage control for increasing DE penetration is a useful ancillary service to keep the PCC voltage of the DE and/or at a remote location within accepted limits [3]–[7]. Also, voltage support provided by DE can alleviate transmission level reactive power shortage. Reference [3] proposed an agent-based approach to schedule DG for voltage control with limited communications. Reference [4] proposed a local, intelligent, and auto-adaptive voltage regulation scheme (steady-state) for DG due to the lack of distribution system measurements and communication. Reference [5] discusses how intelligent distributed voltage control can achieve similar results to centralized voltage control, and that both can better increase DE penetration than power factor (pf) control. Reference [6] proposed a combined method of automatic pf and voltage control for counteracting steady-state overvoltage for distribution systems with DE to maximize their utilization. Reference [7] applied a statistical state-estimation algorithm to estimate the voltage magnitude at each network node and then collaboratively to set the automatic voltage control (AVC) relay target voltage and DE output to maintain acceptable voltages. These studies focused on voltage regulation from a steady-state point of view while we will focus on dynamic voltage regulation control.

In regards to dynamic control, [8]–[14], [18], and [19] illustrated that DE interconnected with the power grid using a power electronics (PE) interface is capable of supplying voltage regulation service dynamically, in particular, with the application of PID controllers in [11]–[14], [18], and [19] because of their simplicity and robustness. However they focused on the control method structure design with little effort on exploring how to set the PID controller parameters systematically. Previous work [15], [16] has shown that the PI controller parameters greatly affect the DE dynamic response for voltage regulation and that incorrect parameter settings may cause inefficient (slow), oscillatory, or worse an unstable response that can lead to system instability. Logically this raises an interesting issue, especially if a large amount of DEs with voltage regulating capability are deployed in the future:

> How do we ensure that control parameters for voltage-regulating DE work efficiently and effectively using a systematic approach?

It is not feasible for utility engineers to perform trial-and-error to find suitable parameters when a new DE is connected. Hence, an autonomous approach is needed to eliminate the manual process. To address the parameter setting issue, a control scheme using intensive centralized communications may be possible such that commands from the substation are continuously sent

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H. Li and F. Li are with the University of Tennessee, Knoxville, TN 37996 USA.

Y. Xu, D. T. Rizy, and J. D. Kueck are with Oak Ridge National Laboratory, Oak Ridge, TN 37831 USA.

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to a DE for it to adjust its settings. Due to the uncertain and dispersed locations and the expected high customer-based DE penetration, this centralized, intensive communication may be costly to install, maintain, and secure. Also, the contingency of a communication outage and how it impacts DE control, especially for major system conditions, would need to be considered. Other approaches, such as the eigenvalue analysis with particle swarm optimization [17], to optimize wind turbine controller parameters to improve system stability, may require detailed system parameters and real-time system information, and thus fast communications. It may not be easily suitable for a real, large distribution system application.

Therefore, an autonomous and adaptive approach is much more advantageous for adjusting control parameters to regulate voltage with no or minimal communications (such as a voltage schedule provided with low-cost communications). This is the motivation of this paper. In the rest of this paper, an adaptive voltage control method which does not require construction of a detailed dynamic model of the power system is presented with theoretical analysis, simulation, and field tests.

The paper is organized as follows. Section II briefly presents the control model for a voltage regulating DE and the challenges. Section III presents the adaptive controller methods followed by a theoretical analysis of the method in Section IV. Sections V and VI present the simulation and test results, respectively. Section VII provides a conclusion and possible future work.

## II. Background and Challenges of DE Control Model for Voltage Regulation

### A. System Configuration

A DE with a power electronic (PE) interface connected in parallel with the distribution system is shown in Fig. 1. The PE interface includes the inverter, a dc-side capacitor with voltage $v_{\rm dc}$, and a DE such as fuel cell or solar panel supplying dc current. There is a coupling inductor $L_c$ between the inverter and the rest of the system. The PE interface is referred to as the compensator because voltage regulation using the DE is the main topic of this paper. The compensator is connected in parallel with the load to the distribution system, which is simplified as an infinite voltage source (utility) with a system impedance of $R_s + j\omega L_s$. The compensator is connected through the coupling inductors $L_c$ at the point of common coupling (PCC), and the PCC voltage is denoted as $v_t$. By generating or consuming a certain amount of reactive power, the compensator regulates $v_t$.

### B. Control Methods

An instantaneous nonactive power theory [18], [19] is adopted in this paper for the real-time DE calculation and control for local voltage regulation. Here, nonactive power includes reactive power in the fundamental frequency plus nonfundamental frequency harmonics. As pointed out in [18] and [19], the generalized definition of nonactive power extends the traditional definition of instantaneous nonactive power from three-phase, balanced, and sinusoidal systems to more general cases. The uniqueness of the definition makes it easy to

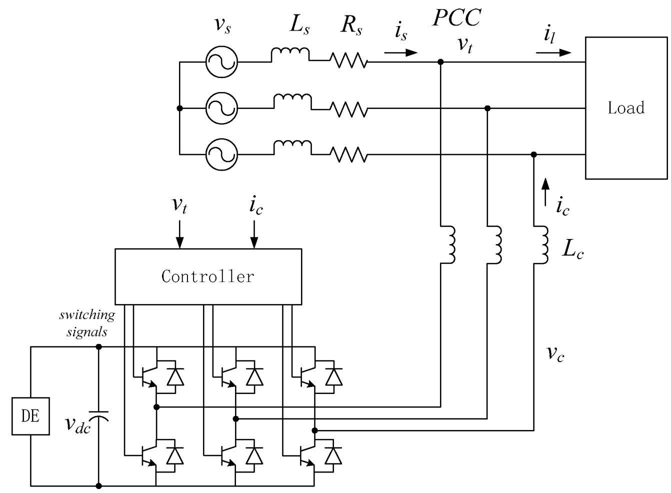


Fig. 1. Parallel connection of a DE with PE converter.

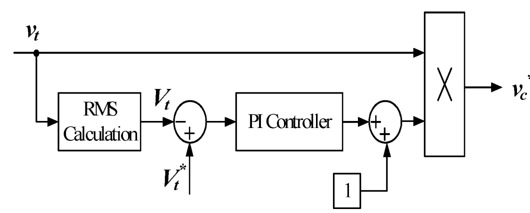


Fig. 2. Control diagram for compensator voltage regulation.

be applied in practical distribution systems in which there are challenges like single-phase, nonsinusoidal, unbalanced, and nonperiodic waveforms. Therefore, it is suitable for real-time control in a real-world system and provides advantages for the design of control schemes.

A voltage regulation method is developed based on the system configuration in Fig. 1 with a PI feedback controller. The control diagram is shown in Fig. 2. The PCC voltage, $v_t$ is measured and its RMS value, $V_t$, is calculated. The RMS value is then compared to a voltage reference, $V_t^*$ (which could be a utility specified voltage schedule and possibly subject to adjustment based on load patterns like daily, seasonally, on-and-off peak, etc.). The error between the actual and reference is fed back to adjust the reference compensator output voltage $v_c^*$, which is the reference for generating pulse-width modulation (PWM) signals to drive the inverter. A sinusoidal PWM is applied here because of its simplicity for implementation. The compensator output voltage, $v_c$, is controlled to regulates $v_t$ to the reference $V_t^*$. The control scheme can be specifically expressed as

$$v_c^* = v_t(t)\left[1 + K_P(V_t^*(t) - V_t(t)) + K_I\int_0^t (V_t^*(t) - V_t(t))\,dt\right] \quad (1)$$

where $K_P$ and $K_I$ are the proportional and integral gain parameters of the PI controller.

Equation (1) leads to reactive power injection only, when $v_c^*$ is in phase with $v_t$. However, if a real power injection is also needed, it can be simply implemented using a desired phase

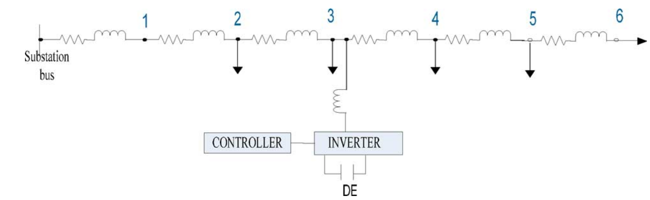


Fig. 3. Radial test distribution system.

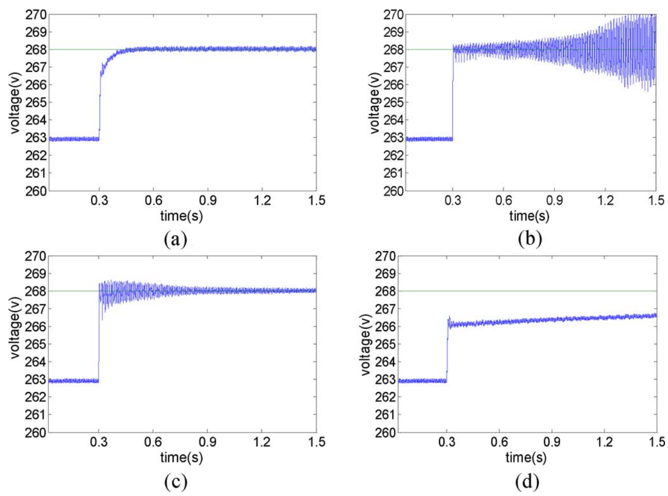


Fig. 4. Voltage regulation with different $K_P$ and $K_I$. (a) $K_P = 0.03$ and $K_I = 0.8$. (b) $K_P = 1.0$ and $K_I = 7.0$. (c) $K_P = 0.2$ and $K_I = 3.0$. (d) $K_P = 0.01$ and $K_I = 0.1$.

angle shift applied to $v_c^*$ in (1) because of the tight coupling between real power and phase angle.

Obviously, the two gain parameters of the PI controller affect the voltage regulation dynamics. An important issue for future utility practice is how to set them to optimize the PI controller performance for an effective and efficient voltage regulation. This is the subject addressed in this paper.

### C. Challenge in Control Parameters on Voltage Regulation

The impact of the PI gains on the voltage regulation dynamic response was tested in a distribution system model. The system diagram is shown in Fig. 3 with a DE connected to Bus 3. The PCC voltage response is shown in Fig. 4 with different $K_P$ and $K_I$ combinations. The target (reference) voltage is set to 268 V after an assumed small disturbance. Fig. 4(a) shows a desirable, smooth dynamic response with well-tuned $K_P$ and $K_I$ parameters. However, with other $K_P$ and $K_I$ values, different responses may occur. Figs. 4(b)–(d) show an unstable, stable but oscillating response, and sluggish response, respectively.

The simulation results in Fig. 4, as well as studies in [16], clearly show the need for a solution to identify control parameters in real time that provide optimal and acceptable response in accordance with system conditions and DE locations. This is especially true for a real-world distribution system which has a shortage of measured, detailed, time-synchronized, and dynamically changing system data. Even if such data were available, it is not practical for utility engineers to perform simulations as a regular practice to adjust control gains to address for system changes. Manual approaches like trial-and-error adjustment will be a very time-consuming, tedious, and costly effort. Plus, the selected gains may be obsolete in a short order. To address these issues, this paper presents an adaptive control method to regulate local voltage using DE.

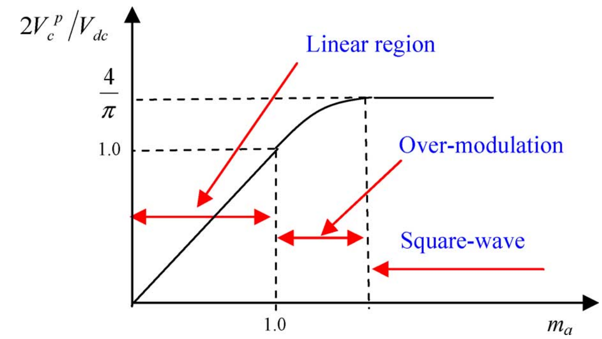


Fig. 5. PWM voltage control by varying modulation index, $m_a$.

## III. Implementation of Adaptive Method for DE Controller

As shown in Section II-C, if $K_P$ or $K_I$ is not chosen appropriately, the system response may be poor and at worst create instability. So preventing these and optimizing the response speed are what is desired for the PI controller design. Thus the goal is to come up with an adaptive PI design that can dynamically adjust the PI controller in real-time based on the system behavior and configuration. The proposed adaptive PI control method, inspired by the generic adaptive control in [20], consists of three procedures:

- determine the DC source voltage of the DE;
- set the initial controller values, $K_P$ and $K_I$;
- adaptively adjust the controller parameters according to the real-time system conditions.

### A. Determine the DC Source Voltage

The DE's PE interface with the utility is a voltage source inverter (VSI) and the PWM method is used to convert the dc source voltage to an ac supply. Fig. 5 shows the relationship between $2V_c^p/V_{\rm dc}$ and the modulation index $m_a$, where $V_c^p$ is the peak voltage of the fundamental-frequency component of the compensator output voltage $v_c$; and $V_{\rm dc}$ is the dc supply voltage.

As shown in Fig. 5, for a given $V_{\rm dc}$, $V_c^p$ varies linearly with the modulation index $m_a$ when it is 1.0 or less. It also shows $V_c^p$ should be less than $(4/\pi) \times (V_{\rm dc})/(2)$ for any $m_a$, even if under the saturated square-wave region. This means that $V_{\rm dc}$ determines the DE's ability to provide voltage regulation. To reduce the DE harmonic injection, $m_a$ is chosen to be no greater than 1. Accordingly, we have

$$V_{\rm dc} \geq 2V_c^p = 2\sqrt{2} \times V_c. \quad (2)$$

Hence, if the DE needs to perform voltage regulation to meet a certain scheduled voltage profile, there is a minimum dc supply voltage requirement. The requirement depends on the system requirement for $V_c$, i.e., the scheduled ac voltage profile. The approach to obtain an effective and acceptable voltage profile can be a separate research topic and will not be covered in this paper. Instead, we simply assume there are some pre-defined, reasonable voltage schedules available, which can be even supplied by the local utility.

### B. Set the Initial PI Controller Gains

Lower gain parameters, $K_P$ and/or $K_I$, are typically chosen initially and only increased after confirming that they do not cause any of the above-mentioned poor response and instability problems. In the following discussion, a method to initialize the gains is proposed.

*1) Setting the Initial $K_P$ Value:* At the initial time $0_+$ (immediately after a voltage transient), the reference compensator output voltage $v_c^*$ can be expressed as (3), since the contribution of the integral controller is 0:

$$v_c^* = v_t^0(t)\left[1 + K_P(V_t^*(t) - V_t^0(t))\right]. \quad (3)$$

To keep the PWM modulation index, $m_a$, no greater than 1, the peak value of $v_c^*$ needs to be less than the peak value of the triangle carrier signal, which is $0.5 \times V_{\rm dc}$. Hence, we have

$$K_P \le \frac{\frac{\frac{1}{2}V_{\rm dc}}{V_t^{0,p}} - 1}{\Delta V_t^0} \quad (4)$$

where $\Delta V_t^0 = V_t^*(t) - V_t^0(t)$ is the initial RMS voltage deviation at time $0_+$. This can be chosen as, and usually is, the maximum voltage deviation from the reference voltage at PCC. Similarly, $V_t^{0,p}$ can be accordingly chosen as the peak value of voltage $v_t$ at time $0_+$. Conservatively, the initial value of $K_P, K_{P0}$, can be empirically set to half of the right-hand side (RHS) value defined by (4), considering efficiency and error tolerance. Certainly, more research may be done about the choice of $K_{P0}$ other than half of the RHS value in (4). Nevertheless, the initial value is only important for the initial transients and will be adjusted by the adaptive control when the system condition changes, as discussed next.

*2) Setting the $K_I$ Initial Value:* The voltage response time of the controller for a voltage transient is set to 0.5 s in order to not interfere with conventional utility voltage control. As can be seen from the simulation in Section II, in an ideal voltage control process, the response of the control system to a step change can be approximated as an exponential decay curve, i.e., $\Delta V(t) = \Delta V_{t0}e^{-(t/\tau)}$ where $\tau$ is the time constant. Here a period of five times the time constant, $5\tau$, is chosen as the response time since this is normally the time needed to reach a new steady-state condition because $e^{-5} = 0.007 \approx 0$. Hence, we have $5\tau \approx 0.5$ s for the controller. When reaching the new steady state, the proportional part of the controller contributes almost nothing, and therefore, we have

$$v_c^* = v_t^{\rm steady}(t)\left[1 + K_I\int_0^{5\tau}\Delta V_t(t)\,dt\right]. \quad (5)$$

Since in this study, PWM works only in the linear area, the amplitude of the triangle carrier signal is $0.5 \times V_{\rm dc}$, so for the fundamental frequency component, compensator output voltage $v_c^*$ defined by (1) should be equal to $v_c$. Replacing $\Delta V_t(t)$ with $\Delta V_{t0}e^{-(t/\tau)}$ and $v_c^*$ with $v_c$, we have

$$K_I = \frac{\frac{V_c^{\rm steady}}{V_t^{\rm steady}} - 1}{\int_0^{5\tau}\Delta V_{t0}e^{-(t/\tau)}\,dt} \quad (6)$$

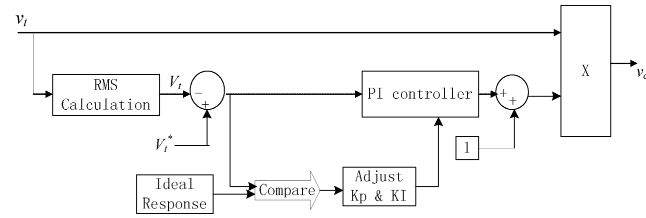


Fig. 6. Adaptive control of the voltage regulation.

where $(V_c^{\rm steady})/(V_t^{\rm steady})$ is the ratio of converter output voltage to the voltage at the PCC which equals $V_t^*$ in the steady state. $V_c^{\rm steady}$ can be calculated in the worst-case situation, which assumes a maximum voltage variation $\Delta V_{t0}$ such as under peak load condition. The initial value of $K_I, K_{I0}$, is set to half of the RHS value in (6) to be conservative for the same reason as $K_{P0}$.

### C. Adaptively Adjusting the PI Controller Gain Parameters

The controller with fixed $K_P$ and $K_I$ may not always reach the desired and acceptable response in power systems since system load and other conditions are constantly changing. Without a centralized communications and control system, the controller has to utilize some self-learning capability to adjust $K_P$ and $K_I$ dynamically. In the case of local voltage needing to be increased as an example, if the control logic shows voltage has increased too rapidly, then $K_P$ and $K_I$ will be adjusted to lower values; contrarily for when it is too slow, $K_P$ and $K_I$ will be adjusted to higher values. Certainly, this needs additional logic to check the present voltage response with respect to the desired voltage response.

Fig. 6 shows the overall logic of the adaptive control method. The key processes of this approach are:

- The voltage deviation of the ideal response $\Delta V_t(t) = \Delta V_{t0}e^{-(t/\tau)}$ is used as the reference. In every step, the actual voltage deviation and the desired voltage deviation are monitored and a scaling factor $r_v = ({\rm actual\ voltage\ deviation})/({\rm ideal\ voltage\ deviation})$ is calculated. Here the *actual voltage deviation* is the voltage difference between the measured $V_t$ and the reference $V_t^*$; and the *ideal voltage deviation* is the difference between the exponential voltage curve and the reference $V_t^*$.
- Next, $K_P$ and $K_I$ are multiplied by the scaling factor $r_v$. When the actual response is faster than the desired exponential curve, it will be slowed down with $K_P$ and $K_I$ multiplied by $r_v < 1$. Similarly, when the actual response is slower than the desired exponential curve, it will be speeded up with $K_P$ and $K_I$ multiplied by $r_v > 1$. This approach avoids the possible issues of slow response, overshoot, oscillation, or instability.

The method of adaptive control is illustrated in Fig. 7. Certainly, some threshold can be applied when scaling $K_P$ and $K_I$ to avoid having too frequent updates. For instance, if the scaling factor $r_v$ is very close to 1.0, no updating is needed and thus the controller can impose maximum and minimum limits for $r_v$ to avoid unnecessary updates.

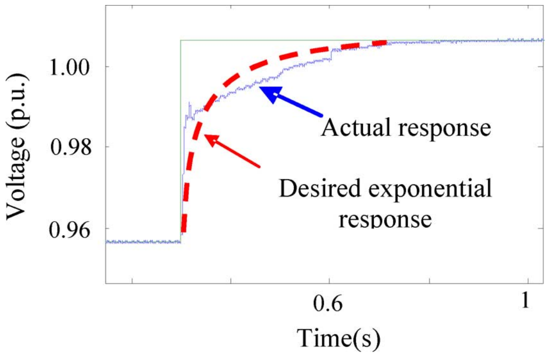


Fig. 7. Desired and actual response of the controller.

The first advantage of this algorithm is the dynamic adjustment of the control parameters $K_P$ and $K_I$ for voltage regulation. Another advantage in addition to performance is the elimination of an extensive and expensive centralized communications system because the parameters track the locally defined ideal voltage response curve. The high frequency sampling rate of modern power electronics and sensors ensures this as demonstrated in the simulations and field testing. Hence, the approach is termed "adaptive voltage control".

## IV. Analytical Formulation of the Adaptive Method

The previous section presented the fundamental idea and algorithm for dynamic $K_P$ and $K_I$ adjustment based on a desired exponential response. Because of the fast data sampling rate, such as 12.5 kHz, in the PI control implementation, this adaptive approach can be very effective as shown in the simulation and field experiment in Sections V and VI, respectively.

The adaptive method in Section III may raise the issue of its validity and thus the question: *Can the adaptive algorithm be expressed in an analytical formulation to provide a theoretical foundation?* If so, it can be verified and generalized to work in other systems. This section will present a theoretical approach for the rigorous formulation of $K_P$ and $K_I$ as functions of time or time-dynamic. The dynamic $K_P$ and $K_I$ values can be calculated from equations and thus the heuristic approach of the adaptive method of previous section can be benchmarked for verification and validity.

First, the DE source, $v_c$, is modeled as a voltage source connected to Bus $i$, as shown in Fig. 8. Without losing generality, it is assumed there may be a voltage source (substation) at each bus. The voltage source, $v_{sl}\,(l = 1 \sim n)$, can be set to 0 if no source exists. In the Laplace $(S)$ domain, the nodal voltage equations can be expressed as

$$Y(s)\begin{bmatrix} v_{t1}(s) \\ \vdots \\ v_{ti}(s) \\ \vdots \\ v_{tn}(s) \end{bmatrix} = \begin{bmatrix} \frac{v_{s1}(s)}{R_1+sL_1} \\ \vdots \\ \frac{v_c(s)}{sL_c} + \frac{v_{si}(s)}{R_i+sL_i} \\ \vdots \\ \frac{v_{sn}(s)}{R_n+sL_n} \end{bmatrix} \tag{7}$$

where $Y(s)$ is the admittance matrix of the system; $v_{ti}(s)$ is the voltage at bus $i$; $v_{sl}(s)$ is the voltage source at bus $l$ $(l = 1 \sim n)$,

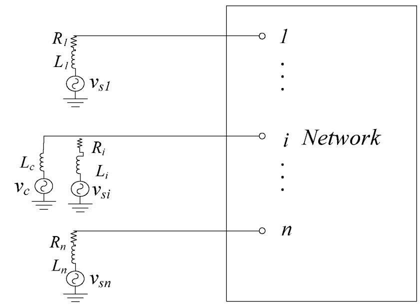


Fig. 8. Schematic diagram of a network and sources.

excluding the DE source output voltage; $R_l + L_l$ is the equivalent impedance for the electrical connection from the voltage source $v_{sl}$ to the terminal buses $l$; $v_c(s)$ is the DE source; and $L_c$ is the inductance for the DE to the terminal bus $i$ connection.

From (7), we can derive the voltages vector as

$$\begin{bmatrix} v_{t1}(s) \\ \vdots \\ v_{ti}(s) \\ \vdots \\ v_{tn}(s) \end{bmatrix} = Z(s)\begin{bmatrix} \frac{v_{s1}(s)}{R_1+sL_1} \\ \vdots \\ \frac{v_c(s)}{sL_c} + \frac{v_{si}(s)}{R_i+sL_i} \\ \vdots \\ \frac{v_{sn}(s)}{R_n+sL_n} \end{bmatrix} \tag{8}$$

where the impedance matrix $Z(S) = [Y(S)]^{-1}$.

From (8), we can obtain the regulated voltage at bus $i$ as follows:

$$v_{ti}(s) = Z_{ii}(s)\frac{v_c(s)}{sL_c} + \sum_{l=1}^{n} Z_{il}(s)\frac{v_{sl}(s)}{R_l + sL_l} \tag{9}$$

where $Z_{ii}\,(S)$ and $Z_{il}(S)$ are the corresponding elements of the matrix $Z(S)$, which only depends on the network parameters.

Given the desired voltage at Bus $i$, we can calculate the support voltage requirement for the DE from (9) as

$$v_c(s) = \frac{v_{ti}(s) - \sum_{l=1}^{n} Z_{il}(s)\frac{v_{sl}(s)}{R_l+sL_l}}{Z_{ii}(s)} \cdot sL_c \tag{10}$$

and $v_c^*$ defined by (1) should be equal to $v_c$, that is

$$v_{ti}(s) \cdot \left[1 + \left(K_P(s) + \frac{K_I(s)}{s}\right)\Delta V_{ti}(s)\right] = v_c(s) \tag{11}$$

where $\Delta V_{ti}(s)$ is the deviation of the RMS value of voltage at Bus $i$ from the reference RMS value $V_{ti}^*(s)$. The PI controller gains are time variant, so they are expressed as $K_P(s)$ and $K_I(s)$.

Since in the adaptive approach, $K_P(s)$ and $K_I(s)$ follow the same pattern to be adjusted, we let $K_I(s) = mK_P(s)$, where $m$ is $K_{I0}/K_{P0}$, the ratio of the initial values of $K_I$ and $K_P$. When we substitute this into (11), we have

$$v_{ti}(s) \cdot \left[1 + \left(K_P(s) + \frac{mK_P(s)}{s}\right)\Delta V_{ti}(s)\right] = v_c(s). \tag{12}$$

Hence

$$K_P(s) = \frac{\frac{v_c(s)}{v_{ti}(s)} - 1}{\Delta V_{ti}\left(1 + \frac{m}{s}\right)}. \tag{13}$$

Since $v_{ti}(s)$ has a zero-crossing value, the ratio of the RMS values of $v_c(s)$ over $v_{ti}(s)$ is used to replace the ratio of the instantaneous values, which is reasonable because we only have the fundamental element. Thus, (13) can be rewritten as

$$K_P(s) = \frac{\frac{\mathrm{V}_c(s)}{\mathrm{V}_{ti}(s)} - 1}{\Delta V_{ti}\left(1 + \frac{m}{s}\right)}. \quad (14)$$

Based on the assumption that the ideal voltage response is an exponential response, we have

$$\Delta V_{ti}(s) = \frac{\Delta V_{\max}}{s + 1/\tau} \quad (15)$$

where $\Delta V_{\max}$ is the magnitude of the voltage step change and $\tau$ is the time constant, which can be defined according to the users' requirement for the response speed.

Hence, the voltage at Bus $i$ can be derived as

$$v_{ti}(t) = \left(V_{ti}^* - \Delta V_{\max} e^{-\frac{t}{\tau}}\right) \cos(2\pi f t + \phi) \quad (16)$$

and

$$V_{ti}(s) = \left(V_{ti}^* - \frac{\Delta V_{\max}}{s + 1/\tau}\right) \quad (17)$$

where $\phi$ is the phase angle of the voltage at terminal Bus $i$, and $f$ is the fundamental frequency.

By substituting (10), (15), and (17) into (14), we can finally calculate $K_P(s)$ and hence $K_I(s)$. They are given as

$$K_P(s) = \frac{\frac{\mathrm{RMS}\left(\frac{A}{Z_{ii}(S)} \cdot sL_c\right)}{\left(V_{ti}^* - \frac{\Delta V_{\max}}{s+1/\tau}\right)} - 1}{\Delta V_{ti}\left(1 + \frac{m}{s}\right)} \quad (18)$$

$$K_I(s) = m \frac{\frac{\mathrm{RMS}\left(\frac{A}{Z_{ii}(S)} \cdot sL_c\right)}{\left(V_{ti}^* - \frac{\Delta V_{\max}}{s+1/\tau}\right)} - 1}{\Delta V_{ti}\left(1 + \frac{m}{s}\right)} \quad (19)$$

$$\text{where} : A = v_{ti}(s) - \sum_{l=1}^{n} Z_{il}(s) \frac{v_{sl}(s)}{R_l + sL_l}. \quad (20)$$

Thus, we have proven that theoretical formulations for both $K_P(s)$ and $K_I(s)$ exist for the ideal, exponential response of the voltage regulation. These formulations will be used to confirm that the heuristic approach for adaptive control is equivalent to using $K_P(s)$ and $K_I(s)$ in (18) and (19).

However, practically in most application cases, we do not have enough data to calculate $K_P(s)$ and $K_I(s)$. Even if we do, it is a tedious and error-prone work to perform since many distribution system parameters are involved. However, given the reference voltage and the desired response speed, $K_P$ and $K_I$ can be automatically adjusted as shown in the adaptive algorithm of Section III to track the defined ideal response.

Fig. 9 shows the comparison of the value of $K_P$ calculated by the theoretical (18) and by the adaptive algorithm in Section III. The simulation is performed on the system shown in Fig. 3 with the DE modeled as an ideally controlled voltage source. A load increase is applied at 0.2 s to mimic a voltage sag. The desired compensator response time is 0.5 s so it must reach the original voltage schedule at 0.7 s. The solid blue line is $K_P$ calculated theoretically using (18) and the dashed red curve is $K_P$ generated by the adaptive control approach. As can be seen, these two curves are extremely close, thus verifying the heuristic approach with the theoretical formulations. Similarly, Fig. 10 shows the comparison of $K_I$ for the two methods which again shows an extremely close match. In addition, Fig. 11 shows the voltage regulation results by adjusting $K_P$ and $K_I$ with the two methods. The dashed red line is the defined ideal response. The solid blue line is the voltage response of adaptive control approach and the dash-dot black line is the voltage response with $K_P$ and $K_I$ calculated by (18)–(19); and the dotted red (flat) line is the reference voltage.

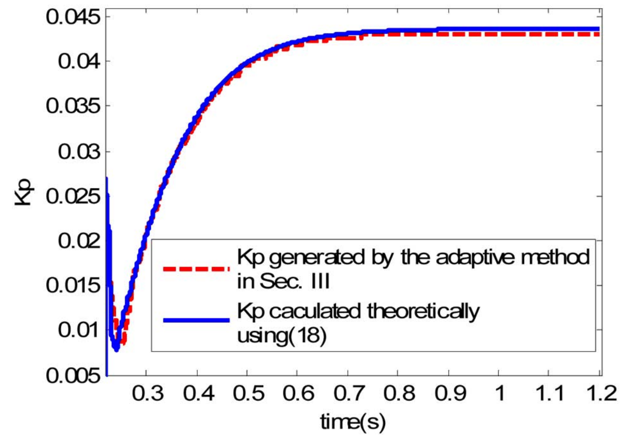

Fig. 9. Comparison of the value of $K_P$ generated by the two methods.

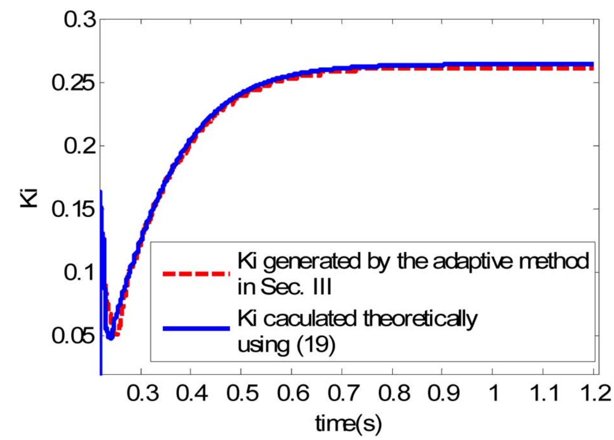

Fig. 10. Comparison of the value of $K_I$ generated by the two methods.

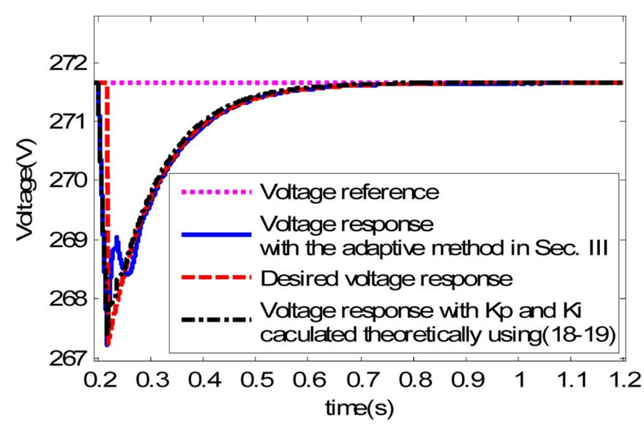

Fig. 11. Tracking ideal response by adjusting $K_P$ and $K_I$ with the two methods.

The results in Figs. 9–11 verify the equivalence of (18)–(19) with the adaptive algorithm of Section III thus verifying the heuristic approach with a theoretical foundation. The ideal response, defined as an exponential response, can be achieved by dynamically adjusting $K_P$ and $K_I$.

## V. Simulation Results

In this section, a step-by-step example is shown to illustrate how to implement the heuristic adaptive algorithm for voltage regulation, discussed in Section III. The system in Fig. 3 is used again for illustration.

### A. Initial Parameter Setting

As before, the DE is connected at Bus 3. The line-to-line voltage on the consumer side of the infinite bus is assumed to be 480 V (RMS). The total load of the system is 70.18 kVA (59 kW, 38 kVar). We assume that the heaviest load condition is when the loads at Bus 4 and Bus 6 increase by 20.93 kVA (20.3 kW, 5.08 kVar) and 27.94 kVA (27.1 kW, 6.8 kVar), respectively. The desired phase voltage profile at Bus 3 is 271.65 V (line-to-neutral, RMS); however, the phase voltage at Bus 3 for the peak load condition is 267.2 V. From this information, we can determine the DE requirements for voltage regulation.

*1) Calculate the DC Voltage Requirement of the DE* $(\mathrm{V_{dc}})$*:* Here the DE and the substation bus can be viewed as the voltage resources. Hence, the voltage at the load buses, such as Bus 3, can be expressed as follows:

$$\bar{V}_3 = a_{3,\mathrm{sub}}\bar{V}_{\mathrm{sub}} + a_{3,\mathrm{DE}}\bar{V}_c$$

where $\bar{V}_3$ is the voltage at Bus 3; $\bar{V}_{\mathrm{sub}}$ is the voltage at the substation bus, which can be viewed as constant; $\bar{V}_c$ is the output voltage of the DE; and the coupling coefficients $a_{3,\mathrm{sub}}$ and $a_{3,\mathrm{DE}}$ represent the sensitivity between the two bus voltages (i.e., $)\partial\bar{V}_3/\partial\bar{V}_{\mathrm{sub}})$ and $(\partial\bar{V}_3/\partial\bar{V}_c)$, respectively), which can be calculated with network parameters or sensitivity analysis.

In this case, we have

$$\bar{V}_3 = (0.8359 + 0.022i)\bar{V}_{\mathrm{sub}} + (0.1278 - 0.0559i)\bar{V}_c$$

and the real power injection from DE, $P$, is given by

$$P = \frac{V_3 V_c}{\omega L_c}\sin(\alpha_c - \alpha_3).$$

$\alpha_c$ and $\alpha_3$ are the phase angles of $\bar{V}_c$ and $\bar{V}_3$, respectively. Here, the real power injection from the DE, i.e., $P$, is set to 35 kW. Also, since the regulation goal is to maintain a voltage schedule at $V_3 = 271.65$ V, we calculate $V_c = 286.9$ V.

Then, considering $V_{\mathrm{dc}} \geq 2V_c^p = 2\sqrt{2} \times V_c$ as shown in (2), we can determine that the dc voltage for the DE should be no less than 811 V, and so we choose 900 V.

*2) Initialize* $K_P$*:* The initial value of $K_P$ can be calculated based on (4):

$$K_{P0} = 0.5 \times \frac{\frac{\frac{1}{2}V_{\mathrm{dc}}}{V_t^{0,p}} - 1}{\Delta V_t^0} = 0.5 \times \frac{\frac{900/2}{\sqrt{2}\times 267.2} - 1}{271.65 - 267.2} = 0.021.$$

*3) Initialize* $K_I$*:* The initial value of $K_I$ can be calculated based on (6):

$$K_{I0} = 0.5 \times \frac{\frac{V_c^{\mathrm{steady}}}{V_t^{\mathrm{steady}}} - 1}{\int_0^{5\tau} \Delta V_{t0} e^{-\frac{t}{\tau}} dt} = 0.5 \times \frac{286.9/271.65 - 1}{\int_0^{0.5} (271.65 - 267.2) e^{-\frac{t}{0.1}} dt} = 0.127.$$

### B. Simulation Results of the Adaptive Control Approach

The adaptive control approach is tested on a DE with an inverter interface. After detecting a large voltage deviation at 0.2 s, the difference of the two voltages is checked every quarter cycle for possible adjustment of $K_P$ and $K_I$. Fig. 12 shows the voltage regulation with adaptive adjustment of $K_P$ and $K_I$. The dotted blue line is the desired voltage response while the solid red line is the actual voltage response. As indicated, the actual voltage tracks the desired voltage response and satisfies the 0.5 s response time requirement. Fig. 13 shows the comparison of the desired and actual voltage deviations. The actual voltage response matches the reference voltage except at the very beginning of the adjustment. The reason for the relatively large difference at the very beginning is due to the initially high sensitivity of voltage and the dominance of the proportional part in (1) over the integral part. Hence, any small inaccuracy tends to lead to a relatively large difference. However, when time approaches 0.3 s, the proportional part has less weight and the integral part has more effect. Therefore, the actual voltage response curve is controlled very close to the desired curve. In addition, Figs. 14 and 15 are the real and reactive power injections, respectively, during the voltage regulation. It should be noted that the P injection in Fig. 14 remains constant except for some small ripples around 0.2–0.4 s, simply because of the terminal voltage dynamics.

For verification purpose, Fig. 16 shows the nonadaptive voltage regulation with gains fixed to their initial values of $K_{P0}$ and $K_{I0}$. The response is much slower as compared to the adaptive control approach. Instead of 0.5 s, it takes more than 1 s to reach the voltage reference. Thus, the proposed adaptive control provides greater response efficiency.

## VI. Field Experiment Results

Field tests were conducted at the Oak Ridge National Laboratory (ORNL)'s Distributed Energy Communications & Controls (DECC) Laboratory, which is interfaced to the ORNL distribution system and receives its power from the Tennessee Valley Authority (TVA)'s bulk transmission system as shown in Fig. 17. The inverter of the DE test system, which is rated at 150 A, is connected to a 480 V/600 A power panel (Panel PP3) that is fed from circuit #2 of the 3000 substation of the ORNL distribution system.

A sudden load change of 20 kW (from 80 to 100 kW) and 37.5 kVar (from 37.5 to 75 kVar) is applied which causes a voltage sag in the system. The load change results in a sustained voltage drop if there is no voltage regulation. The PCC voltage at the inverter (average RMS of all three phases) is shown in Fig. 18

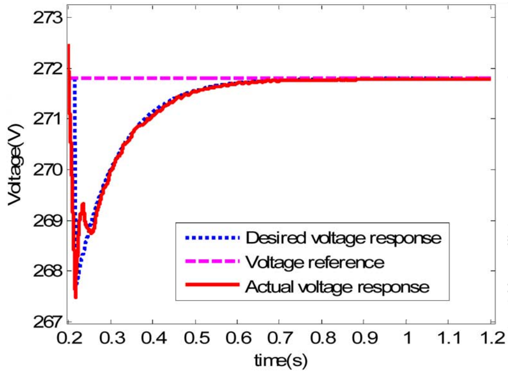


Fig. 12. Voltage regulation with adaptive adjustment of $K_P$ and $K_I$.

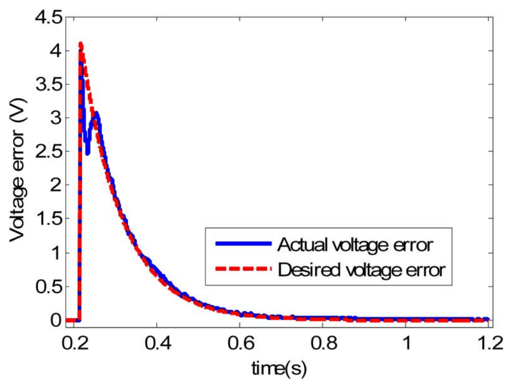


Fig. 13. Comparing the desired and actual voltage deviations.

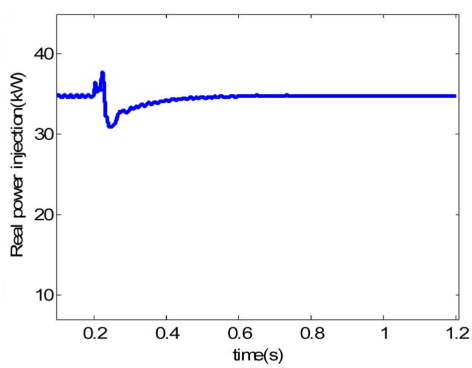


Fig. 14. Real power injection.

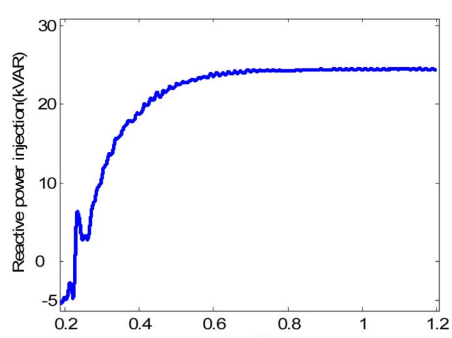


Fig. 15. Reactive power injection.

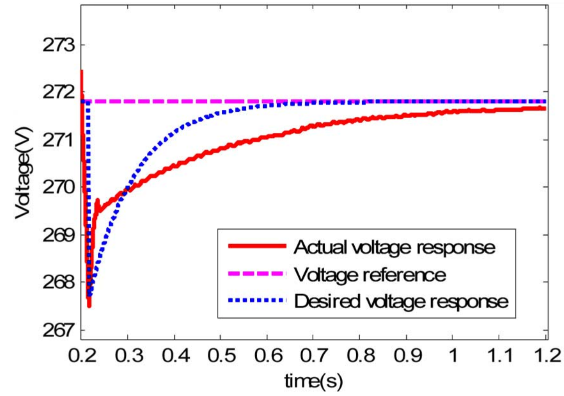


Fig. 16. Nonadaptive voltage regulation with $K_P$ and $K_I$ fixed at the initial values.

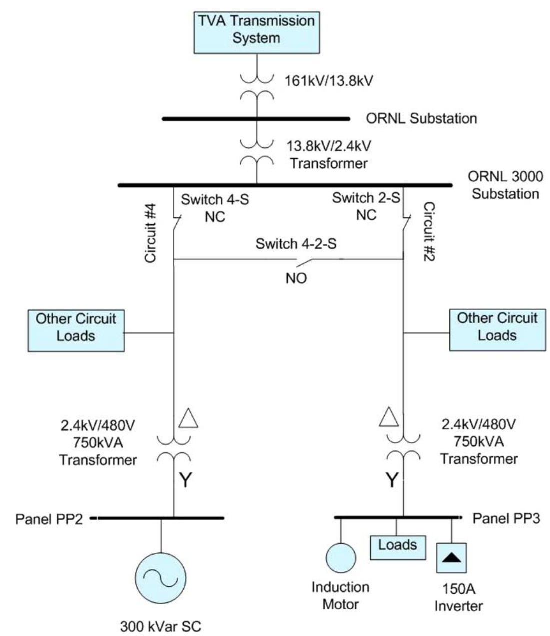


Fig. 17. ORNL's DECC Laboratory.

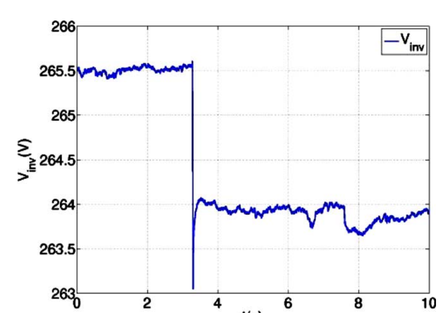


Fig. 18. PCC voltage at the inverter without voltage regulation.

when there is no voltage regulation. The voltage drops 1.5 V because of the load increase. Fig. 19 shows the PCC voltage (at Panel PP3 in Fig. 17) using the DE to provide voltage regulation with the nonadaptive approach. The same load change is applied during the voltage regulation test and the response time is 2.42 s. By applying the same sudden load change as shown in Fig. 18, the adaptive voltage regulation control is implemented and the test results are shown in Fig. 20. The response time is significantly shortened to 0.44 s without any overshoot or oscillation

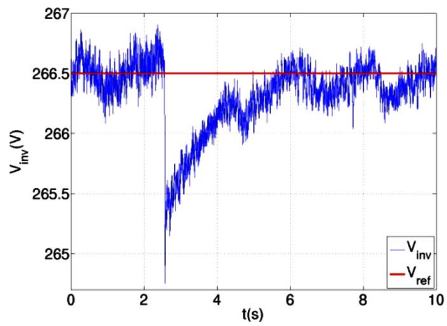


Fig. 19. PCC voltage (in RMS) with nonadaptive voltage regulation.

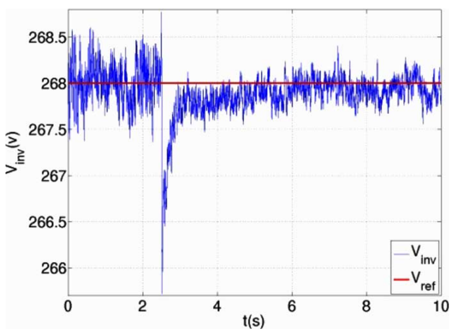


Fig. 20. PCC voltage (in RMS) with adaptive voltage regulation.

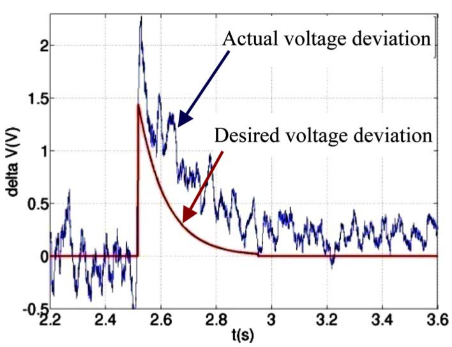


Fig. 21. Comparison of the desired and actual voltage deviations.

or instability problem. Fig. 21 shows the actual voltage deviation from the experiment (blue line with ripples) and the desired voltage deviation under the ideal exponential response (smooth red line). The actual deviation decay time closely matches the $5\tau$ decay time of the ideal curve (0.5 s). The experimental result verifies the advantage of the adaptive control approach.

## VII. Conclusion and Future Work

The voltage control of the electric power system is a complex issue and is driven by the availability and transport of reactive power. DEs can be part of the solution to prevent voltage instability and possible voltage collapse since they can control reactive power injection and voltage locally and dynamically with the right controls and capacity. There has been work conducted in related areas, such as setting the voltage profile with distributed generation, DE interface design, and controller structure design for voltage regulation with DE. However, little work has been done in utility application of DEs for voltage regulation, which needs to consider the dynamic impacts on actual distribution networks. Parameter setting for the compensation controllers for inverter-based DE, especially, is an overlooked area. This is the targeted contribution of this research work. The findings and contribution of this paper can be summarized as follows:

- If the PI control parameters are not appropriately chosen, this may lead to voltage response problems including oscillation, slow response, or even instability.
- An adaptive voltage control approach using PI feedback control which is based on the local voltage variation and nonactive power theory is developed. The approach has a wide adaptability and is easy to implement by practicing engineers since it does not require detailed system data or extensive simulations.
- A theoretical analysis proves the existence of a corresponding analytical formulation of the dynamic control parameters, $K_P$ and $K_I$, for the adaptive approach. Since the theoretical formulation requires detailed system parameters, it is not preferred for practicing utility engineers. However, the analytical formulation shows that the adaptive approach has a solid theoretical foundation.
- Finally, the simulation and field experiment results show that the proposed adaptive approach satisfies the rapid response and performance requirements needed for integration with existing system equipment. The adaptive voltage control approach and experimental verification make this paper unique from many previous works which are based on simulation only.

In future work, additional research needs to focus on using multiple DEs to control voltage with the adaptive control approach as well as the theoretical analysis. Field experiments with multiple DEs can follow when a second inverter test system is completed at the DECC Lab in the near future. Also, research work on more complicated real power control for frequency regulation may be studied for the Microgrid or the Smart Grid application. In addition, voltage schedules are assumed to be given in this work. The actual assignment of voltage schedules based on seasonal or emergent conditions can also be a future research topic.

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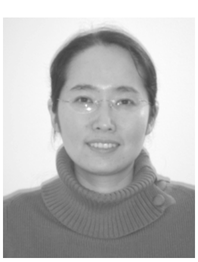

**Huijuan Li** (S'07) received the B.S.E.E. and M.S.E.E. degrees in electrical engineering from North China Electrical Power University, Beijing, China, in 1999 and 2002, respectively. She is presently pursuing the Ph.D. degree in electrical engineering at The University of Tennessee (UT), Knoxville.

She previously worked as a Research Engineer at Shanghai Siyuan Electrical Company, Shanghai, China, on the field of ungrounded neutral distribution systems from 2002 to 2006.

Ms. Li's poster presentation based on this paper won the First Place Prize award at the Student Poster Contest during IEEE PES General Meeting 2009 (GM09), held in Calgary, AB, Canada, in July 2009.

**Fangxing (Fran) Li** (M'01–SM'05) received the B.S.E.E. and M.S.E.E. degrees from Southeast University, Nanjing, China, in 1994 and 1997, respectively, and the Ph.D. degree from Virginia Tech, Blacksburg, in 2001.

He has been an Assistant Professor at The University of Tennessee (UT), Knoxville, since August 2005. Prior to joining UT, he worked at ABB Electrical System Consulting (ESC), Raleigh, NC, as a Senior and then a Principal R&D Engineer for 4 and a half years. His current interests include distributed energy resources, reactive power, energy market, and reliability.

Dr. Li is a registered Professional Engineer in the state of North Carolina.

**Yan Xu** (S'02–M'06) received the B.S. degree from Shanghai Jiaotong University, Shanghai, China, in 1995, the M.S. degree from North China Electric Power University, Beijing, China, in 2002, and the Ph.D. degree in electrical engineering at The University of Tennessee, Knoxville, in 2006.

She is currently working as a research staff member at Oak Ridge National Laboratory (ORNL), Oak Ridge, TN. Her research interests include power electronics applications in power systems and utility interface of distributed energy resources.

**D. Tom Rizy** (M'77–SM'87) received the M.S.E.E. and B.S.E.E. degree from Virginia Tech, Blacksburg, and the University of Virginia, Charlottesville, respectively.

He is a Senior Research Power Systems Engineer in the Power & Energy Systems Group at Oak Ridge National Laboratory (ORNL), Oak Ridge, TN. His current interest and activities focus is on new controls for distributed energy resources (DE) and applications for synchro-phasor measurements. He is a co-founder of the Distribution Energy Communications and Control Laboratory (DECC) at ORNL for testing dynamic voltage regulation controls using DE. He has over 30 years of experience in power systems R&D. He is a chapter author of the book on the Athens Automation and Control Experiment, a large-scale distribution automation project conducted in the late 1980s by DOE, TVA, and EPRI.

Mr. Rizy is a co-recipient of the IEEE Prize Paper Award (1990) for "Adaptive relaying concepts for improved performance". He is the chair of the IEEE PES Volt/Var Control Task Force and co-chair of the WG on Smart Grid Sensors.

**John D. Kueck** (M'75–SM'00) received the B.S. degree in physics from Purdue University, West Lafayette, IN, in 1971 and the M.S. degree in electrical engineering—power systems, from Ohio State University, Columbus, in 1972.

Over the first 20 years of his career, he worked in the design and operation of fossil fuel and nuclear generating stations. From 1992 to the present, he has been a researcher at the Oak Ridge National Laboratory, Oak Ridge, TN. His major interest is the local supply of reactive power from distributed energy resources as a reliability service.