Coordination of Multiple Distributed Energy Resources to Regulate the Voltage using Adaptive Voltage Control Method

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Abstract: An adaptive voltage control method has been proposed to dynamically modify the control parameters of a single Distributed energy (DE) to respond to system changes such that the ideal response can be achieved. Theoretical analysis shows that a corresponding formulation of the dynamic control parameters exists; hence, the adaptive control method is theoretically solid. Then, control methods have been discussed in the case of multiple Distributed energy resources regulating voltages considering the availability of communications among all the Distributed energy resources. When communications are readily available, a method is proposed to directly calculate the needed adaptive change of the Distributed energy resource control parameters in order to achieve the ideal response. When there is no communication available, an approach to adaptively and incrementally adjust the control parameters based on the local voltage changes is proposed. Since the impact from other Distributed energy resources is implicitly considered in this approach, multiple Distributed energy resources can collectively regulate voltages closely following the ideal response curve.

Keywords: Distributed energy resources, Adaptive Voltage Control, point of common coupling (PCC).

I. INTRODUCTION

Conventionally, electrical power is generated centrally and transported over a long distance to the end users. However, since the last decade, there has been increasing interest in distributed energy resources (DE). Contrary to the conventional power plants, DE systems are small-scale electric power sources, typically ranging from 1kW to 10MW, located at or near the end users. Typically, DE includes distributed generation (DG), distributed energy storage, and demand response efforts. A DE with a PE interface can provide a wide range of ancillary services, including voltage regulation which has drawn much interest because of the reactive power shortage and transportation problems in power systems. In this section, the implementation of a PE interface and control design for voltage regulation is introduced. Fig1 shows a parallel connection of the DE with a distribution system through a PE interface. The PE interface includes the inverter, a DC side capacitance or Vdc, and a DE such as a fuel cell, solar panel, or energy storage supplying a DC current. Coupling inductors Lc are also inserted between the inverter and the rest of the system.

Fig1. Parallel connection of a DE with PE converter.

The PE interface is referred to as the compensator because voltage regulation using the DE is our primary concern. 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 Rs+jωLs. The parallel compensator is connected through the coupling inductors Lc at the point of common coupling (PCC). The PCC voltage is denoted as Vt. By generating or consuming a certain amount of reactive power, the compensator regulates the PCC voltage Vt. An instantaneous non-active power theory [9][10] is adopted for the real-time calculation and control of DE voltage regulation. Here, non-active power can be referred to as reactive power in the fundamental frequency plus non-fundamental frequency harmonics. In all the following equations, all the definitions are functions of time t. For instantaneous voltage v(t) and instantaneous current i(t):

\[ v(t) = [v_x(t), v_y(t), v_z(t)]^T \]  
\[ i(t) = [i_x(t), i_y(t), i_z(t)]^T \]  

Instantaneous real power p(t) and average real power P(t) are defined as:

\[ p(t) = v(t)^T i(t) = \sum_{k=1}^{3} v_k(t) i_k(t) \]
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\[ P(t) = \frac{1}{T_c} \int_{-\infty}^{\infty} p(\tau) d\tau \]  
\[ V(t) = \frac{1}{\sqrt{T_c}} \int_{-\infty}^{\infty} v^*(\tau) v(\tau) d\tau \]  
\[ I(t) = \frac{1}{\sqrt{T_c}} \int_{-\infty}^{\infty} i^*(\tau) i(\tau) d\tau \]

In a periodic system with period \( T \), \( T_c \) is normally chosen as integral multiples of \( T/2 \) to eliminate current harmonics. \( V(t) \) and \( I(t) \) are defined as:

As pointed out in \([9][10]\), the generalized definition of non-active power extends the traditional definition of instantaneous non-active power from three-phase, balanced, and sinusoidal systems to more general cases. This unique feature makes it easy to apply in practical distribution systems in which there are challenges like single-phase, non-sinusoidal, unbalanced, and non-periodic waveforms. Therefore, it is suitable for real-time control in a real-world system and provides advantages for the design of control schemes. A voltage regulation method is developed, based on the system configuration in Figure 1.1, with a PI feedback controller. The control diagram is shown in Figure 1.2. 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, and on-and-off peak).

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 the 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 regulate \( V_t \) to the reference \( V_t* \). The control scheme can be specifically expressed as:

\[ V_c* = V_t(t) + K_P (V_t(\tau) - V_t* + K_I \int (V_t(\tau) - V_t*) d\tau) \]  
\[ V_c* = V_t(t) + K_P (V_t(\tau) - V_t*) + K_I \int (V_t(\tau) - V_t*) d\tau \]  

Where \( K_P \) and \( K_I \) are the proportional and integral gain parameters of the PI controller.

Equation (7) leads to reactive injection only when \( V* \) is in phase with \( V_t \). However, if a real power injection is also needed, it can be simply implemented using a desired phase angle shift applied to \( V^*c \) in Eq. (7) because of the tight coupling between real power and phase angle.

\[ V_c = V_t [1 + P_e/V_o] \]  
\[ V_c = V_t [1 + P_e/V_o] \]  
\[ V_c = V_t [1 + P_e/V_o] \]  

Where \( P_e \) is the real power error.

II. ADAPTIVE VOLTAGE CONTROL WITH A SINGLE DE

The controller with a 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 communication and control system, the controller has to utilize a self-learning capability to adjust \( K_P \) and \( K_I \) dynamically. Using the case of local voltage requiring an increase as an example, if the control logic shows that the voltage has increased too rapidly, then \( K_P \) and \( K_I \) will be adjusted to lower values. On the contrary 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. Figure 3 shows the overall logic of the adaptive control method. The key processes of this approach are:

\[ V_c* = V_t(t)[1 + K_P(V_t*(t) - V_t(t))] \]  
\[ V_c* = V_t(t)[1 + K_P(V_t*(t) - V_t(t))] \]  
\[ V_c* = V_t(t)[1 + K_P(V_t*(t) - V_t(t))] \]  

To keep the PWM modulation index, \( ma \), 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 5.0 x \( V_{dc} \). Hence, we have:

\[ K_P \leq \frac{\frac{1}{2} V_{dc}}{V_o} - 1 \]  
\[ K_P \leq \frac{\frac{1}{2} V_{dc}}{V_o} - 1 \]  
\[ K_P \leq \frac{\frac{1}{2} V_{dc}}{V_o} - 1 \]  

The initial value of \( K_P, K_I \) can be empirically set to half of the RHS value defined by (9), when considering efficiency and error tolerance. Certainly, more research may be preferred regarding the choice of \( K_P \) other than half of the RHS value in (9). 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. The fundamental idea and algorithm for a 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
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The adaptive approach can be very effective as shown in the following simulation and field experiments in last chapter. Where only DEs are shown while the controllers are not drawn for simplicity. The nodal voltage equation can be expressed as:

\[
Y(s) \begin{bmatrix} v_{i1}(s) \\ \vdots \\ v_{in}(s) \end{bmatrix} = \begin{bmatrix} \frac{v_{i1}(s)}{R_i + sL_i} \\ \vdots \\ \frac{v_{in}(s)}{R_i + sL_i} \end{bmatrix}
\]

where \(Y(s)\) is the admittance matrix of the system; \(v_{il}(s)\) is the voltage at Bus \(i\); \(v_{il}(s)\) is the voltage source at Bus \(l\) (\(l=1\ldots n\)), excluding the DE source; \(R_i+sL_i\) 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 Equation (1.3.1), we can derive the voltage’s vector as:

\[
Y(s) \begin{bmatrix} v_{i1}(s) \\ \vdots \\ v_{in}(s) \end{bmatrix} = \begin{bmatrix} \frac{v_{i1}(s)}{R_i + sL_i} \\ \vdots \\ \frac{v_{in}(s)}{R_i + sL_i} \end{bmatrix}
\]

Where the impedance matrix is \(Z(S) = [Y(S)]\) From Eq. (11), we can obtain the regulated Voltage at Bus \(i\) as follows:

\[
v_c(s) = Z(s) v_i(s) + \sum_{l=1}^{n} Z(s) v_{sl}(s)
\]

Where \(Z(S)\) and \(Z(s)\) 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 (2) as:

\[
v_{il}(s) = \frac{v_c(s) - \sum_{l=1}^{n} Z(s) v_{sl}(s)}{Z_{ii}(s) \cdot R_i + sL_i}
\]

As we know the equation of

\[
v_c(s) \cdot [1 + K(s) \cdot \frac{sL_c}{s}] = v_i(s)
\]

III. ADAPTIVE VOLTAGE CONTROL WITH A MULTIPLE DE

When multiple DEs connected in the systems participate in the voltage regulation, the interference among these DEs makes the voltage control process more complicated. As shown in the simulations in next chapter, the controller parameters suited for voltage regulation with a single DE may fail to generate satisfactory performance in voltage regulation in the two DEs case. The problem of coordination among all the DE controllers needs to be considered as the DEs have similar response time that may cause them to chase each other which could lead to instability or oscillations.

![Fig. 4. A radial test system installed with two Des.](image)

Note that in a practical operation, we may choose only a limited number of DEs for voltage control, similar to the practice in AGC control. DEs with voltage regulation ability can bid for providing this service such as in the ancillary service market. This should reduce complexity while maintaining an acceptable efficiency. However, the exploration of how to implement the process of choosing voltage regulating DEs in a large distribution system is beyond the scope of this research and therefore will not be discussed in this dissertation. Instead, it is assumed that the locations of the voltage regulating DEs are known.

In next chapter simulations, it is assumed that two DEs are installed at bus 3 (DE1) and bus 6 (DE2), respectively, as shown in Fig. 4. The real power injection of DE1 and DE2 is 30kW and 10kW, respectively, and remains constant. The voltage references for bus 3 and bus 6 are 275.85 v and 275.70 v. Assume after a load increase, the voltages at bus 3 and bus 6 drop to 270.85 v and 270.70 v, respectively. The adjustment cycle is 1/60 s (i.e., the adjustment frequency is aligned with the electricity frequency).

A. Calculating the coefficient vector.

\[
\frac{\partial f_1}{\partial V_1} = \begin{bmatrix} \frac{\partial f_1}{\partial V_2} \\ \vdots \\ \frac{\partial f_1}{\partial V_n} \end{bmatrix}
\]

\[
V(0) = [270.85, 270.70]^T, Vc(0) = [271.1726, 270.1228]^T.
\]

Increase DE output voltage by \(\Delta Vc = [0.1, 0.1]^T\) and \(\Delta Vc = [0.1, 0.15]^T\) in two consecutive adjustment processes. Then we have \(Vc(1) = [271.2726, 270.2228]^T\) and \(Vc(2) = [271.3726, 270.3728]^T\). The corresponding terminal voltages are \(V(1) = [270.8758, 270.5267]^T\) and \(V(2) = [270.9074, 270.5598]^T\).

For DE1, we have

\[
\begin{bmatrix} \frac{\partial f_1}{\partial V_1} \\ \frac{\partial f_1}{\partial V_2} \end{bmatrix} = \begin{bmatrix} \Delta V_{e1}^{(1)} \\ \Delta V_{e2}^{(1)} \end{bmatrix} = \begin{bmatrix} \Delta V_{e1}^{(2)} \\ \Delta V_{e2}^{(2)} \end{bmatrix} = \begin{bmatrix} \Delta V_{e1}^{(3)} \\ \Delta V_{e2}^{(3)} \end{bmatrix}
\]

\[
= \begin{bmatrix} 270.8758 - 270.85 \\ 270.5267 - 270.70 \end{bmatrix} \cdot [0.1]
\]

\[
= \begin{bmatrix} 270.9074 - 270.8758 \\ 270.5598 - 270.5267 \end{bmatrix} \cdot [0.1]
\]

\[
= \begin{bmatrix} 66.7170 \\ -60.7167 \end{bmatrix}
\]
For DE2, we have
\[
\begin{bmatrix}
\frac{\partial f_2}{\partial V_1^2} \\
\frac{\partial f_2}{\partial V_2^2}
\end{bmatrix} = \begin{bmatrix}
\Delta V_1^{(2)} & \Delta V_2^{(2)} & \Delta V_1^{\text{desired}}_1 & \Delta V_2^{\text{desired}}_2
\end{bmatrix}
\]
\[
= \begin{bmatrix}
270.8758 & 270.5267 - 270.5 & 0.15
\end{bmatrix}
\]
\[
= \begin{bmatrix}
-70.8723 \\
72.2351
\end{bmatrix}
\]
(18)

B. Adjusting DE output voltages to make terminal voltage match the desired Response

\[
\begin{bmatrix}
\frac{\partial f_2}{\partial V_1^1} & \frac{\partial f_2}{\partial V_2^1}
\end{bmatrix} = \begin{bmatrix}
\Delta V_1^{(1)} & \Delta V_2^{(1)} & \Delta V_1^{\text{desired}}_1 & \Delta V_2^{\text{desired}}_2
\end{bmatrix}
\]
\[
= \begin{bmatrix}
66.7170 & -60.7167 & 272.8173 - 270.9074
\end{bmatrix}
\]
\[
= \begin{bmatrix}
6.8265 \\
72.2351
\end{bmatrix}
\]
(19)

After the adjustments, the output voltages of two DEs are

\[
\begin{bmatrix}
V_1^{(1)} \\
V_2^{(1)}
\end{bmatrix} = \begin{bmatrix}
271.3726 + 6.8265 \\
270.3728 + 8.1155
\end{bmatrix} = \begin{bmatrix}
278.1991 \\
278.4883
\end{bmatrix}
\]

The corresponding terminal voltages are V(3) = [272.8061, 272.5350]T, which are very close to the desired response.

For the next adjusting process, we have the desired response as

\[
\begin{bmatrix}
V_1^{\text{desired}} \\
V_2^{\text{desired}}
\end{bmatrix} = \begin{bmatrix}
275.85 - 5e^{-5} \\
275.75 - 5.2e^{-5}
\end{bmatrix} = \begin{bmatrix}
273.2829 \\
273.0302
\end{bmatrix}
\]
(20)

To match the desired response, the DEs output voltages need to be

\[
\begin{bmatrix}
V_1^{(2)} \\
V_2^{(2)}
\end{bmatrix} = \begin{bmatrix}
V_1^{\text{desired}} \\
V_2^{\text{desired}}
\end{bmatrix} + \begin{bmatrix}
\frac{\partial f_2}{\partial V_1^1} & \frac{\partial f_2}{\partial V_2^1}
\end{bmatrix} \Delta V_1^{\text{desired}}
\]
\[
= \begin{bmatrix}
278.1991 \\
278.4883
\end{bmatrix} + \begin{bmatrix}
66.7170 & -60.7167
\end{bmatrix} \begin{bmatrix}
272.8173 - 270.9074
\end{bmatrix}
\]
\[
= \begin{bmatrix}
279.9337 \\
280.4736
\end{bmatrix}
\]
(21)

The actual voltages are Vt(4)=[273.2768, 273.0242]T. The voltage responses at both buses follow the desired response. Similar patterns will be repeated for the following processes.

C. Adjusting DE output based on the ratio of voltage change between two consecutive adjusting steps.

If the voltage responses perfectly follow the desired responses without any error, the ratio of the two consecutive voltage changes can be calculated by applying equation (23) as

\[
r = \frac{e^{\Delta t} - e^{-\Delta t}}{1 - e^{\Delta t}} = \frac{1.8906 - 0.15}{1 - 0.15} = 0.8465
\]
(23)

For multiple DEs, we can take the average value of all the DEs to neutralize the random errors. In this case, we have

\[
r = \frac{273.6770 - 273.2768 + 273.4401 - 273.0242}{2} = 0.8502
\]
(24)

And hence, the DE output for this step should be

\[
\begin{bmatrix}
V_1^{(4)} \\
V_2^{(4)}
\end{bmatrix} = \begin{bmatrix}
279.9337 \\
280.4736
\end{bmatrix} + 0.8502 \begin{bmatrix}
1.7385 \\
1.9853
\end{bmatrix} = \begin{bmatrix}
281.4152 \\
282.1614
\end{bmatrix}
\]
(25)

The corresponding terminal voltages are Vt(5)=[273.6760, 273.4392]T. The actual voltages closely follow the desired responses. For the following adjusting steps, this operation will be repeated until the actual responses reach the voltage references.

IV. SIMULATION RESULTS ON CASE STUDIES

The applications of the adaptive control method are further demonstrated with more detailed results for three case studies to demonstrate the flexibility of the control method.

Case 1: Two DEs starting voltage regulation asynchronously.

In actual system operations, the voltage-regulating DEs may start their voltage regulation at different times. When this happens, the DEs already in service will synchronize with the new DEs coming into operation by restarting its regulation process to achieve coordination among all the DEs. To feature this phenomenon in Case 1, the Base Case is reconfigured by starting DE1’s voltage regulation first and then starting DE2.

Fig5. Voltage response of DE1 case 1.
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Fig.6. Voltage response of DE2 in case 2.

Fig8. Voltage response of DE2 in case 2.

Fig.7. Voltage response of DE1 in case 2.

Fig9. Voltage response of DE1 in case 3.

In this case, the system conditions and initial disturbances are identical to those in the Base Case; however, at 0.05 s, the disturbances disappear resulting in voltage rise at both DEs terminals. Since the voltage for either DE deviates from the initial desired response substantially, the voltage regulation process starts all over. The desired response curves for both DEs are updated using the new starting points, as shown by the dash curves after 0.05 s in both Figure 5.2 (a) and (b). The response speed of both is speeded up and within the next 0.15 s, the voltages of both Des are brought back to their references. The simulation results in this case demonstrate that by restarting the control cycle when detecting the deviation from the desired response curve, the proposed method is able to handle the disappearance of disturbances in the middle of the regulation process. Both the simulation results of Cases 1 and 2 verify that the flexible recalculation of the coefficients of the proposed control successfully addresses a wide range of disturbances (e.g., the startup of another voltage-regulating DE or another load change) which can occur in the middle of the original voltage regulation activity.

Case 3-Three voltage-regulating des in a looped system

Some distribution systems are meshed such as urban distribution networks. Thus, the Base Case is modified with a loop as shown in Fig. 4.1.1 to demonstrate the application of the proposed adaptive control method in a meshed system. A new load of 10 kW and 2 KVAR is connected at the new
bus7. Also, this case study considers three voltage-regulating DEs connected at buses 3, 4, and 6, respectively, to further demonstrate the application of the proposed method. The active power injections of the three DEs are 20, 20, and 10 kW, respectively.

![Fig10. Voltage response of DE2 in case3.](image)

![Fig11. Voltage response of DE3 in case3.](image)

Voltage references are 280.63, 280.60, and 280.30 V, respectively. We assume that load increases at bus 3 and bus 6 cause the voltage at the three DEs’ buses to drop to 273.20, 273.11, and 272.84 V, respectively. Fig. 9-11 shows the voltage responses of the three DEs after the load change in comparison with the desired responses. As can be seen, voltage responses of the three DEs match the desired responses after the calculation of initial coefficients is finished. These results verify that the proposed control can track the desired response very closely in loop systems and is scalable to distribution systems with more than two DEs. The response can track the desired response very well under different systems or different operating conditions due to the autonomous learning capability in the control algorithm. This demonstrates the plug and play feature which makes the control highly suitable for future utility applications.

**V. CONCLUSION**

In this paper, the contribution and finding of this paper can be summarized as follows:

- When multiple DEs participate in voltage regulation, the terminal voltage response of each DE is the result of the aggregated regulation behavior of all DE’s, and the local measurement of one DE’s terminal voltage can reflect the aggregated impact. Thus, it can still be used as feedback information to adjust the controller parameters.
- The voltage correction of the other DEs may result in over voltage at another DE’s terminal bus. In this case, the flat reference voltage fails as a good indicator of injecting or absorbing reactive power and thus fails to provide a timely regulation direction signal and overshoot of voltage is in evitable with fixed gains. A more dynamic reference, like the desired response curve, is preferred.
- Communication latency does slightly impact the performance of the proposed control. However, since the proposed method only requires limited communications at the very beginning, the communication latency does not impair the overall response speed, as shown by a preliminary study in this paper considering communication delay. System level regulating equipment, such as under load tap changing transformers and voltage regulators, needs to be studied.

**VI. REFERENCES**


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