Interaction of Multiple Distributed Energy Resources in Voltage Regulation

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

***Abstract*--Distributed energy resources (DE) with power electronics (PE) interfaces with the right control are capable of providing reactive power related ancillary services; voltage regulation in particular has drawn much attention. In this paper the problem of how to coordinate control multiple DEs to regulate the local voltage in the distribution system is addressed. A control method for voltage regulation using the DE PE controller is presented and based on the proposed control scheme; the voltage regulation of a distribution system with one DE and two DEs are tested, respectively. The factors affecting the gain parameters of the PE controller are investigated. The simulation results show that the parameters of the controller determine its dynamic response for voltage regulation and the factors associated with the network characteristics, such as locations of DEs and the amount of load, affect the impact range of the controller. The research work presented in this paper can be potentially used for the control system design of Smart Grid or Utility of the Future.**

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

I. Introduction

THE concern for energy security and the environment has contributed to the growth and development of distributed energy resources in U.S. The total installed DE capacity for installations smaller than 5MW in the U.S is estimated around 195GW; the reactive-power-capable DE is estimated at 10% of the total [1]. DEs connected to the grid with power electronics interface can provide several reactive power services [2]-[4] and have the ability to regulate their local voltage, which has drawn much interest because reactive power shortage and transport issues have been contributing factors to major cascading outages. The installation of DE with voltage regulation provision can have a beneficial impact on transmission system stability by supplying reactive power at the distribution level [5]. Also, integrated voltage regulation using multiple DEs can increase the voltage regulation capability and range and reduce the capital and operating costs. In previous work [6], the integrated control of a synchronous condenser and a DE with an inverter interface was implemented. The voltage control schemes of the inverter and the synchronous condenser were developed based on the different dynamic response of the inverter and the synchronous condenser. Additional research is needed to extend it to the integrated control of multiple DEs with the same dynamic response, such as all inverters. This may be an important part of the control system design of Smart Grid or Utility of the Future. In this paper, first the previously proposed voltage control scheme is introduced; then the factors affecting the performance of the controller parameters are analyzed. The simulation results for one DE and two DEs cases are given. Finally, conclusions from the simulations are presented.

H. Li and F. Li are with the Department of Electrical Engineering and Computer Science, The University of Tennessee, Knoxville, TN 37996.

Y. Xu, D. T. Rizy and J. D. Kueck are with Oak Ridge National Laboratory, One Bethel Valley Road, Oak Ridge, TN 37831.

Contact: F. Li, 1-865-974-8401 (Phone) or fli6@utk.edu (Email).

II. Control Model of DE for Voltage Regulation

A. System Configuration

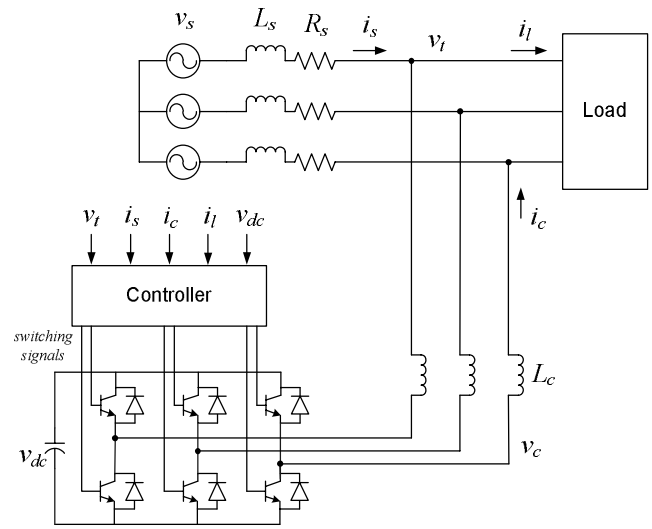


Fig. 1. Parallel connection of a DER with power electronics converter

A parallel-connected DE with a power electronics interface is shown in Fig. 1. The PE interface, including the inverter, the DC side capacitor v_{dc}, and the coupling inductor L_c, 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, and the rest of the system is simplified as an infinite voltage source (utility) with a system impedance of $R_s+j\omega L_s$. The parallel compensator is connected through the coupling inductor L_c at the point of common coupling (PCC), and the PCC voltage is denoted as $\boldsymbol{v_t}$. By generating or consuming a certain amount of reactive

©2008 IEEE.

Authorized licensed use limited to: IEEE Xplore. Downloaded on January 14, 2009 at 15:39 from IEEE Xplore. Restrictions apply.

power, the compensator can regulate the PCC voltage V_t. Since in this case, the compensator only controls reactive power, the compensator current i_c only contains the reactive power component.

B. Control Methods

A voltage regulation method is developed based on the system configuration in Fig. 1. The control diagram is shown in Fig. 2. The PCC voltage is measured and the rms value of V_t is calculated. The rms value is compared to a voltage reference V_t^* (which could be a voltage specified by the utility) and the error is fed to a proportional-integral (PI) controller. The compensator output voltage V_c^* is the reference to generate PWM signals to drive the inverter. The output voltage of the compensator is controlled so that it is in phase with the PCC voltage and the magnitude of the compensator output voltage is controlled so that the PCC voltage is regulated at a given level V_t^*. The control scheme is shown in (1).

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

where K_P, K_I are the gain parameters of the PI controller.

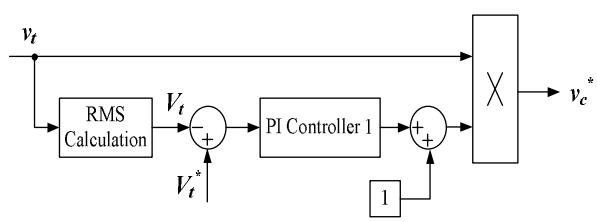


Fig. 2. Control diagram for compensator voltage regulation

In a three-phase system, the voltages or currents are balanced if the magnitudes of all phases are equal and the voltage angles are all 120 degrees apart. Most of the voltage unbalance in power systems is because of magnitude inequalities, and only this case is considered in this paper. In this control method, the rms value of the voltage in each phase is controlled independently; therefore the unbalance in the PCC voltage can be corrected by the compensator.

The two parameters of the PI controller, K_P, K_I determine the dynamic capability of the compensator and thus the voltage regulation dynamics. Inappropriate parameters may result in long settling (to reach steady-state) time, oscillation, over/under damped or even instability of the system. As a study, this study started to look at appropriate ranges of K_P, K_I.

III. Factors Determining Parameters of PI Controller

The proposed control method is based on feedback control and the error between the PCC voltage and reference voltage is the feedback signal. A simplified model representing the control of multiple DEs interfaced to the utility network is shown in Fig. 3. The control signal of the PI controller is applied to the inverter to generate a voltage at the PCC with the distribution system. Ideally the inverters generate the same voltage as their inputs. So only the distribution network characteristics affect the response of the voltage regulation, and therefore affect the appropriate range of K_P, K_I. In the following study of the impact of distribution network on the PI controller parameters, loads are modeled as constant impedance. A future effort could consider voltage sensitive loads, such as constant current or constant impedance or some combination of constant power, current and impedance. The DEs including their PE interface are modeled as voltage sources. All the buses in the system are grouped into two types: voltage source buses where there is current injection (or absorption); and load buses where the current injection is zero. The analysis is in the S domain and the nodal voltage equation is shown in (2).

$$\begin{bmatrix} I_G(S) \\ \underline{0} \end{bmatrix} = \begin{bmatrix} Y_{GG}(S) & Y_{GL}(S) \\ Y_{LG}(S) & Y_{LL}(S) \end{bmatrix} \begin{bmatrix} V_G(S) \\ V_L(S) \end{bmatrix} \quad (2)$$

where $I_G(S)$ is vector of the current injection at the buses connected with voltage sources; $V_G(S)$ is the corresponding voltage vector; $V_L(S)$ is the voltage vector of the load buses; $Y_{GG}(S)$,$Y_{GL}(s)$,$Y_{LG}(S)$ and $Y_{LL}(S)$ are the sub matrix of the admittance matrix.

After network reduction [7], we can get the voltages at the load buses as shown in equation (3) which includes the PCCs. As indicated in (3), the PCC voltages are a function of network structure, line parameters and loads, and support from the voltage sources. Since the voltage at each PCC is the feedback signal, the parameters K_P, K_I of each PI controller are hence determined by those factors.

$$V_L(S) = -Y_{LL}^{-1}(S) * Y_{LG}(S) * V_G(S) \quad (3)$$

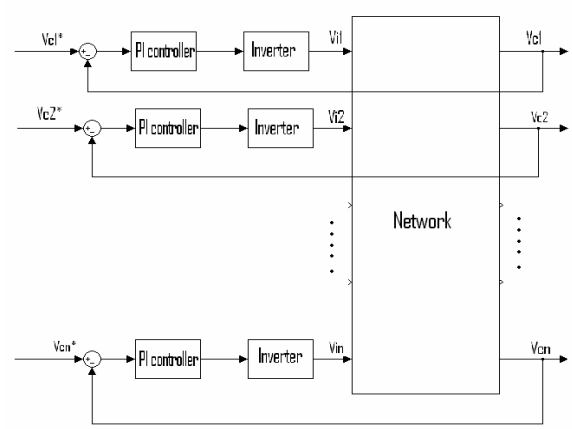


Fig. 3. Simplified model of the distribution system with multiple controllable DEs interfaced to it.

IV. Voltage Regulation In Distribution Systems

In this section the impact of K_P, K_I on the dynamic

Authorized licensed use limited to: IEEE Xplore. Downloaded on January 14, 2009 at 15:39 from IEEE Xplore. Restrictions apply.

response of the voltage regulation and the factors determining the range of K_P, K_I are tested in a distribution system with one DE and two DEs, respectively. The system diagram is shown in Fig. 4. It is a typical radial distribution network with two DEs with PE interface connected at bus 2 and bus 5 respectively. The only difference between the two cases is the omission of the DE at bus 5 for the single DE case.

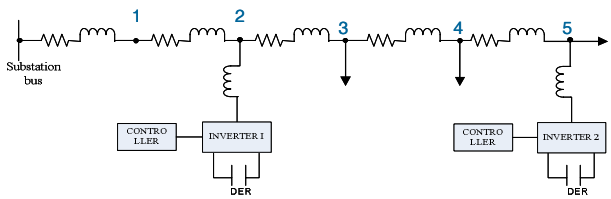
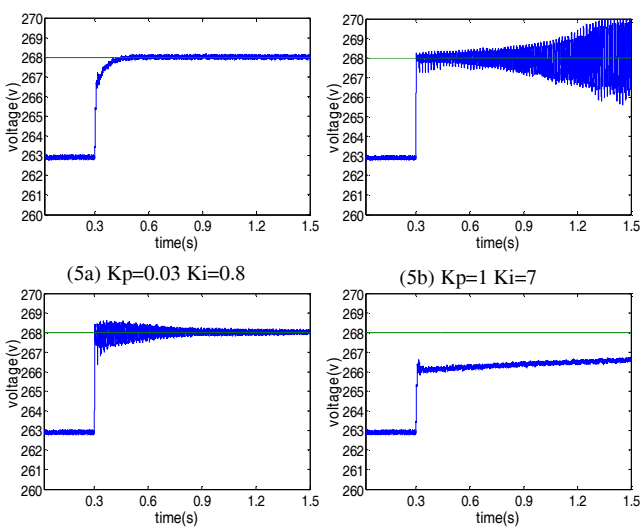


Fig. 4. Single line diagram of the distribution system with DE.

A. Impact of K_p and K_I on Voltage Regulation

1) Case of a single DE

The first case is the system shown in Fig. 4 with only one DE at bus 2. Its PE controller was tested with different combinations of K_p and K_I. The different responses are shown in Fig. 5. The straight green line is the reference voltage while the blue curve is the voltage at the PCC. The PCC voltage was 263 V before regulation and the reference voltage is set at 268 V for regulation. From 0 to 0.3s, there is no regulation and from 0.3s to 1.5s the compensation is performed. As shown in Fig. 5, there is a stable range of K_p and K_I; Fig.5a shows a desirable dynamic response with well designed K_P, K_I. If outside of this range the system becomes unstable, as is shown in Fig.5b. Even in the stable range, inappropriate values for K_p and K_I may cause undesired response; the compensation speed is too slow due to a too small value of K_I value as in Fig.5d or an overshoot and oscillation at the start as shown in Fig.5c.



(5a) Kp=0.03 Ki=0.8

(5b) Kp=1 Ki=7

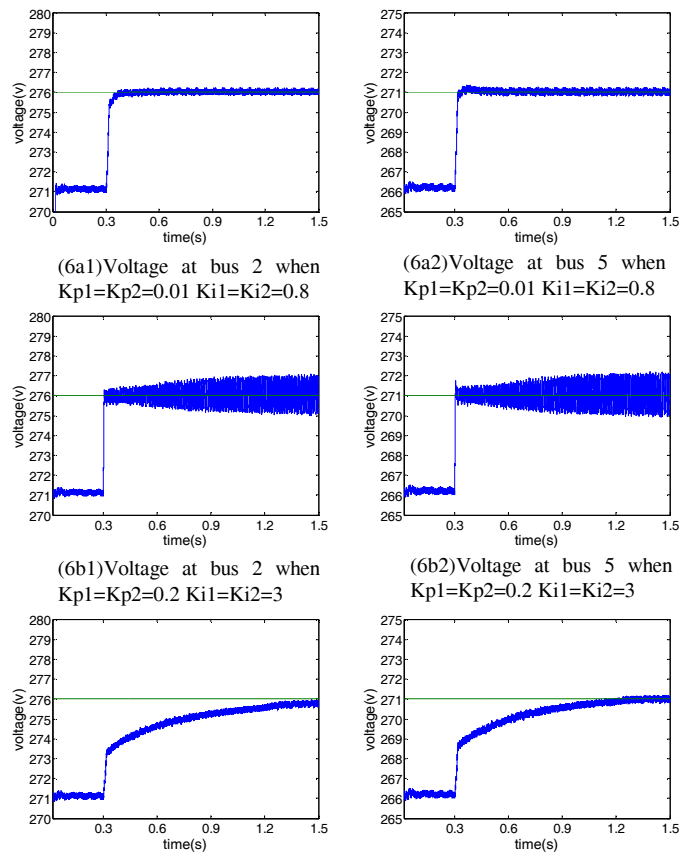
(5c) Kp=0.2 Ki=3

(5d) Kp=0.01 Ki=0.1

Fig.5. Voltage regulation with different K_P, K_I-one DE case

2) Case with multiple (Two in this case) DEs

Next, the distribution system with two DEs was tested with different combinations of K_p and K_I. The test results are shown in Fig.6. The left side shows the voltage response at bus 2 with respect to different K_p and K_I while the right side shows the voltage at bus 5 for similar changes in the gain parameters. Prior to 0.3s, there is no regulation and from 0.3s to 1.5s the compensation is performed. Similar to the one DE case, the value of K_P and K_I determine the response of the voltage regulation. However in this case with multiple DEs, the range of K_P and K_I becomes different, which is clearly demonstrated by comparing Fig.5c with Fig. 6b1 and Fig. 6b2. Even with the same value of K_P and K_I, the two DE case is unstable while the one DE case is stable. It suggests that the parameter range suited for a single DE case may not be directly used for voltage regulation with multiple DEs. In order for them to work correctly together requires a coordinated design of the controller parameters for the multiple DEs.



(6a1)Voltage at bus 2 when Kp1=Kp2=0.01 Ki1=Ki2=0.8

(6a2)Voltage at bus 5 when Kp1=Kp2=0.01 Ki1=Ki2=0.8

(6b1)Voltage at bus 2 when Kp1=Kp2=0.2 Ki1=Ki2=3

(6b2)Voltage at bus 5 when Kp1=Kp2=0.2 Ki1=Ki2=3

(6c1)Voltage at bus 2 when Kp1=Kp2=0.01 Ki1=Ki2=0.05

(6c2)Voltage at bus 5 when Kp1=Kp2=0.01 Ki1=Ki2=0.05

Fig.6. Voltage regulation with different K_P, K_I-two DEs case

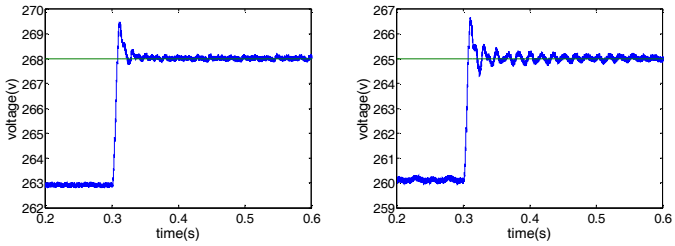
B. Impact of DE Location on Voltage Regulation

From the previous analysis of the factors determining the controller parameters, we can see that the locations of DEs affect the grouping of the buses; hence affect the structure of the reduced network and finally affect the appropriate range of the controller parameters. In this section, the results of the

Authorized licensed use limited to: IEEE Xplore. Downloaded on January 14, 2009 at 15:39 from IEEE Xplore. Restrictions apply.

two cases from before with respect to DE location is investigated, respectively.

1) Case with one DE

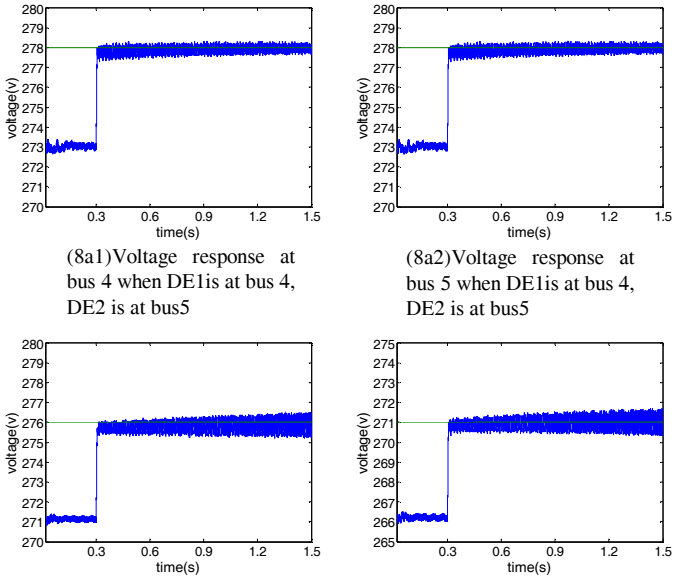


(7a) DE at bus 2 (7b) DE at bus 5

Fig.7. Voltage regulation with different locations of DER--one DER case

Fig.7a. and Fig.7b show the voltage responses corresponding to the DE at bus 2 and at bus 5, respectively. There's more dynamic oscillation when the DE is connected at bus 5, although both eventually reach the same steady state.

2) Case with Multiple (two in this case) DEs



(8a1)Voltage response at bus 4 when DE1is at bus 4, DE2 is at bus5

(8a2)Voltage response at bus 5 when DE1is at bus 4, DE2 is at bus5

(8b1)Voltage response at bus 2 when DE1is at bus 2, DE2 is at bus5

(8b2) Voltage response at bus 5 when DE1is at bus 2, DE2 is at bus5

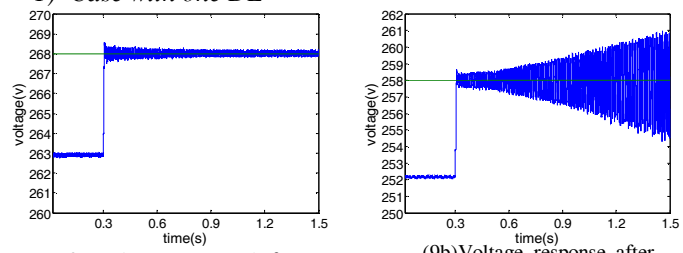
Fig.8. Voltage regulation with different location of DERs--two DER case

In this second case, the impact of DE location on voltage regulation dynamics is more obvious. Fig.8. shows the comparison of the voltage regulation dynamics with respect to different DE locations. Fig.8a1 and Fig. 8a2 show the voltage response where the DEs are connected at bus 4 and bus 5. Fig.8b1 and Fig 8b2 show the voltage response where DE1 is moved to bus 2 with all other conditions unchanged. As is shown the change of the DE1 location not only affects the voltage regulation of DE1itself, but also affects DE2 at bus5.

C. Impact of Load on Voltage Regulation Performance

The voltage regulation is also affected by the loading. In this study, the loads are modeled as constant impedances. Again the, two cases with one DE and then two DEs are investigated to test the impact of the amount of the load, respectively.

1) Case with one DE



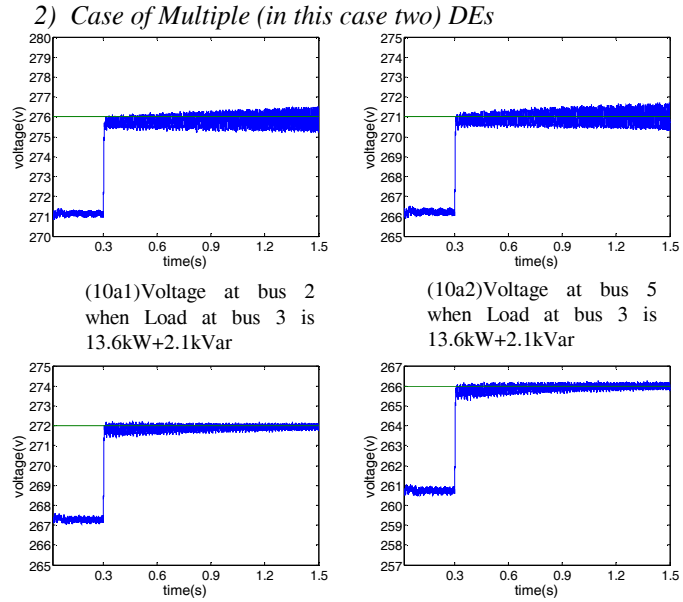
(9a)Voltage response before load change

(9b)Voltage response after load change

Fig.9. Voltage regulation with different amount of load—one DER case

Fig. 9 shows the impact of load change on the voltage regulation response. For Fig.9a, the load at bus 3 and bus 4 are 3.4kW+j2.2kVar and 50kW+j40kVar, respectively. For Fig.9b the load at bus 3 and bus 4 has been changed to 17kW+j0Var and 66.6kW+j40kVar.The difference caused by the load change is clearly shown. In Fig. 9a the voltage eventually reaches the desired steady state while as shown in Fig. 9b the voltage oscillates into stability.

2) Case of Multiple (in this case two) DEs



(10a1)Voltage at bus 2 when Load at bus 3 is 13.6kW+2.1kVar

(10a2)Voltage at bus 5 when Load at bus 3 is 13.6kW+2.1kVar

(10b1)Voltage at bus 2 when Load at bus 3 is 27.2kW+2.1kVar

(10b2)Voltage at bus 2 when Load at bus 3 is 27.2kW+2.1kVar

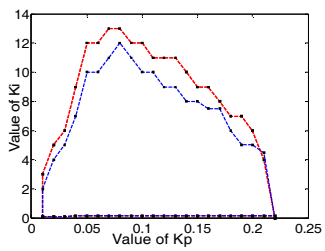
Fig.10. Voltage regulation with different amount of load—two DERs

Figures 10a and 10b show the voltage regulation responses before and after the real load at bus 3 increases by 13.6 kW. The gain parameters are the same for both load conditions: K_P1=0.21, K_P2=0.15, K_I1=0.15, K_I2=0.5.As is shown in Fig. 10. the previous unstable system becomes stable after the load increase with the gain parameters unchanged. The comparison clearly demonstrates loading affects the voltage dynamic responses with DEs in the distribution system.

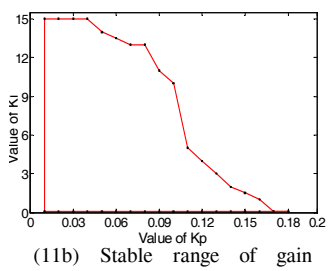
Authorized licensed use limited to: IEEE Xplore. Downloaded on January 14, 2009 at 15:39 from IEEE Xplore. Restrictions apply.

D. Impact from other DEs in grid

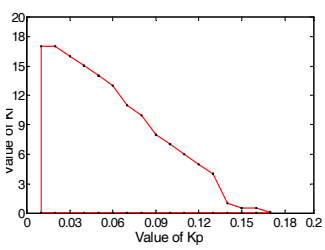
Due to almost the same response speed of two DEs in the simulation, the voltage regulation of one DE is inevitably affected by the other DE in the grid. Here the range of the parameters to keep the system stable is tested to study the impact from other DEs. Fig. 11a gives the stable range of the gain parameters in the case of a single DE. The red curve is the stable range of DE1 parameters and the blue curve is for DE2. Fig. 11b gives the stable range of the parameters of DE2 when DE1 is also connected to the grid with parameters K_p =0.21 and K_I =0.15. These two values are the maximum possible values that a single DE2 maintains stable response. It can be seen the stable range of the parameters of DE2 changes greatly, especially the range for K_p reduces considerably. Figures 11c and 11d give the results when the parameters K_p and K_I of DE1 are set to 0.07 and 13, and 0.17 and 2**.** Each of these two pairs represents a case that the gain parameters of DE1 are in the middle of its stable range. The results also demonstrate the same trend as in Fig.11b. For all the cases the closer to the maximum boundary of K_p, the smaller is the range for K_I.



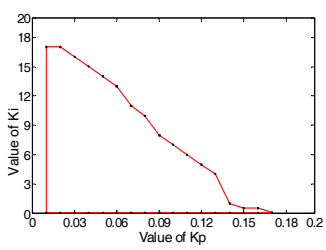
(11a) Stable range of gain parameters in case with single DE for both DEs



(11b) Stable range of gain parameters of DE2, while DE1 has K_P=0.21 And K_I=0.15



(11c) Stable range of gain parameters of DE2, while DE1 has K_P=0.07 And K_I=13



(11d) Stable range of gain parameters of DE2, while DE1 has K_P=0.17 And K_I=2

Fig. 11. The stable range of gain parameters

V. Conclusion And Future Work

Clearly the performance of DEs using PI based controllers for varying the output from the power electronics can impact the voltage regulation of the distribution system differently depending upon the PI gain settings, DE count, DE locations and loading. It is also shown that the parameters designed with the grid simplified as an infinite system may not be applicable in the practical use. The network characteristics that affect the feedback signal in the control scheme need to be considered in determining the parameters of the controller.

The results presented in this paper are preliminary and by no means exhaustive. Future research will focus on more complex networks, studies with more DE with greater range of performance capabilities, and on ways to better design the control parameters for the expected operating range for the DE system. Furthermore, we need to look at the impact on PI based control when one or more DEs shuts down when the parameters have been designed for multiple DE operation. It may be similar to the two cases studied. We expect that additional intelligence will be needed to change the parameters as the distribution system conditions changes such as new DE is installed or a new load is added or the system is reconfigured. This may require some limited communication, such as wireless on the distribution system or additional sensing by the DE to sense that another DE is presence or some other change as occurred relevant to the control.

VI. References

[1] F. Li, J. Kueck, T. Rizy, T. King, 2006, "A preliminary analysis of the economics of using distributed energy as a source of reactive power supply," *Oak Ridge National Laboratory First Quarterly Repoert for Fiscal Year 2006,* Oak Ridge, TN.

[2] B. Meyer, Y. Bamberger, I. Bel, "Electricite de France and integration of distributed energy resources," *IEEE Power Engineering Society General Meeting*, June 2006, Montreal, Canada.

[3] B.Kroposki, C. Pink, R. DeBlasio, H. Thomas, M. Simoes, P. K. Sen, 2006, "Benefits of power electronic interfaces for distributed energy systems," *IEEE Power Engineering Society General Meeting*, June 2006, Montreal, Canada.

[4] J. B. Campbell, I. J .King, B. Ozpineci, D.T. Rizy, L. M. Tolbert, Y. Xu, X.Yu, 2005, "Ancillary services provided from DER," *Oak Ridge National Laboratory Report,ORNL/TM-2005/263*

[5] R. T. Guttromson, 2002, "Modeling distributed energy resource dynamics on the transmission system," *IEEE Trans. on Power Systems*, vol. 17, no. 4, pp. 1148-1153.

[6] Y. Xu, T. Rizy, F. Li, J. Kueck, 2007, "Dynamic Voltage Regulation Using Distributed Energy Resources," *the 19th International Conference on Electricity Distribution (CIRED 2007), May 21-24, 2007, Vienna, Austria*

[7] H. Saadat, *Power Systems Analysis*, 2nd ed., New York: McGraw-Hill, 2002.

VII. Biographies

Huijuan Li (S'07) is presently a Ph.D. student in electrical engineering at The University of Tennessee. She received her B.S.E.E. and M.S.E.E. in electrical engineering from North China Electrical Power University, China in 1999 and 2002 respectively. She previously worked as a research engineer at Shanghai Sieyuan Electrical Company in China on the field of ungrounded neutral distribution systems.

Fangxing (Fran) Li (M'01, SM'05) received the Ph.D. degree from Virginia Tech in 2001. He has been an Assistant Professor at The University of Tennessee (UT), Knoxville, TN and an adjunct researcher at ORNL since August 2005. Prior to joining UT, he worked at ABB, Raleigh, NC, as a senior and then a principal R&D engineer for four and a half years. His current interests include energy market, reactive power, and distributed energy resources. Dr. Li is a registered Professional Engineer in the state of North Carolina.

Yan Xu (S'02, M'06) received her Ph.D. in electrical engineering at The University of Tennessee in 2006. She is a post doctoral research member at Oak Ridge National Laboratory. She received the BS degree from Shanghai Jiaotong University, China in 1995 and the MS degree from North China Electric Power

Authorized licensed use limited to: IEEE Xplore. Downloaded on January 14, 2009 at 15:39 from IEEE Xplore. Restrictions apply.

University, China in 2002. Her research interests include power electronics applications in power systems and distributed energy resources.

D. Tom Rizy (SM'87) is a senior research power systems engineer at Oak Ridge National Laboratory (ORNL) in the Engineering Science and Technology Division. His current interest and activities focus on new controls for distributed energy resources (DER) and applications for synchro-phasor measurements. He is a cofounder of the Distribution Energy Communications and Control Laboratory (DECC) at ORNL for testing dynamic voltage regulation controls using DER. He has over 29 years experience in power systems R&D and received his MSEE and BSEE from Virginia Tech and the University of Virginia, respectively. His is a co-recipient of the IEEE Prize Paper Award (1990) for "Adaptive Relaying Concepts for Improved Performance" and a chapter author of the book on the Athens Automation and Control Experiment, a large-scale distribution automation project conducted in the 80s by DOE, TVA and EPRI.

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

Authorized licensed use limited to: IEEE Xplore. Downloaded on January 14, 2009 at 15:39 from IEEE Xplore. Restrictions apply.