Adaptive Voltage Control Using Multiple Distributed Energy Resources with Fuzzy Controller

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Abstract: Distributed energy resources (DE) with power electronics interfaces and logic control using local measurements are capable of providing reactive power related to 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 dissertation addresses the challenges of controlling the DEs to regulate the local voltage in distribution systems. First, an adaptive voltage control method has been proposed to dynamically modify the control parameters of a single DE to respond to system changes such that the ideal response can be achieved. Then, control methods have been discussed in the case of multiple DEs regulating voltages considering the availability of communications among all the DEs. When communications are readily available, a method is proposed to directly calculate the needed adaptive change of the DE 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 proposed adaptive voltage regulation method in the case of multiple Des without communication, has a high tolerance to real-time data shortage and can still provide good enough performance, it is more suitable for broad utility applications. The approach of multiple DEs with communication can be considered as a high-end solution, which gives faster and more precise results at a higher cost.

Keywords: Adaptive control, ancillary services, communication latency, distributed energy resources, distributed generation, inverter control, microgrid, PI control, reactive power, smart grid, voltage control.

I. INTRODUCTION

1.1. Background

The electrical power system grid is composed of the generation system, the transmission system, and the distribution system. Economies of scale in electricity generation lead to a large power output from generators. 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. These are reforming power systems. Renewable energy technologies contribute to the development of DE. Some distributed generations are powered by renewable fuel, such as wind energy, solar energy, and biomass. Besides the technological innovations, the environment of power systems deregulation, energy security, and environmental concerns all boost the development of DE

DE provides participants in the electricity market more flexibility in the changing market conditions.

- First, because many distributed generation technologies are flexible in operation, size, and expandability, they can provide standby capacity and peak shaving; and thus help reduce the price volatility in market.
- Secondly, DE can enhance the system’s reliability by picking up part or all of the lost outputs from the failed generators.
- Third, because DEs supply electrical power locally, they could reduce transmission and distribution congestions, thus saving the investment on expanding transmission and distribution capacity.
- Fourth, DE can also provide ancillary services for the grid support both in real power related services, such as load following, and reactive power related services, such as voltage regulation.

1.2. Types of Distributed Energy Resources

The most common types of distributed energy systems are summarized in this section

A. Reciprocating Internal Combustion (IC) Engines
Reciprocating IC engines convert chemical (or heat) energy to mechanical energy from moving pistons. The pistons then spin a shaft and convert the mechanical energy into electrical energy

through an electric generator. These engines can burn natural gas, propane, gasoline, etc.

B. Gas Turbine

A gas turbine is a rotary engine that extracts energy from a flow of combustion gas. High temperature, high pressure air is the heat transfer medium. Air is allowed to expand in the turbine thus converting the heat energy into mechanical energy that spins a shaft. The shaft is connected to a series of reduction gears that spin a synchronous generator directly connected to the electric power system.

C. Small Hydro-electrical Systems

Hydro-electric power systems can be driven from a water stream or accumulation reservoir and convert the potential energy into electricity. They are also directly connected to the grid without additional interfaces.

D. Microturbines

Microturbines work in a similar way to gas turbines. The majority of commercial devices use natural gas as the primary fuel. They can also burn gasoline, diesel, and alcohol. The generator is typically a high-speed permanent magnet generator (PMG) and produces high frequency electricity. Hence, the generator cannot be connected directly to the grid.

E. Fuel cells

Fuel cells are electrochemical devices producing electricity continuously through the chemical reaction between the fuel (on the anode side), such as liquid hydrogen, and an oxidant (on the cathode side), in the presence of an electrolyte. There are several different types of fuel cells are currently available including phosphoric acid, molten carbonate, solid oxide, and proton exchange membrane (PEM). Fuel cells produce DC power,.

F. Photovoltaic Systems

Photovoltaic (PV) systems directly convert solar light into electricity. PV modules consist of many photovoltaic cells, which are semiconductor devices capable of converting incident solar energy into DC current. Like fuel cells, PV modules also need a PE interface to convert DC power into AC power which is compatible with the electric power system.

II. REVIEW OF ADAPTIVE VOLTAGE CONTROL METHOD

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.

Figure 1.1 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 $v$dc, 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. 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 $Rs+j\omega Ls$. 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.

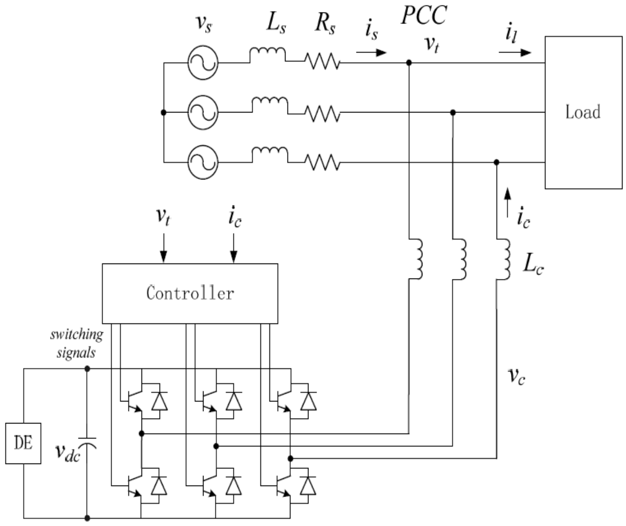

Figure 1.1. Parallel connection of a DE with PE converter

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, vt is measured and its RMS value, Vt, is calculated. The RMS value is then compared to a voltage reference, Vt* (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).

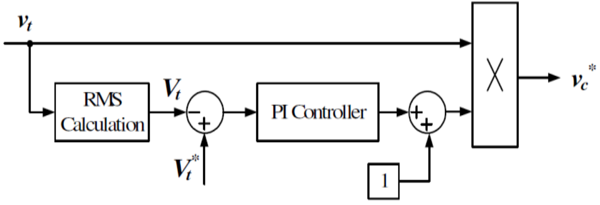

Figure 1.2. Control diagram for voltage regulation.

The error between the actual and reference is fed back to adjust the reference compensator output voltage vc*, 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, *vc* is controlled to regulate *vt* to the reference *Vt* *. The control scheme can be specifically expressed as:

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

Where *KP* and *KI* are the proportional and integral gain parameters of the PI controller. The above Equation leads to reactive injection only when *v* c* is in phase with *vt*. 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 above equation because of the tight coupling between real power and phase angle.

III. CHALLENGES OF MULTIPLE DES FOR VOLTAGE REGULATION

The impact of voltage regulation by multiple DEs on one of the DEs is tested in a distribution system model. The system diagram is shown in Figure. 3 with two DEs connected to Bus 3 and Bus 6, respectively. Also, both DE controllers are set with Fixed control gains. The paper refers to this as the *Base Case*.

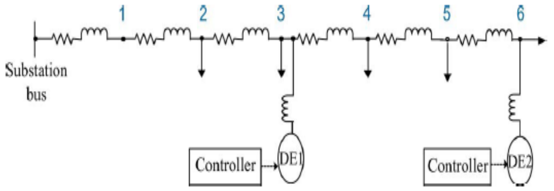

Figure. 3. Base case of the paper

The reference setting of DE1 is varied while that of DE2 is held fixed to test the impact on DE2. The results are shown in Figure. 4. The simulation results in Fig. 4 clearly show that voltage regulation of DE1 affects DE2’s regulation speed. Therefore, in the case of multiple voltage-regulating DEs, each DE needs to take into consideration the impacts from the other DEs in determining its own regulation output.

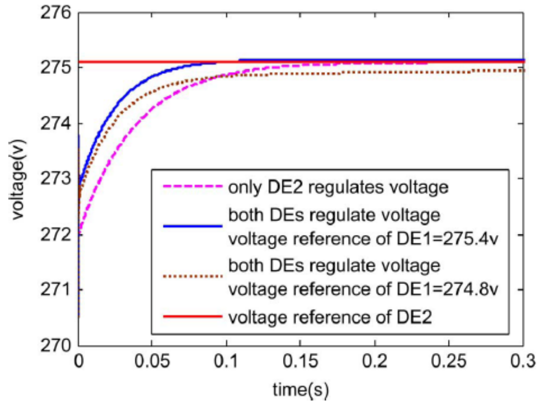

Figure. 4. Voltage responses of DE2 for different DE1 voltage reference settings

Besides the impact on the response speed, multiple voltage regulating DEs complicate the var compensation direction. For instance, assume that initially, a DE’s local voltage is under its reference setting, which usually requires var injection. However, due to the simultaneous var injection from the other DEs, eventually this DE may be required to absorb vars to offset the local overvoltage. With the voltage profile along a feeder changed by the dispersed real power injections of DEs, this phenomenon would become common. Hence, it is important to draw the following conclusion: With the case of multiple voltage-regulating DEs, the local voltage w.r.t. voltage reference may be a false indicator of absorption or injection of vars in regulating local voltage. As shown in Fig. 5, the dashed curve shows the terminal voltage response of DE2 when only DE1 regulates its own terminal voltage. It exceeds the voltage reference (i.e., the flat line). Hence, DE2 needs to control voltage to reduce it to the voltage reference, if DE2 also participates in the regulation. However, the blue dotted curve shows that when both DE1 and DE2 regulate their voltages, DE2 injects vars to increase the voltage before reaching the reference. It starts to reduce the voltage after the overshoot occurs. The reason is that it starts to absorb vars to bring the terminal voltage down only when the terminal voltage is higher than the reference voltage.

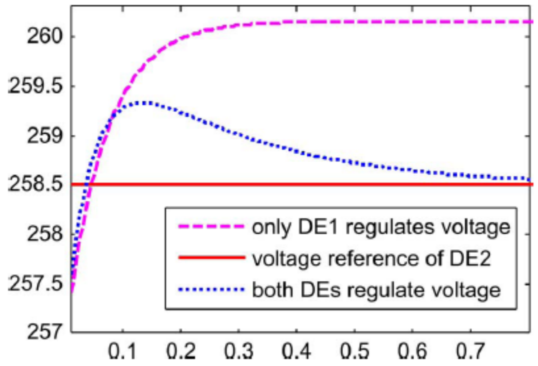

Fig. 5. Voltage overshoot of DE2 caused by DE1

Therefore, in this case, the error sign between the reference and actual voltages, which works well in a single DE case, fails to provide the right information about whether the DE should increase or decrease its var output. Accordingly, the voltage Overshoot may occur.

IV. IMPLEMENTATION OF ADAPTIVE METHOD FOR DE CONTROLLER

As discussed earlier, if *KP* or *KI* is not chosen appropriately, the system response may be poor and at worst, create instability. So preventing a poor system response and optimizing the response speed are what is desired from the PI controller design. Thus the goal is to create an adaptive PI design that can dynamically adjust the PI controller in real-time based on the system’s behavior and configuration. The proposed adaptive PI control method, inspired by the generic adaptive control method in, consists of three procedures:

- Determine the DC source voltage of the DE;
- Set the initial controller values, *KP* and *KI*; and
- Adaptively adjust the controller parameters according to real-time system conditions.

4.1. 1Determine the DC Source Voltage

DE's PE interface with the utility is a VSI and the PWM method is used to convert the DC source voltage to an AC supply. Figure 5 shows the relationship between $2V_C^P / V_{dc}$ and the modulation index *ma*, where V_C^P is the peak voltage of the fundamental-frequency component of the compensator output voltage *vc* and V_{dc} is the voltage of the DC supply.

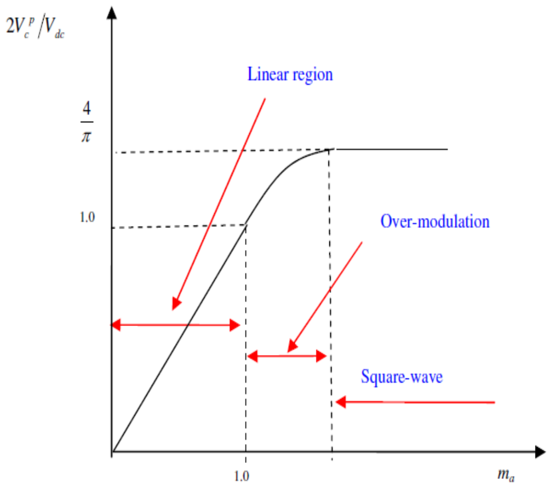

Figure 5. PWM voltage control by varying modulation index ma.

As shown in Figure 5, for a given V_C^P, V_{dc} varies linearly with the modulation index *ma* when it is 1.0 or less. This means that *dc V* determines the DE's ability to provide voltage regulation. To reduce the DE harmonic injection, *ma* is chosen to be no greater than 1. Accordingly, we have:

$$V_{dc} \geq 2V_C^P = 2\sqrt{2} * Vc$$

Hence, if the DE needs to perform a 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 *Vc*, i.e., the scheduled AC voltage profile.

4.1.2. Set the Initial PI Controller Gains

Lower gain parameters, KP and/or KI, 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.

A. Set the Initial KP Value

At the initial time 0+ (immediately after a voltage transient), the reference compensator output voltage V* can be expressed as (4.2), since the contribution of the integral controller is 0:

$$v_c^* = v_t^0(t)[1 + Kp\big(V^*(t) - v_t^0(t)\big)]$$

B. Setting the Initial *KI* Value

The voltage response time of the controller for a voltage transient is set to 0.5 seconds in order to not interfere with the conventional utility voltage control.

4.1.3. Adaptively Adjusting the PI Controller Gain Parameters

The controller with a fixed *KP* and *KI* 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 *KP* and *KI* 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 *KP* and *KI* will be adjusted to lower values. On the contrary for when it is too slow, *KP* and *KI* will be adjusted to higher values. Certainly, this needs additional logic to check the present voltage response with respect to the desired voltage response.

4.2. 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 0.2s, the difference of the two voltages is checked at every quarter cycle for the possible adjustment of *KP* and *KI*. Figure 6 shows the voltage regulation with an adaptive adjustment of *KP* and *KI*.

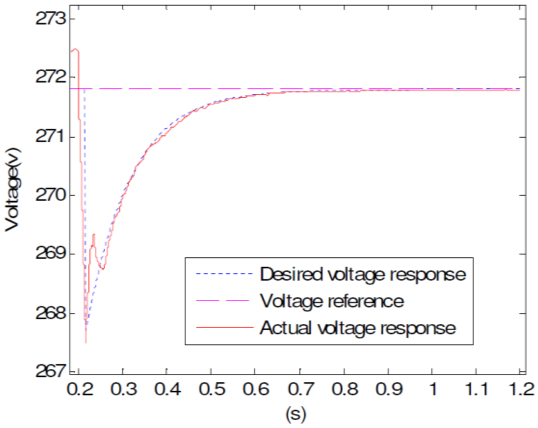

Figure 6. Voltage regulation with adaptive adjustment of KP and KI.

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 0.5s response time requirement. Figure 7 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 initial high sensitivity of the voltage and the dominance of the proportional part in above equation over the integral part. Hence, any small inaccuracy tends to lead to a relatively large difference.

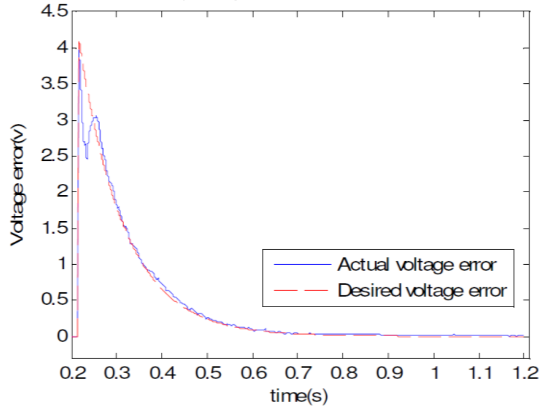

Figure 7. Comparing the desired and actual voltage deviations

Therefore, the actual voltage response curve is controlled very close to the desired curve.

In addition, Figures 8 and 9 are the real and reactive power injections, respectively, during the voltage regulation. It should be noted that the P injection in Figure 8 remains constant except for small ripples around 0.2-0.4 s. These occur simply because of the terminal voltage dynamics.

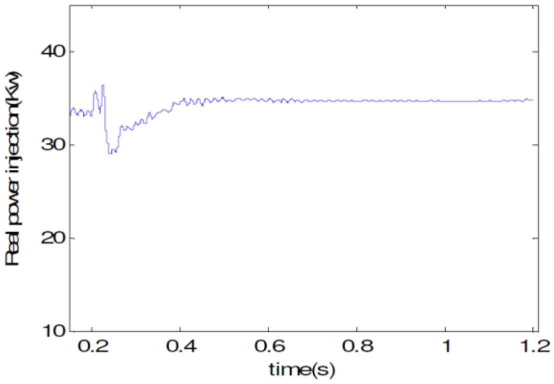

Figure 8. Real power injection

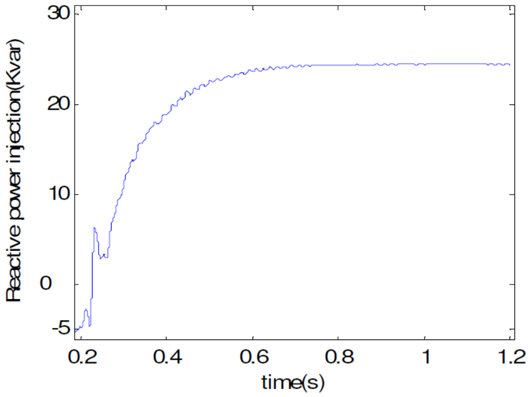

Figure 9. Reactive power injection

For verification purposes, Figure 10 shows the non-adaptive voltage regulation with gains fixed to their initial values of *KP0* and *KI0*. The response is much slower when compared to the adaptive control approach. Instead of 0.5s, it takes more than 1s to reach the voltage reference. Thus, the proposed adaptive control approach provides greater response efficiency.

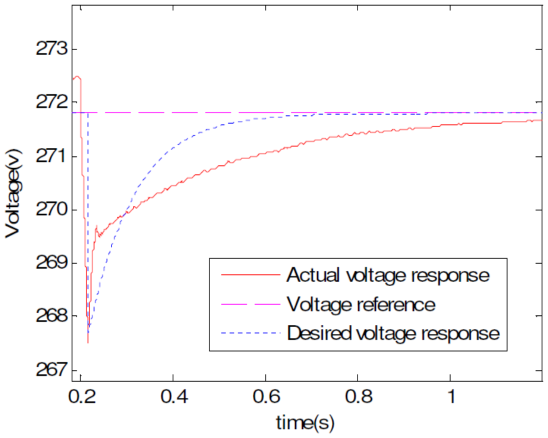

Figure 10. Non-adaptive voltage regulation with *KP* and *KI* fixed at the initial values.

V.CONCLUSION AND FUTURE WORK

In this paper, the contribution and findings 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 overvoltage at another DEs 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 inevitable with fixed gains. A more dynamic reference, like the desired response curve, is preferred.
- Theoretical analysis proves that a unique, time-varying solution for the gain parameters does exist for multiple voltage-regulating DEs. The gains may be negative in the case that one DE needs to absorb reactive power even if its reference voltage is higher than its terminal voltage. The theoretical analysis is model-based and requires detailed system data, so it is not likely preferred for practicing utility engineers. However, the analytical formulation does verify that the proposed adaptive control approach has a solid theoretical foundation.

REFERENCES

[1] F. Li, J. Kueck, T. Rizy, and T. King, A Preliminary Analysis of the Economics of Using Distributed Energy as a Source of Reactive Power Supply, Oak Ridge National Laboratory (ORNL), Oak Ridge, TN, 2006, Tech. Rep. (ORNL/TM-2006/014).

[2] J. Driesen and R. Belmans, " Distributed generation: Challenges and possible solutions," in *Proc. IEEE PES General Meeting*, 2006.

[3] M. E. Baran and I. M. El-Markabi, " An adaptive local learning-based methodology for voltage regulation in distribution networks with dispersed generation," *IEEE Trans. Power Syst.*, vol. 21, no. 3, pp. 1131–1140, Aug. 2006.

[4] M. E. Baran and I. M. El-Markabi, " A multiagent-based dispatching scheme for distributed generators for voltage support on distribution feeders," *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 52–59, Feb. 2007.

[5] T. Tran-Quoc *et al.*, " Intelligent voltage control in distribution network with distributed generation, " in *Proc. 19th Int. Conf. ElectricityDistribution (CIRED 2007)*, 2007.

[6] P. N. Vovos, A. E. Kiprakis, A. R. Wallace, and G. P. Harrison, " Centralized and distributed voltage control: Impact on distributed generation penetration," *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 476–483, Feb. 2007.

[7] D. N. Gaonkar, P. C. Rao, and R. N. Patel, " Hybrid method for voltage regulation of distribution system with maximum utilization of connected distributed generation source," in *Proc. IEEE Power India Conf.*, 2006.

[8] C.M. Hird,H.Leite, N. Jenkins, andH.Li, " Network voltage controller for distributed generation, " *Proc. Inst. Elect. Eng., Gen., Transm., Distrib.*, vol. 151, no. 2, pp. 150–156, Mar. 2004.

[9] M. Prodanovic, K. De Brabandere, J. Van Den Keybus, T. Green, and J. Driesen, "Harmonic and reactive power compensation as ancillary services in inverter-based distributed generation, " *IET Proc. Gen., Transm., Distrib.*, vol. 1, no. 3, pp. 432–438, May 2007.

[10] S. R.Wall, " Performance of inverter interfaced distributed generation," in *Proc. IEEE T&D Conf. Expo.*, 2001.

[11]. A.A. Thatte and M.D. Ilic, "An Assessment of Reactive Power/Voltage Control Devices In Distribution Networks," *IEEE PES General Meeting 2006*, June 18-22, 2006.

[12]. T. Tran-Quoc, M. Braun, J. Marti, C. Kieny, N. Hadjsaid and S. Bacha, "Using Control Capabilities of DER to Participate in Distribution System Operation," *IEEE PowerTech Conference 2007*, pp. 561 – 566, July 1-5, 2007.

[13]. J. Driesen, and R. Belmans, "Distributed generation: challenges and possible solutions," *IEEE PESGeneral Meeting 2006*, June 18-22, 2006.

[14]. N.D. Hatziargyriou and A.P. Sakis Meliopoulos, "Distributed Energy Sources: Technical Challenges," *IEEE PES Winter Meeting 2002*, vol. 2, pp. 1017 – 1022, Jan. 27-31, 2002.

[15]. H.Y. Li and H. Leite, "Increasing Distributed Generation Using Automatic Voltage Reference Setting Technique," *2008 IEEE PES General Meeting*, July 20-24, 2008.

[16]. T.G. Hazel, N. Hiscock and J. Hiscock, "Voltage Regulation at Sites with Distributed Generation," *IEEE Transactions on Inductry Application*, vol.44, issue 2, pp. 445-454, March 2008.