Bao-Cheng Wang, Xiao-Qiang Guo, Xin-Ke Huang, Wei-Yang Wu

Yanshan University

Flexible Control of Three-Phase Distributed Generation Systems for Voltage Rise Mitigation in Microgrid

***Abstract**. Microgrid integrated with renewable energy source (RES) is experiencing a rapid development nowadays. Many technical challenges appear with the high penetration of RES into the microgrid. One of the most important issues is the voltage rise at the point of common coupling (PCC). The voltage profile of PCC not only depends on the active and reactive powers, but also on the ratio (R/X) of line impedance. In order to mitigate the voltage rise, two control strategies are discussed, namely, active power curtailment and reactive power absorption. Theoretical analysis and experiment results are presented to validate the effectiveness of the proposed control schemes for voltage rise mitigation. It indicates that both control strategies may work well, but reactive power control enables the higher penetration of RES.*

***Streszczenie.** W celu zmniejszenia niebezpieczeństwa zwiększania napięcia w sieci microgrid z odnawialnymi źródłami energii zaproponowano dwie strategie – ograniczenie mocy czynnej i absorpcja mocy biernej. Przedstawiono analizę teoretyczną i wyniki eksperymentów. Wyniki te wskazują, że metoda sterowania mocą bierną jest bardziej skuteczna. (**Elastyczne sterowanie systemem dystrybucji trójfazowej w celu ograniczeni a ryzyka wzrostu napięcia w sieci typu microgrid**)*

Keywords: Microgrid, distributed generation, grid-interfaced inverter, voltage rise
Słowa kluczowe: microgrid, sieć dystrybucyjna, wzrost napięcia

Introduction

The environmental concerns and electric utility deregulation promote the development of distributed generation (DG) in a rapid pace [1-5]. The high penetration of DG brings about a concept of the microgrid [4]. It is defined as a cluster of DG units (such as wind turbines and photovoltaics), storage devices and loads, which can operate in the grid-connected mode, autonomous mode, and ride-through between two modes. However, with the increasing penetration of DG systems in a microgrid, many technical challenges should be dealt with. One of the most important issues is the voltage rise at the PCC [6-9]. Conventionally, On-Load Tap Changer (NLTC) or Automatic Voltage Control Relay (AVCR) has been widely used for voltage regulation in power systems. In practice, however, it is expensive with poor dynamic responses. On the other hand, with the development of power electronics, many interesting electronically-interfaced compensation devices have been put into use, such as Static Var Generator (SVG), which can regulate the voltage profile by injecting the reactive power into power systems [10]. But installation of a specific voltage regulation device needs the additional investment and maintenance cost. Another interesting solution is to integrate the voltage regulation function into DG systems. That is, DG not only provides the active power to microgrid, but also has the additional function of voltage regulation.

The objective of the paper is to discuss the feasibility of two possible solutions to voltage rise mitigation. Performance evaluations of both solutions are provided in this paper, along with the experimental validity.

Voltage Rise Issue

Fig.1 illustrates the schematic diagram of the microgrid. It comprises of the primary energy sources (PV, wind, et al.) with optional energy storages, dc/dc or ac/dc converters and dc/ac inverters. The inverters can provide an interface for the flexible functions such as energy conversion and power quality improvement. The inverter output may either feed the local loads independently in autonomous mode or in conjunction with the electric utility by static switch (STS) in grid connected mode. This paper will focus on the latter mode.

For simplicity, only the DG unit is considered. And it can be extended to other DG units. As shown in Fig.2, the simplified model consists of DG unit, local load, line impedance, and microgrid bus. Note that V_s represents the microgrid bus voltage. Z is the impedance of the transmission feeder, which consists of the resistance component R and the inductance component L; P and Q represent the active and reactive powers from the microgrid bus. P_L and Q_L are the local load active and reactive powers. V_{pcc} is the voltage of the PCC. P_G is the active power from DG, and Q_G is the reactive power exchange between DG and PCC.

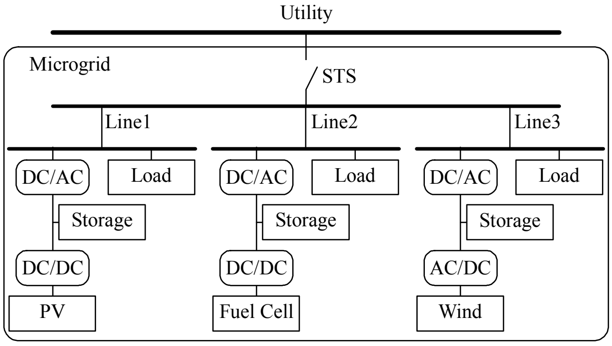


Fig.1. Schematic diagram of the microgrid

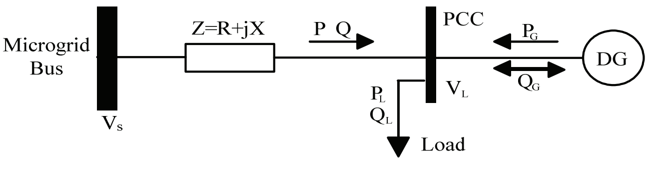


Fig. 2 Simplified model of DG connected to microgrid bus

The complex power from microgrid bus to PCC can be derived from Fig.2 as:

$$\tilde{S} = P + jQ \tag{1}$$

From (1) and Fig.2, the current through the line impedance (Z) can be obtained.

(2) $$\dot{I} = \left(\frac{\bar{S}}{\dot{U}_{\mathrm{PCC}}} \right)^* = \left(\frac{P + \mathrm{j}Q}{\dot{U}_{\mathrm{PCC}}} \right)^* = \frac{P - \mathrm{j}Q}{\dot{U}^*_{\mathrm{PCC}}}$$

The voltage drop between microgrid bus and PCC is:

(3) $$\Delta \dot{V} = \dot{V}_S - \dot{V}_{pcc} = \dot{I}(R + jX)$$

Substitute (2) into (3), it can be obtained that

(4) $$\Delta \dot{V} = \dot{V}_S - \dot{V}_{pcc} = \frac{R \cdot P + X \cdot Q}{\dot{V}_{pcc}} + j\frac{X \cdot P - R \cdot Q}{\dot{V}_{pcc}}$$

where $X = \omega L$, $P = -P_G + P_L$ and $Q = \pm Q_G + Q_L$.

Considering $\dot{V}_{pcc}$ as the voltage reference with zero angle, i.e. $\dot{V}_{pcc} = V_{pcc}\angle 0^\circ$. In practice, the real part is much greater than the imaginary part in (4), so the imaginary part may be neglected, and equation (4) can be rewritten as:

(5) $$V_{pcc} \approx V_s + \frac{R \cdot P + X \cdot Q}{V_{pcc}}$$

From the analysis above, it can be concluded that the PCC voltage may rise to a certain level when many DG systems are integrated into the microgrid. More specifically, the voltage of PCC not only depends on the active and reactive powers, but also the ratio (R/X) of line impedance. Note that the distribution network and microgrid with different voltage levels have the unequal value of line impedance, as shown in Table I.

Table Ⅰ Parameters of the line impedance in Microgrid

Voltage greed	$R/\Omega\times\mathrm{km}^{-1}$	$X/\Omega\times\mathrm{km}^{-1}$	R/X
Low Voltage	0.642	0.083	7.7
Middle Voltage	0.161	0.190	0.85
High Voltage	0.060	0.191	0.31

Voltage Rise Mitigation

This section will disucss the feasiblity of the voltage rise mitigation with the DG system. Fig.3 shows an extended model of Fig.2. Note that the dc-link bus is supported by the first power stage (See Fig.1). and thus it is resonablely assumed to be constant as U_{dc} .

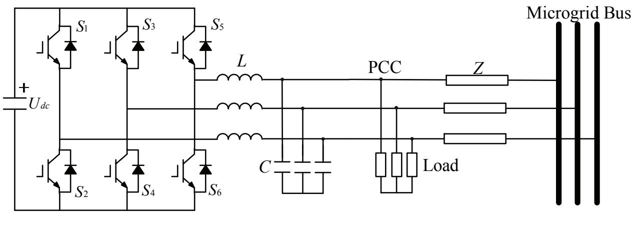
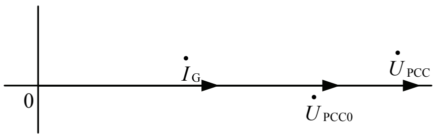


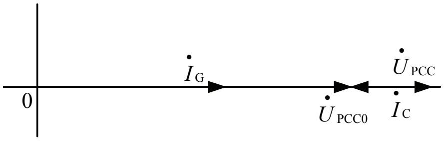
Fig. 3 Extended model of Fig.2

A. Voltage regulation with active power

Assuming that the line impedance is dominantly resistive (first case), a voltage rise may appear if any DG in microgrid injects an active current $\dot{I}_{\mathrm{G}}$ through the line impedance, as shown in Fig.4a, from which it can be observed that the PCC voltage is increased from $\dot{U}_{\mathrm{PCC0}}$ to $\dot{U}_{\mathrm{PCC}}$. On the other hand, if DG injects a compensated current $\dot{I}_{\mathrm{C}}$, the PCC voltage rise will be mitigated, as illustrated in Fig.4b.



(a) PCC voltage rise



(b) voltage rise mitigation

Fig.4 Phasor diagram of voltage rise mitigation

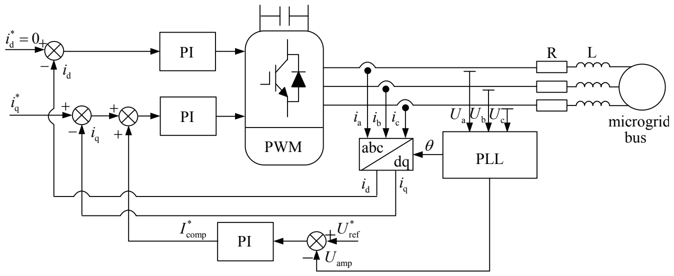
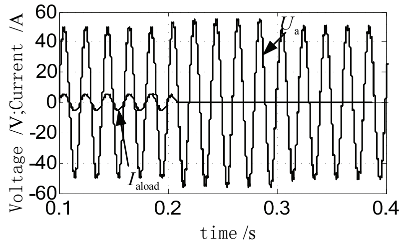
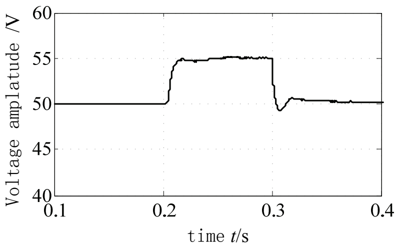


Fig.5 Control diagram of voltage rise mitgation

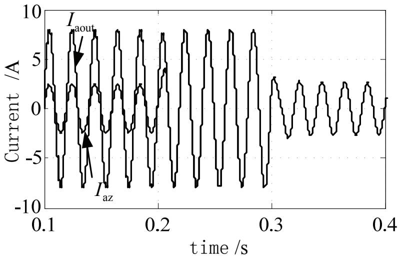
Fig.5 shows the control diagram of voltage rise mitigation with active current regulation. Following will provide a performance evaluation of the abovementioned solution. Note that the voltage rise is emulated by shedding the local loads at PCC.



(a) PCC Voltage and load current of phase A



(b) PCC Voltage amplitude



(c) DG Output current I_{aout} and line impedance current I_{az}

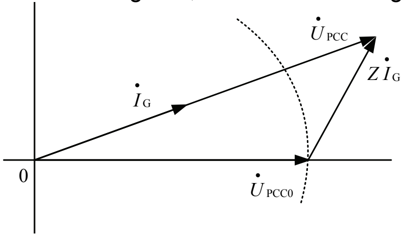
Fig.6 Evaluation results of voltage rise mitigation

From Fig.6a and Fig.6b, it can be observed that the PCC voltage increases from 50V to 55V (peak value) after the local loads are shed at 0.2s. And the DG output current I_{aout} is flowing through the line impedance totally, that is, $I_{\text{az}} = I_{\text{aout}}$. After 0.3s, DG output current I_{aout} is decreased, so is the line impedance current I_{az} . And then the PCC voltage rise is mitigated as shown in Fig.6b.

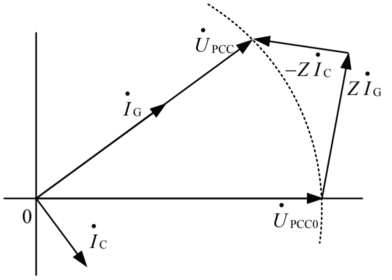
From the evaluation results, it can be concluded that the above solution is feasible.

B. Voltage regulation with reactive power

Assuming the line impedance is dominantly resistive (second), a voltage rise may appear if any DG in microgrid injects an active current $\dot{I}_{\text{G}}$ through the line impedance, as shown in Fig.7a, from which it can be observed that the PCC voltage is increased from $\dot{U}_{\text{PCC0}}$ to $\dot{U}_{\text{PCC}}$. On the other hand, if DG injects a compensated current $\dot{I}_{\text{C}}$, the PCC voltage rise will be mitigated, as illustrated in Fig.7b.



(a) PCC voltage rise



(b) voltage rise mitigation

Fig.7 Phasor diagram of voltage rise mitigation

Fig.8 shows the control diagram of voltage rise mitigation with reactive current regulation. Following will provide a performance evaluation of the abovementioned solution.

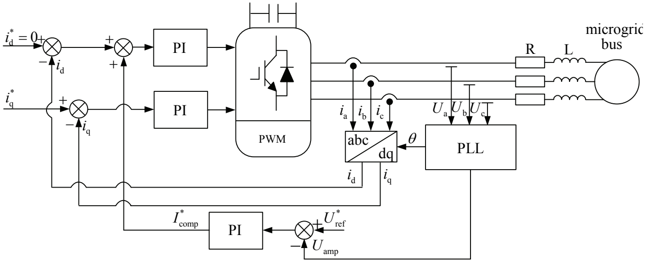
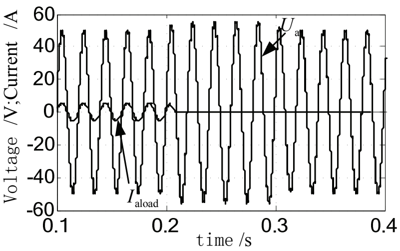
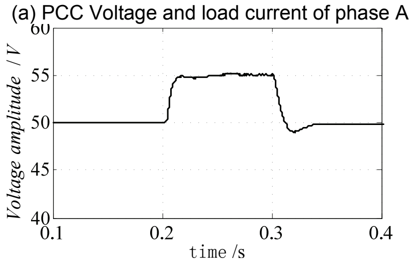


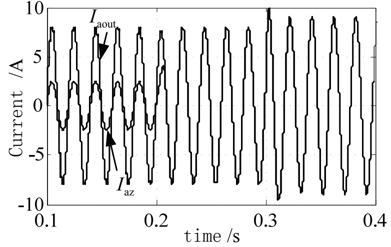
Fig.8 Control diagram of voltage rise mitgation



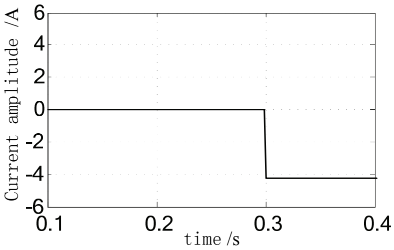
(a) PCC Voltage and load current of phase A



(b) PCC Voltage amplitude



(c) DG Output current I_{aout} and line impedance current I_{az}



(d) DG Output compensated current (reactive current)

Fig.9 Evaluation results of voltage rise mitigation

From Fig.9a and Fig.9b, it can be observed that the PCC voltage increases from 50V to 55V (peak value) after the local loads are cut off at 0.2s. And the DG output current I_{aout} is flowing through the line impedance totally, that is, $I_{\text{az}} = I_{\text{aout}}$. After 0.3s, DG injects the reactive current. And then the PCC voltage rise is mitigated as shown in Fig.9b. From the evaluation results, it can be concluded that the above solution is feasible as well.

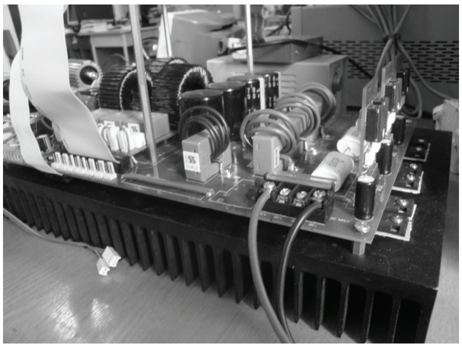
Experimental results

In order to verify the effectiveness of the above soltions, the experimental tests are carried out. And the system parameters are listed in Table II.

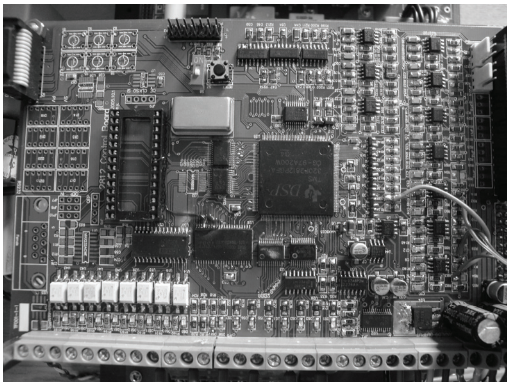
Table-Ⅱ System Parameters

U_{dc}	120V	I	8A
$u_{abc,o}$	50V	k_{ip}	0.1
L_{abc}	5mH	k_{ii}	20
C_{abc}	9.4 μF	k_{vp}	1
R	1 Ω	k_{vi}	20
L	3mH	R_{load}	9 Ω

Where k_{ip} and k_{ii} are the proportional and integral gains of the current loop; k_{vp} and k_{vi} are the proportional and integral gains of the voltage loop. *I* represents of rated current of the inverter. R represents of the load connected at PCC. The line impedance R/X ratio is set as 1 to test the effect of the line impedance ratio on the voltage regulation.



(a) Power circuit

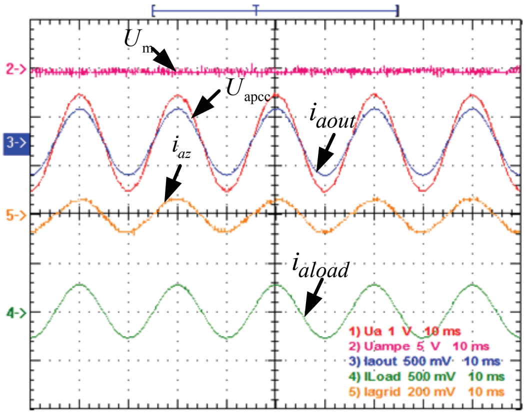


(b) TMS320F2812 based control board

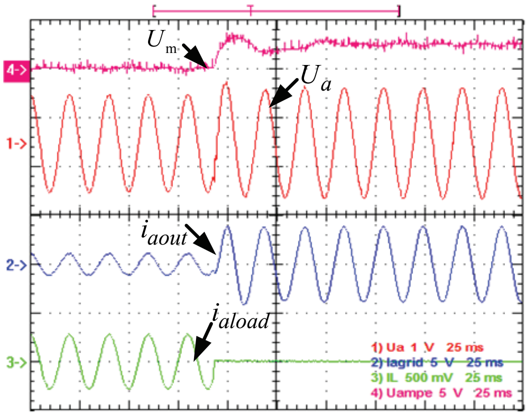
Fig. 10 Pictures of experimental platform

Fig.11 (a) shows the steady-state waveforms of voltage and current before load shedding. It can be observed that DG works in unity power factor mode, namely the output current of DG is the in phase with the PCC voltage, and the difference between DG current I_{aout} and load current I_{aload} is the line impedance current I_{az} .

After load shedding, as shown in Fig.11 (b), the DG output current I_{aout} flows through the line impedance totally, that is, $I_{\mathrm{az}} = I_{\mathrm{aout}}$. And the PCC voltage rise appears due to the voltage drop variation across the line impedance.



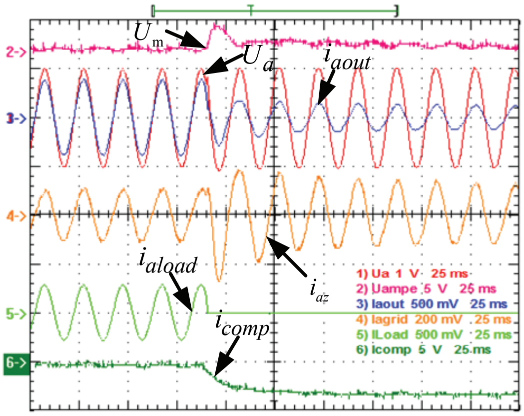
(a) Steady state before load shedding



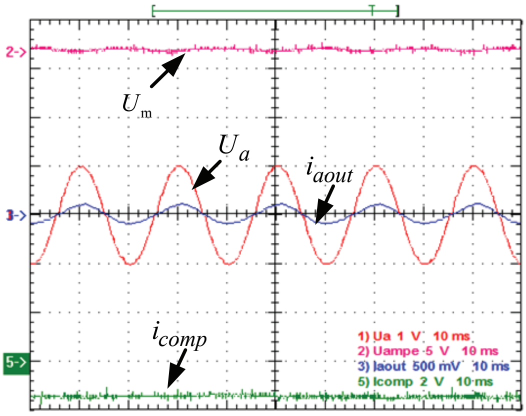
(b) Transient without compensation

Fig. 11 Experimental results without compensation

A. Voltage regulation with active power



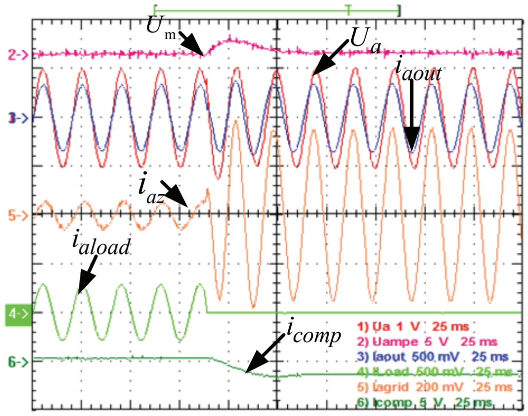
(a) Transient with compensation



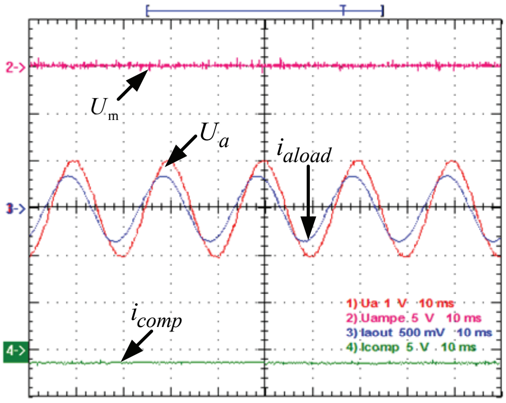
(b)Steady state after compensation

Fig. 12 Experimental results with compensation

Fig.12 shows the experimental results with active power compensation. It can be observed that this solution can regulate the PCC voltage to a reasonable level when the PCC voltage rises. However, the DG output current is significantly reduced in this case, which implies that this solution can't make full use of DG, and thus could prevent the high penetration of DG systems. On the other hand, he output current of DG is the in phase with the PCC voltage, as shown in Fig.12b, which indicates that the DG works in unity power factor mode.



(a) Transient with compensation



(b)Steady state after compensation

Fig. 13 Experimental results with compensation

Fig.13 shows the experimental results with reactive power compensation. It can be observed that this solution can regulate the PCC voltage to a reasonable level when the PCC voltage rises. It should be noted that the active current or active power control of DG is not affected in this case. And the full use of DG systems can be achieved. Therefore, it is beneficial to the high penetration of DG systems.

Conclusion and future work

Voltage rise is one of the most important issues in case of integration with renewable energy sources into microgrid. This paper has discussed two solutions for voltage rise mitigation with consideration of the ratio (R/X) of line impedance. From the theoretical analysis and experimental results, it can be concluded that both solutions are theoretically feasible, but the reactive power compensation solution will be preferred for high penetration of DG systems. In practice, however, further consideration should be noted such as the physical constraints of DG systems. For example, the reactive power compensation should not exceed the DG capacity to prevent the system overcurrent. Another interesting solution is the combination of the active and reactive power compensation, which will be reported in the future paper.

Acknowledgement

This work was supported by the National Natural Science Foundation of China (50837003, 50977081), Hebei Province Universities Science Research Project (2011249), Hebei Province Natural Science Foundation (E2012203023).

REFERENCES

[1] B.V. Mathiesen, H Lund. Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources. IET Renewable Power Generation, vol.3, no.2, pp. 190-204, 2009.
[2] A. Hajizadeh, M. A. Golkar. Fuzzy neural control of a hybrid fuel cell/battery distributed power generation system. IET Renewable Power Generation, vol.3, no.4, pp.402-414, 2009.
[3] A. K. Saha, S. Chowdhury, S. P.Chowdhury, Y. H. Song. Application of solid-oxide fuel cell in distributed power generation. IET Renewable Power Generation, vol.1, no.4, pp.193-202, 2007.
[4] Y. W. Li, D. M. Vilathgamuwa, and P. C. Loh. Design, analysis, and real-time testing of a controller for multibus microgrid system. IEEE Transactions on Power Electronics, vol. 19, no. 5, pp. 1195–1204, Sep. 2004.
[5] D. Mahinda Vilathgamuwa, Poh Chiang Loh, Yunwei Li. Protection of microgrids during utility voltage sags. IEEE Transactions on Industrial Electronics, vol. 53, no. 5, pp. 1427-1436, 2006.
[6] C. L. Masters, “Voltage rise-the big issue when connecting embedded generate on to long 11 kV overhead lines,” Power Engineering Journal .Feb. 2002.
[7] Woyte, A., Thong, V., Belmans, R., and Nijs J.: ‘Voltage fluctuations on distribution level introduced by photovoltaic systems’, IEEE Transactions on Energy Conversion, 2006, 21, (1), pp. 202–209
[8] Vovos, P.N., Kiprakis, A.E., Wallace, A.R., and Harrison, G.P.: ‘Centralized and distributed voltage control: impact on distributed generation penetration’, IEEE Transactions on Power Systems, 2007, 22, (1), pp. 476–483
[9] Scott, N.C., Atkinson, D.J., and Morrell, J.E.: ‘Use of load control to regulate voltage on distribution networks with embedded generation’, IEEE Transactions on Power Systems, 2002, 17, (2), pp. 510–515
[10] J. Dixon, L. Morán, J. Rodríguez, et al. Reactive power compensation technologies: State-of-the-art review. Proceedings of the IEEE, 2005, 93(12): 2144-2164.

Corresponding Author
Xiao-Qiang. Guo, Key Lab of Power Electronics for Energy Conservation and Motor drive of Hebei province, Department of Electrical Engineering, Yanshan University, Qinhuangdao 066004, China. Email: gxq@ysu.edu.cn