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Comparison of Decentralized Voltage Control Methods for Managing Voltage Rise in Active Distribution Networks

***Abstract**. Integration of distributed generations (DGs) to distribution systems has posed several technical challenges for network operators. One of the main problems that has received widespread attention is the voltage rise issue. This issue has led researchers worldwide to find ways to control voltage so that an acceptable limit is maintained and delivered to consumers. In networks with DGs, the methods of voltage control have been identified as coordinated or centralized control and decentralized control. This paper presents the results and comparisons of a simulation that used these decentralized voltage control methods in managing voltage rise issues in distribution systems with DGs.*

***Streszczenie.** W artykule przedstawiono porównanie metod sterowania zdecentralizowanego, wykorzystywanego do kontroli dopuszczalnej amplitudy napięcia w sieci, zawierającej rozproszone generatory energii elektrycznej. W tego rodzaju sieci możliwe są nieoczekiwane, skoki napięcia, co przekłada się na jakość energii, dostarczanej do użytkowników i działanie odbiorników. (**Porównanie zdecentralizowanych metod kontroli napięcia w kontroli skoków napięcia w aktywnych sieciach elektroenergetycznych**).*

Keywords: Distributed generations (DGs), voltage rise, centralized and decentralized methods, voltage control.
Słowakluczowe: Generacja rozproszona (DGs), skok napięcia, metody zcentralizowane i zdecentralizowane, kontrola napięcia.

1. Introduction

The presence of distributed generations (DGs) in distribution systems has created several challenges and disadvantages in terms of delivery of power quality, protection issues, and voltage support. The need for distribution network operators (DNOs) to control voltage at its acceptable limits is required to maintain the delivery of power to the customers. Effective delivery of power consequently reduces the issues of power quality and losses.

According to [1], an active distribution network (ADN) is defined as a distribution network with systems capable of controlling distributed energy resources consisting of generators and storage. An ADN should also be able to adopt the integration of control and communication technologies for the effective management of the new distribution network by DNOs [2]. However, several challenges have to be tackled in the implementation of distribution networks in the presence of DGs. These challenges include issues on voltage levels and power flow, equipment thermal rating, fault current level, and protection issues [3]. Hence, to tackle all these rising issues, an active network management (ANM) scheme is needed to provide control and coordination to power system operation. According to [4], ANM is the use of real-time control and communication systems to provide a means to better integrate renewable distributed generators. The power system has been working on a system with unidirectional power flow. However, the integration of DGs in the system has resulted in a bidirectional power flow that causes problems associated with steady state voltage rise, thermal rating of equipment, stability, system fault level, losses, power quality, and protection issues [5].

DNOs consider three worst-case operating scenarios in ensuring that their network and their customers will not be adversely affected. These scenarios are categorized into: i) no generation and maximum system demand, ii) maximum generation and maximum system demand, and iii) maximum generation and minimum system demand. As increasing the generation reverses the power flow along the line from the generator to the substation, the voltage rises and becomes more severe in the absence of demand because all local generation is exported back to the primary substation. This problem usually arises when connecting the DG to a weak rural distribution area where the demand for power is usually low. Hence, the issue of voltage rise calls for a management scheme that can alleviate excessive voltage rise issues.

2. Voltage Control Methods for Distribution Networks with Distributed Generation

Two main categories of voltage control with DGs are identified: the centralized or coordinated control and the semi-coordinated and decentralized control strategies. As its name suggests, the centralized or coordinated control strategy provides voltage regulation from the substation to the rest of the network while using a wide range of communication systems, such as an on-load tap changer (OLTC) and a voltage regulator, to coordinate different devices in the systems. The semi-coordinated and decentralized or distributed control strategies must be able to control the DG unit locally in an active manner while coordinating it with a limited number of other network devices. These decentralized approaches have been proven to improve overall network performance with limited cost because of low communication system requirements [6]. Different voltage control strategies have been found effective in managing voltage rise issues in the presence of DGs [7-9].

Coordinated voltage control methods determine their control actions based on information about the entire distribution network. Therefore, data transfer and communication between network nodes are required. Examples of coordinated voltage management for distribution systems include the centralized distribution management system control and the coordination of distribution network components, such as the OLTC and the switched capacitor control. Studies on managing voltage rise issues in distribution systems with DGs using decentralized control have also been carried out. This topic is explored in the present paper. One major advantage of decentralized control is that its control actions can be performed with a limited number of communications, thereby limiting the costs incurred.

Several studies deal with decentralized voltage control methods, including power factor control (PFC), OLTC, and generation curtailment. Also explored are intelligent or heuristics decentralized control methods, which involve techniques such as artificial neural network, genetic algorithm, fuzzy logic, ant colony, evolutionary programming, multi agent system, and so on that are used to optimize further the control actions taken. For the PFC, control is usually carried out by increasing the amount of generation input while maintaining a fixed power factor operation [4, 6, 10]. Other methods of voltage rise mitigation are combined with this PFC to handle the voltage rise problem. The work in [11] suggested that to manage the issue of voltage rise, generators adopt three different modes of operations; unitary, capacitive, or inductive, depending on the regulatory operating rules.

For OLTC control, researchers have been finding new ways to enhance their control over voltage fluctuation issues because the commonly applied tap changer control can no longer withstand the power flow with the integration of DG. In [12], the principles of operation of OLTCs with and without line drop compensation (LDC) were studied, together with the effect of DG on OLTC and LDC regulation. The work in [13] presented a new automatic voltage control relay called the transformer automatic paralleling package scheme. The transformer can be maintained at a suitable tap position under varying power factor conditions and load currents without degrading the LDC function. In [14], a more advanced tap changer control at the transformer known as the super transformer automatic paralleling package n+ relay scheme was presented. The control action is implemented based on locally obtained measurements at the substation level combined with a state estimation technique.

Generation is curtailed by trimming off the power that is generated during worst-case scenarios (e.g., minimum demand, maximum generation). This method is cost-effective when the occurrence of such scenarios are low and when such worst scenarios have been used as part of an active management scheme [15]. This method is usually implemented as a last resort to handle voltage rise when generators have exhausted their voltage control. The amount of reactive power that can be absorbed or injected by generators is limited. In such cases, curtailment is the only way to stay within the statutory voltage limits [4]. In [16-18], an active power curtailment scheme that utilizes the droop control technique was presented. This approach results in an equal sharing of output power losses.

The intelligent or heuristics decentralized control approach is often applied to optimize the management of voltage fluctuation issues, wherein objective functions, such as minimizing losses or connecting large DG sizes or capacities, are usually the main targets to be achieved. The heuristic methods are intelligently used to control the voltage using inputs from the condition of the network. As an example, the active and reactive powers of DGs were used as inputs to a decision support system based on artificial neural network in [19]. In [20], the power flow information from the transformer was used as basis to control the setting of OLTC using fuzzy logic. These methods are just a few examples among the many intelligently developed algorithms that have been developed by researchers who are seeking the best option to control voltage.

3. Simulation and Test System

Simulations are carried out on an IEEE 13 bus system to identify and to compare the available voltage control methods in terms of the management of voltage fluctuation issues in distribution networks with DG. The simulations are performed using the DigSilent Power Factory software. Two DGs with total generation capacities ranging from 1 MW to 3 MW are applied to the test system. The two DGs are connected to buses 675 and 680, and the simulations are performed using the three decentralized control methods, namely, the PFC, on load tap changing control, and the generation curtailment control schemes that are applied to the test system.

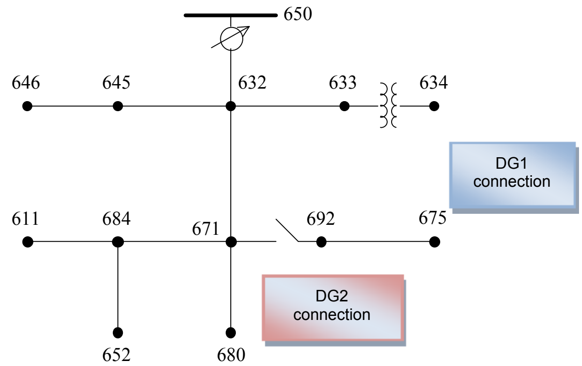

Fig.1. The IEEE 13 bus system

4. Test Results

The results obtained are presented in the following sections.

4.1 Power factor control

PFC indicates the reactive power output of the generating unit maintained in proportion to the real power (MW) output such that the power factor remains constant. To ensure proper voltage and Var control within the distribution system, DGs must be equipped with voltage control and PFC capabilities. The reactive capability of a typical generator at a full load normally ranges between 0.85 lagging and 0.95 leading. The DNO in Malaysia (i.e.,Tenaga Nasional Berhad) is under obligation to maintain the power factor at the main intake substation at a power factor not less than 0.9 [21]. The distribution code in Ireland and elsewhere requires all generators connecting to the network to operate between the power factors of 0.90 leading and lagging [22].

For the simulation work on the test system, the PFC of DG is conducted at three different states of operations: a) unity power factor, b) leading power factor, and c) lagging power factor. From the results obtained in Figures 2 and 3, operating the DG at unity power factor, on the one hand, results in voltage rise at the load buses. On the other hand, operating the DG at leading power factor (absorbing Q) results in a low voltage at the load buses. This finding is similar to the work in [23] and [24], where operating the DG in leading power factor was found to mitigate the voltage rise issues. Operating the DG at lagging power factor also results in high voltage values recorded at the load buses.

Three different power factors values; 0.95, 0.90, and 0.80 are adopted in the test system. Comparisons of the results obtained by applying PFC in the test system to manage voltage rise have shown that operations at 0.90 and 0.80 can both limit the voltage within the permissible limits of ±5% (between 0.95 and 1.05 p.u.).

4.2 On-load tap changing control method

The on load tap changing control is applied to the test system by setting the minimum and maximum allowable voltage limits. However, this control depends on the tapping limit capability of the transformer. The typical values of the lower limit of the deadband of the OLTC range from 0.85 p.u. to 0.90 p.u., whereas those of the upper limit usually range from 1.10 p.u. to 1.15 p.u. [25]. The work based in Sweden [26] assumed that the maximum deadband to be used is 1.20 p.u., and that the step size is 1.67% or 0.0167. In addition, the maximum tap setting was set using two step sizes equivalent to 1.033 p.u., which were found to be effective in managing the voltage rise issue in the system tested.

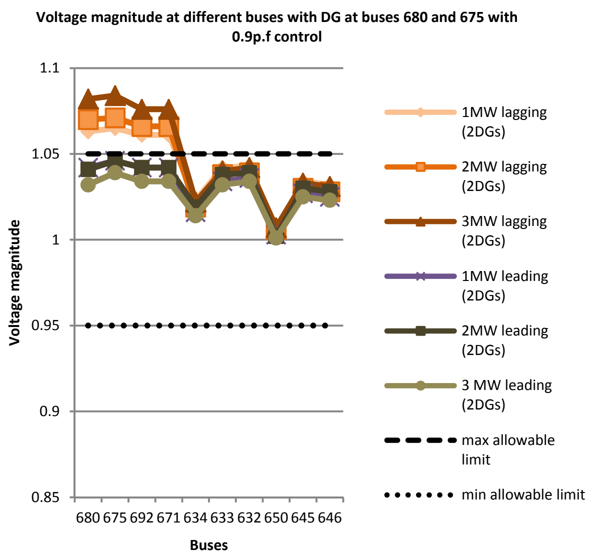

Fig. 2: Voltage magnitude at different buses with DG operating at 0.90 p.f.

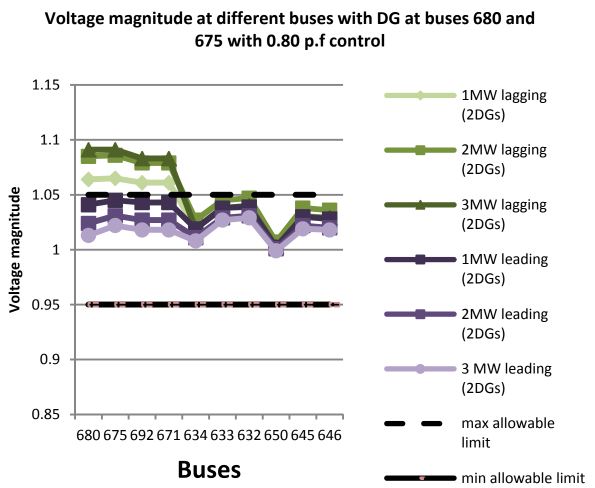

Fig. 3: Voltage magnitude at different buses with DG operating at 0.80 p.f.

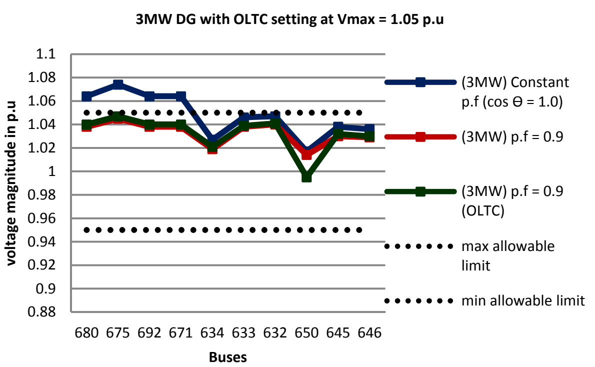

Fig. 4: Voltage magnitude at different buses with 3 MW of DG operating at constant power factor set at (i) 1.0 p.f., (ii) 0.90 p.f., and (iii) 0.90 p.f., with OLTC set at V max = 1.05 p.u.

In [27], the OLTC set point set between 1.014 and 1.025 p.u. was found to be effective in managing voltage fluctuations and in limiting network losses in the study. A more advanced on-load tap changing control method for managing voltage rise issues using OLTC and LDC was performed in [12]. Lowering the OLTC setting to 1.03 p.u. was found to increase the DG integration limit. The DG integration limit also increased significantly with the installation of a voltage regulator (VR) with OLTC set at 1.02 p.u. In the simulation work performed, two different settings, Vmax = 1.05 p.u. and Vmax = 1.02 p.u. were tested and compared with the DG operated at unity power factor and at 0.9 power factor. From the results shown in Figures 4 and 5, the setting of the OLTC at 1.02 p.u. was found to be more effective than the setting of 1.05 p.u. in managing the voltage rise in the system.

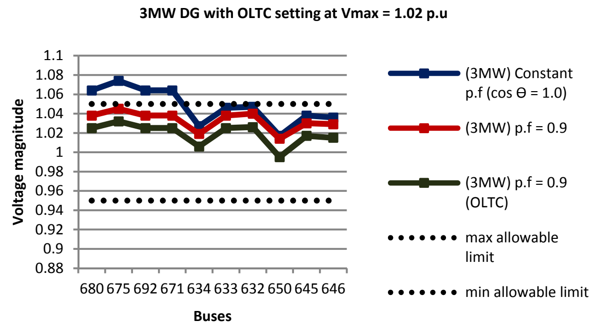

Fig. 5: Voltage magnitude at different buses with 3 MW DG operating at constant power factor set at (i) 1.0 p.f., (ii) 0.90 p.f., and (iii) 0.90 p.f., with OLTC set at V max = 1.02 p.u.

4.3 Generation curtailment

The amount of generation to be curtailed depends on various factors, such as voltage limit, sensitivity of network, operational response, capacity of DG unit, and load characteristics [28]. To date, most of the energy curtailment of DG involves wind energy curtailment, and several examples of wind energy curtailment practices are carried out in several states in the United States as well as in several other countries, such as Canada, Germany, New Zealand, Ireland, and Spain [29]. Normally, conventional generators are required to operate within ±1.5% of their scheduled amount.

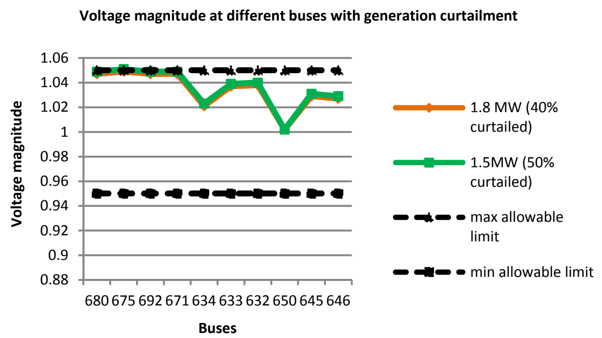

Fig. 6: Voltage magnitude at different buses with generation curtailment option.

However, with the connection of DGs to accommodate wind energy variability, the Electric Reliability Council of Texas (ERCOT) has granted wind generators the right to deviate from scheduled amounts by ±50%. Although the percentage of the wind curtailed in ERCOT considerably varies daily, it has exceeded 30% on 20 occasions, over 40% in nine days, and over 50% on one day. The maximum reduction in power can normally reach up to 60% for two to three hours in certain regions in Germany. For example, the work in [26] that used a simple seven-bus system with 3 MW of DG suggested that 41% of the active power must be curtailed to manage voltage rise. However, the reasonability of the percentage of curtailment depends also on the duration of the curtailment.

In the simulation work carried out, the amount of generation was curtailed to 40% and 50% of the total generation. As shown in Figure 6, the voltage profile was maintained within its operating point limits below the maximum of 1.05 p.u. and above 0.95 p.u with 40% of curtailment showing better voltage profile compared to 50% curtailment.

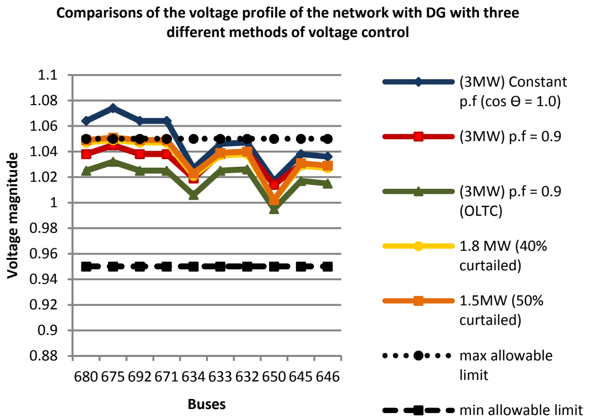

Fig. 7: Comparison of the effectiveness of the three different voltage control methods in managing voltage rise issues in an IEEE 13 bus network with DG.

Figure 7 shows the comparison of the voltage profiles of DG networks with three different methods of voltage control. Operating the DG at a constant power factor of 1 is found to result in high voltage rise, unlike when DG is operated at a power of 0.9. The voltage level is maintained at operating levels below 1.05 p.u. with 40% and 50% curtailment. The voltage level at the load buses is shown to be best maintained at its permissible level with the DG operating at 0.9 p.f., together with the OLTC control set at 1.02 p.u.

Conclusion

This paper discusses the decentralized voltage control methods simulated in an IEEE 13 bus test system. The control methods tested include the PFC, the on load tap changing control, and the generation curtailment method. The PFC method is performed by keeping the generator's power factor constant (i.e., by varying the reactive power of the generator according to the real power input). This method of voltage control is proven effective to a certain extent, wherein increasing the generator's input power results in high voltage rise. Operating the DG under OLTC control with two different tap settings, V max = 1.05 and 1.02 p.u., is also found to be capable of mitigating the voltage rise, with the latter operating condition of 1.02 p.u. as more effective in managing the rise. The option of generation curtailment, which is done by reducing input power, is also found effective in mitigating voltage rise, with a reduction of 40% and 50% in the input generation. However, other related issues related to the curtailment issue, such as the duration and cost of curtailment, are important considerations when opting for this method of voltage control. The decentralized voltage controls tested in the study is found to be capable of mitigating voltage rise within their limitations. Hence, further studies on coordinated voltage control with high levels of voltage mitigation options must be conducted in the future.

REFERENCES

[1] D'Adamo, Jupe, and Abbey, Global survey on planning and operation of active distribution networks - Update of CIGRE C6.11 working group activities, in *Electricity Distribution - Part 1, 2009. CIRED 2009. 20th International Conference and Exhibition on*, 2009, 1-4.
[2]Hidalgo, Abbey, Joo, A review of active distribution networks enabling technologies, in *Power and Energy Society General Meeting, 2010 IEEE*, 2010, 1-9.
[3]Nick Jenkins, *Embedded Generation*: The Institution of Electrical Engineers, London, 2000.
[4]Sansawatt, Ochoa, and Harrison, Integrating distributed generation using decentralised voltage regulation, in *Power and Energy Society General Meeting, 2010 IEEE*, 2010, 1-6.
[5]Masters, Voltage rise: the big issue when connecting embedded generation to long 11 kV overhead lines. *Power Engineering Journal,* (2002) No.16, 5-12.
[6]Sansawatt, O'Donnell, Ochoa, and Harrison, Decentralised voltage control for active Distribution Networks, in *Universities Power Engineering Conference (UPEC), 2009 Proceedings of the 44th International*, 2009, 1-5.
[7]T.Xu, Voltage Control Techniques for Electrical Distribution Networks including Distributed Generation, in *17th World Congress The International Federation of Automatic Control* Seoul, Korea, 2008.
[8]O'Gorman and Redfern, Voltage control problems on modern distribution systems, in *Power Engineering Society General Meeting, 2004. IEEE*, 2004, 662-667 Vol.1.
[9]Mutale, Benefits of Active Management of Distribution Networks with Distributed Generation, in *Power Systems Conference and Exposition, 2006. PSCE '06. 2006 IEEE PES*, 2006, 601-606.
[10]Thipnatee Sansawatt, "Decentralised Voltage and Thermal Management to enable more Distributed Generation Connection " presented at the CIRED Workshop, Lyon, 2010.
[11]Freitas, Vieira, Morelato, and Xu, Influence of excitation system control modes on the allowable penetration level of distributed synchronous generators. *Energy Conversion, IEEE Transactions on,* (2005) No.20, 474-480.
[12]Viawan, Sannino, and Daalder, Voltage control with on-load tap changers in medium voltage feeders in presence of distributed generation. *Electric Power Systems Research,* (2007) No.77, 1314-1322.
[13]Fila, Taylor, Irving, Hiscock, Lang, and Aston, Systematic modelling and analysis of TAPP voltage control schemes, in *Universities Power Engineering Conference, 2007. UPEC 2007. 42nd International*, 2007, 349-356.
[14]Fila, Taylor, Hiscock, Irving, and Lang, Flexible voltage control to support Distributed Generation in distribution networks, in *Universities Power Engineering Conference, 2008. UPEC 2008. 43rd International*, 2008, 1-5.
[15]Ochoa, Keane, Dent, and Harrison, Applying active network management schemes to an Irish distribution network for wind power maximisation, in *Electricity Distribution - Part 1, 2009. CIRED 2009. 20th International Conference and Exhibition on*, 2009, 1-4.
[16]Tonkoski, Lopes, and Turcotte, Active power curtailment of PV inverters in diesel hybrid mini-grids, in *Electrical Power & Energy Conference (EPEC), 2009 IEEE*, 2009, 1-6.
[17]Tonkoski, Lopes, and El-Fouly, Droop-based active power curtailment for overvoltage prevention in grid connected PV inverters, in *Industrial Electronics (ISIE), 2010 IEEE International Symposium on*, 2010, 2388-2393.
[18]Tonkoski, Lopes, and El-Fouly, Coordinated Active Power Curtailment of Grid Connected PV Inverters for Overvoltage Prevention. *Sustainable Energy, IEEE Transactions on,* (2011) No.2, 139-147.
[19]Ugranli, Ersavas, and Karatepe, Neural network based distributed generation allocation for minimizing voltage fluctuation due to uncertainty of the output power, in *Innovations in Intelligent Systems and Applications (INISTA), 2011 International Symposium on*, 2011, 415-419.
[20]Shalwala and Bleijs, Voltage control scheme using Fuzzy Logic for residential area networks with PV generators in Saudi

Arabia, in *Innovative Smart Grid Technologies (ISGT), 2011 IEEE PES*, 2011, 1-6.
[21]*Technical Guidebook for the Connection of Generation to the Distribution Network*: TNB Research Sdn Bhd in collaboration with APS Sdn Bhd Malaysia and RWE Npower PLC, UK, 2005.
[22]*Irish Distribution Code*: ESB Networks Std v 1.2, 2002.
[23]Kiprakis and Wallace, Maximising energy capture from distributed generators in weak networks. *Generation, Transmission and Distribution, IEE Proceedings-,* (2004) No.151, 611-618.
[24]Lianxiang Tang, Determination of Distibuted Generation Capacity from a Voltage Regulation Perspective, in *IEEE Transaction on Power Delivery*, Orlando Florida, 2012.
[25]*Distribution Planning Guidelines*: Planning and Asset Development Dept, Distribution Division,Tenaga Nasional Berhad, 2008.
[26]Leibe, "Integration of Wind Power in Medium Voltage Networks – Voltage Control and Losses," PHD in Electrical Engineering, Dept. of Measurement Technology and Industrial Electrical Engineering, Lund University, 2011.
[27]Viawan and Karlsson, Coordinated voltage and reactive power control in the presence of distributed generation, in *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE*, 2008, 1-6.
[28]Currie, Ault, Fordyce, MacLeman, Smith, and McDonald, Actively Managing Wind Farm Power Output. *Power Systems, IEEE Transactions on,* (2008) No.23, 1523-1524.
[29]S. Fink, "Wind Energy Curtailment Case Studies- May 2008-May 2009," Exeter Associates Inc, Columbia, Maryland2008-2009.

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