

Research on the Voltage Fluctuation Rules of Power System Containing Wind Farms

Yixi Chen, Guchao Xu, Gang Ma*, Feng Li and Rong Ju

School of Electrical and Automation Engineering, Nanjing Normal University,
Nanjing, 210042, China

* Corresponding author: nnumg@njnu.edu.cn

Abstract. The global energy shortage and environmental problems have contributed to the rapid development of wind power. However, due to the randomness and volatility of wind power, large-scale access may cause voltage fluctuation in power grid. Therefore, the reactive power control of power system containing wind farms has become a hot research topic in recent years, in which finding key nodes of voltage fluctuation is a foundation work. In this paper, the power model of wind farm is established first. Then, the influence on nodes voltage when wind farms access simple power system is analysed, and promoted to complex power systems in order to reveal the fluctuation rules of nodes voltage, and to summarize the distribution characteristics of key nodes of voltage fluctuation, which can provide the basis for reactive power optimization. At last, the conclusions are verified by IEEE 30-node system.

1. Introduction

Energy saving and emission reduction jointly lead to the rapid development of renewable energy power generation [1-2]. As one of the types of renewable energy power generation, wind power has strong volatility and is difficult to be predicted, due to the intermittent characteristic of wind energy [3]. The fluctuation of wind power will pose a great threat to the voltage stability of power system, which is one of the main restrictions of the large-scale utilization of wind power [4].

In order to solve the problem of nodes voltage fluctuation caused by the random power variation of wind farms, and also to lay the foundation for the research of reactive power control, it is important to find key nodes of voltage fluctuation in power systems containing wind farms. For that reason, it is urgently required to research on the voltage fluctuation rules of power system containing wind farms, and to summarize the distribution characteristics of key nodes of voltage fluctuation [5-6].

In this paper, the power model of wind farm is established firstly. Then, the influence on nodes voltage when wind farms access simple power system is analysed, and promoted to complex power systems subsequently, in order to reveal the fluctuation rules of nodes voltage after wind farms access, and to summarize the distribution characteristics of key nodes of voltage fluctuation, which can provide the basis for reactive power optimization of power system containing wind farms. At last, the conclusions are verified by IEEE 30-node system.

2. The power model of wind farm

In order to study on the voltage fluctuation rules of power system containing wind farms, the power model of wind farm should be established firstly. In traditional power flow calculation, nodes are divided into PQ nodes, PV nodes and slack nodes according to different natures. The access point of



wind farm can be regarded as PQ node to participate in power flow analysis, just as the common load nodes. That is, according to the given wind speed and power factor, get the active power and reactive power of wind farm, and then start the power flow calculation [7-8].

The curve about the relationship between wind speed and active power output of wind generator, which is called the operating characteristic curve of wind generator is shown as figure 1. When the wind speed is smaller than the cut-in speed, the wind wheel cannot rotate and therefore the active power output is zero. When the wind speed is between the cut-in speed and the rated speed, the active power output increases with the increase of wind speed. When the wind speed is between the rated speed and the cut-out speed, the active power output equals to the rated power. When the wind speed is greater than the cut-out speed, the wind generator stops in order to ensure safety [9]. Accordingly, the active power output of wind farm can be approximately expressed as:

$$P_{\text{out}} = \begin{cases} 0 & V(t) < V_{\text{in}} \text{ or } V(t) > V_{\text{out}} \\ \sum_{i=1}^N \left(\frac{V(t) - V_{\text{in}}}{V_{\text{n}} - V_{\text{in}}} \cdot P_{\text{ni}} \right) & V_{\text{in}} \leq V(t) \leq V_{\text{n}} \\ \sum_{i=1}^N P_{\text{ni}} & V_{\text{n}} \leq V(t) \leq V_{\text{out}} \end{cases} \quad (1)$$

where V_{in} is the cut-in speed of wind generator, V_{n} is the rated speed of wind generator, V_{out} is the cut-out speed of wind generator, P_{ni} is the rated power of the wind generator i in the wind farm, $V_{(t)}$ is the real time wind speed, N is the number of generators in wind farm.

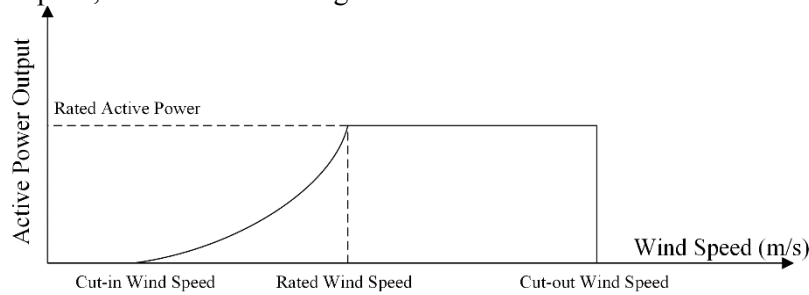


Figure 1. The operating characteristic curve of wind power generator.

Equation (1) has presented the method of calculating the active power output of wind farm, for the reactive power absorbed, it can be obtained by the power factor angle of wind generator [10], as:

$$Q_{\text{in}} = P_{\text{out}} \times \tan \varphi \quad (2)$$

3. The fluctuation rules of power system containing wind farms

3.1. Wind farms access simple power system

In order to summarize the distribution characteristics of key nodes of voltage fluctuation, the influence on nodes voltage when wind farms access power system has to be analysed.

For the simple power system as shown in figure 2, the transmission power of each line before the access of wind farm can be expressed as:

$$\left\{ \begin{array}{l} S_1 = \sum_{i=1}^4 (P_i + jQ_i) - (P_s + jQ_s) \\ S_{12} = \sum_{i=2}^4 (P_i + jQ_i) - (P_s + jQ_s) \\ S_{23} = \sum_{i=3}^4 (P_i + jQ_i) \\ S_{34} = \sum_{i=4}^4 (P_i + jQ_i) \end{array} \right. \quad (3)$$

Figure 2. The schematic diagram of a simple power system.

The transmission power of each line after the access of wind farm can be expressed as:

$$\left\{ \begin{array}{l} S_1 = \sum_{i=1}^4 (P_i + jQ_i) - [P_s - P_w(t) + jQ_s + jQ_{w1}(t)] - [P_w(t) - jQ_w(t)] \\ S_{12} = \sum_{i=2}^4 (P_i + jQ_i) - [P_s - P_w(t) + jQ_s + jQ_{w1}(t)] - [P_w(t) - jQ_w(t)] \\ S_{23} = \sum_{i=3}^4 (P_i + jQ_i) - [P_w(t) - jQ_w(t)] \\ S_{34} = \sum_{i=4}^4 (P_i + jQ_i) \end{array} \right. \quad (4)$$

where Q_{w1} is the reactive power compensation provided by the slack node (i.e., frequency regulation power plant).

As compared with the change of wind power, the load change is slower, and compared with the wind speed forecasting technology, the technology of load forecasting is relatively more mature, so the load change is not considered in this paper. Therefore, according to equation (4), the variable quantity of transmission power can be obtained as:

$$\left\{ \begin{array}{l} \Delta S_1 = \Delta j [Q_w(t) - Q_{w1}(t)] \\ \Delta S_{12} = \Delta j [Q_w(t) - Q_{w1}(t)] \\ \Delta S_{23} = -\Delta P_w(t) + \Delta j Q_w(t) \\ \Delta S_{34} = 0 \end{array} \right. \quad (5)$$

The fluctuation of transmission power showed in equation (5) can cause the fluctuation of voltage drop in lines, which would lead to the fluctuation of nodes voltage finally.

As the active power output of PV node (i.e., normal power plant) is a constant value, so the voltage fluctuation caused by the active power changes of wind farms is only reflected through paths from access nodes to slack nodes.

However, as both PV nodes and slack nodes can provide reactive power for wind farms, so the voltage fluctuation caused by the reactive power changes of wind farms is reflected through paths from the access nodes to slack nodes or to PV nodes.

3.2. Wind farms access complex power system

In the above, the power flow of a simple system has been analysed, and the influence on nodes voltage when wind farms access has been studied on, the voltage fluctuation rules of the simple power system have also been obtained. However, while analyse a complex power system, the direct power flow analysis are difficult, so we extend the voltage fluctuation rules of simple power system to complex power system, based on which, the distribution characteristics of key nodes of voltage fluctuation can be summarized.

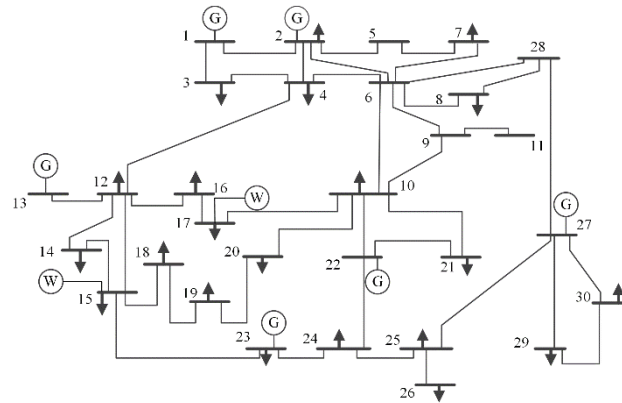


Figure 3. The schematic diagram of IEEE 30-node system containing wind farms.

Take the IEEE 30-node system as shown in figure 3 as an example, two wind farms are accessed at node 15 and node 17 respectively. According to the conclusions in 3.1, the voltage fluctuation caused by the active power changes of wind farms is only reflected through paths from access nodes to slack nodes, which can be called as flow paths of $\Delta P_{W(t)}$, while the voltage fluctuation caused by the reactive power changes of wind farms is reflected through paths from the access points to slack nodes or to PV nodes, which can be called as flow paths of $\Delta Q_{W(t)}$.

As the line resistance is much smaller than the line reactance in transmission lines, so compared with the effect of $\Delta Q_{W(t)}$ on voltage drop, the effect of $\Delta P_{W(t)}$ on voltage drop is much smaller. Therefore, it is reasonable that summarize the distribution characteristics of key nodes of voltage fluctuation considering $\Delta Q_{W(t)}$ only.

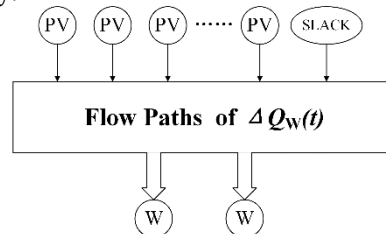


Figure 4. The flow paths schematic diagram of $\Delta Q_{W(t)}$.

Different from simple power systems, there are much more flow paths of $\Delta Q_{W(t)}$ in complex power system like figure 3. The flow paths of $\Delta Q_{W(t)}$ in complex power system can be expressed as figure 4, where the block represents the complex transmission network containing a great many flow paths of $\Delta Q_{W(t)}$.

In the block showed in figure 4, there must be some nodes which are the junctions of several flow paths of $\Delta Q_{W(t)}$. As shown in figure 5, the reactive power flowing through such nodes and also their adjacent nodes has a larger change rate. Especially when all flow paths of $\Delta Q_{W(t)}$ converge at one node, the variable quantity of the reactive power flowing through this node will be exactly equal to the whole reactive power variation of wind farms.

Therefore, the voltage fluctuation of nodes which are the junctions of several flow paths of $\Delta Q_{W(t)}$, and also the voltage fluctuation of their adjacent nodes are bigger. These nodes are the key nodes of voltage fluctuation, and should be paid much more attention in reactive power control.

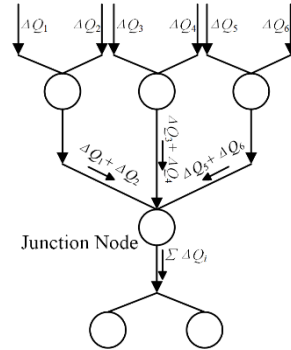


Figure 5. The schematic diagram of flow paths of $\Delta Q_{W(t)}$ near a junction node.

4. Case Analysis

In order to verify the correctness of the conclusions above, the IEEE 30-node system has been used. As shown in figure 3, node 15 and node 17 have been selected to be the access nodes of wind farms, and the capacity are both 10MW (i.e., wind power penetration $\approx 10\%$), the power factor of wind generator is set as 0.9. The type of wind generator is selected as PGE35KW, and the relating parameters are shown in table 1.

Table 1. Parameters of the Wind Generator PGE35KW.

Rated power (P_n)	35kW	Rated wind speed (V_n)	14m/s
Cut-in wind speed (V_{in})	4.8m/s	Cut-out wind speed (V_{out})	25m/s

The wind speed is simulated from 0 m/s to 20 m/s, so the voltage fluctuation curves of 30 nodes can be obtained as figure 6, where the curve clusters are lines of same wind speeds.

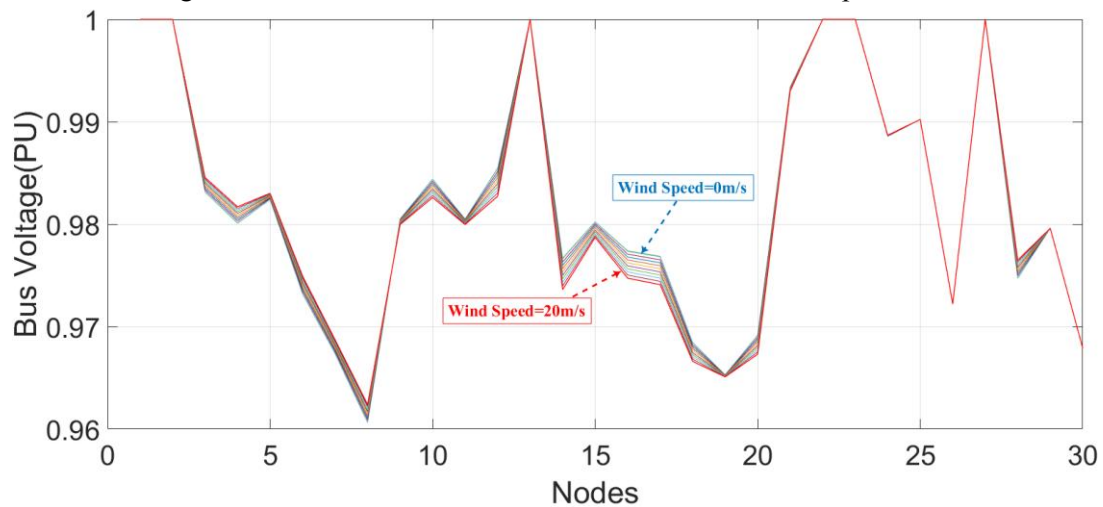


Figure 6. Node voltage fluctuation curves of IEEE 30-node system containing wind farms under different wind speeds.

As shown in figure 6, the node set with a relatively larger voltage fluctuation is $\{3, 4, 6, 7, 8, 10, 12, 14, 15, 16, 17, 18, 20, 28\}$. As shown in figure 3, some of these nodes are intersection nodes of several lines or their adjacent nodes, other nodes are the access nodes of wind farms or their adjacent nodes. Several flow paths of $\Delta Q_{W(i)}$ converge near or at these nodes, leading to bigger voltage fluctuation, which is in accord with the distribution characteristics of key nodes of voltage fluctuation summarized in this paper.

Therefore, when in the research of reactive power control, it is feasible to look for key nodes of voltage fluctuation in power system containing wind farms based on the conclusions of this paper.

5. Conclusion

The power model of wind farm has been established in this paper. Then, the influence on nodes voltage when wind farms access simple power system has been analysed, and been promoted to complex power systems subsequently, therefore the fluctuation rules of nodes voltage after wind farms access have been obtained, and the distribution characteristics of key nodes of voltage fluctuation have been summarized. At last, the conclusions have been verified by IEEE 30-node system, the results of case analysis have proved that it is feasible to look for key nodes of voltage fluctuation in power system containing wind farms based on the conclusions of this paper.

Acknowledgments

This research was supported by NSF of China (51607093), NSF of Jiangsu Province (BK20141452) and High level talents in Nanjing Normal University research start-up research project (2014111XGQ0078).

References

- [1] Woodrow W. Clark III and Grant Cooke 2014 *The Green Industrial Revolution: Energy, Engineering and Economics* (UK: Butterworth-Heinemann)
- [2] Zhang Wenliang, Liu Zhuangzhi, Wang Mingjun and Yang Xusheng 2009 *Power System Technology* **33** 1-11
- [3] Sun Yuanzhang, Wu Jun, Li Guojie and He Jian 2009 *Proceedings of the CSEE* **29** 41-47
- [4] Shi Hongtao, Yang Jingling, Ding Maosheng and Wang Jinmei 2011 *Automation of electric power systems* **35** 44-48
- [5] Wang Chengfu, Liang Jun, Zhang Li, Feng Hongxia and Han Xueshan 2012 *Automation of electric power systems* **36** 119-24
- [6] Li Hongxin, Li Yinhong and Li Zhihuan 2013 *Power System Technology* **37** 1651-58
- [7] Wu Yichun, Ding Ming and Zhang Lijun 2005 *Proceedings of the CSEE* **25** 36-39
- [8] Zhu Xingyang, Liu Wenxia and Zhang Jianhua 2013 *Proceedings of the CSEE* **33** 77-85
- [9] Gang Ma, Guchao Xu, Rong Ju and Tiantian Wu 2015 *International Journal of Sustainable Energy* doi: 10.1080/14786451.2015.1081908
- [10] Z. Saad-Saoud and N. Jenkins 1999 *IEEE Transactions on Energy Conversion* **14** 743-48