Risk Assessment Model for Wind Generator Tripping Off

Chen, Q., Littler, T., Han, S., & Wang, H. (2015). Risk Assessment Model for Wind Generator Tripping Off. Proceedings of the CSEE, 35(3). DOI: 10.13334/j.0258-8013.pcsee.2015.03.009

Published in:
Proceedings of the CSEE

DOI：10.13334/j.0258-8013.pcsee.2015.03.009 文章编号：0258-8013 (2015) 03-0576-07 中图分类号：TM 71

风电机组脱网的风险评估

陈麒宇[1]，Tim Littler[1]，韩树山[2]，王海风[3]

(1. 贝尔法斯特女王大学电子电气与计算机科学学院，英国 贝尔法斯特 BT9 5AH; 2. 国网山东电力公司，山东省 济南市 250000; 3. 华北电力大学电气与电子工程学院，北京市 昌平区 102206)

Risk Assessment Model for Wind Generator Tripping Off

CHEN Qiyu[1], Tim Littler[1], HAN Shushan[2], WANG Haifeng[3]

(1. School of Electronics, Electrical Engineering and Computer Science, Queen’s University Belfast, Belfast BT9 5AH, UK; 2. Shandong Power Company, SGCC, Jinan 250000, Shandong Province, China; 3. School of Electrical and Electronics Engineering, North China Electric Power University, Changping District, Beijing 102206, China)

ABSTRACT: With wind farms being rapidly integrated into power systems, the impacts of wind power on power system operation obviously emerges. Wind generator trip-off happens frequently in China, which has impacted power system operation. In order to keep a power system with wind generation operating safely, a risk assessment model for wind generator trip-off was established. It is impossible to calculate all of the possible faults online, because of the explosion of faults and the consumption of calculation time. Therefore, the wind generator trip-off index was designed to calculate the probability of wind generator trip-off when a fault occurs. Besides considering power system states, the failure in the wind farms was also taken into account based on the actual trip-off statistics in the index. The anticipating fault set was generated based on the index and the electrical distance from wind farm to fault location. The fault subset, which may cause wind generator trip-off, was sorted and filtered from the fault set by the probability of tripping off. Therefore, only the faults in the subset are scanning on line, and providing warning information simultaneously. The risk assessment model for wind generator trip-off can calculate wind farm trip-off capacity, and analyze the state of system stability. Both the accuracy and effectiveness of the proposed risk assessment model are verified by simulation results from Gansu Power Grid of China online data.

KEY WORDS: wind power; tripping off index; contingency set; risk assessment model

摘要： 随着风电机组大规模并网，风电对电力系统的影响逐渐显现。我国多次发生风电机组连锁脱网事故，影响了电力系统的运行。为了预警风电机组脱网，保证电力系统的安全运行，提出风电机组脱网的风险评估模型。由于故障组合数量爆炸，不可能在线分析所有的可能故障。因此，建立风电机组脱网指标，来衡量发生故障时风电机组的脱网概率。该指标不但考虑电力系统故障，同时也考虑了风电场内部故障。根据脱网指标和风电场到故障点的电气距离，对预想故障进行排序和筛选，生成有效预想故障子集；仅对有效故障集内的可能故障进行在线风险评估和风电机组脱网预警。该模型可以给出风电机组脱网容量。对某省电网在线数据仿真分析，验证了理论方法的正确性和预警模型有效性。

关键词： 风电；脱网指标；故障集；风险评估模型

0 INTRODUCTION

Wind power generation is one of the most mature renewable energy technologies. However, as large-scale wind farms are integrated into the power system, the security of power system operation draws more and more attention. From 2011 to 2012, 205 wind turbine trip-off faults occurred in China. In the middle of December 2012, during the low voltage ride through (LVRT) test in Jiuquan Wind Power Base, some wind turbines with LVRT also tripped off. Most wind turbines under 1 MW do not take LVRT rebuild. The total wind capacity in China is around 7 500 GW and the wind farms distribute intensively all over the China, the capacity of wind farms range from several hundred MW to several GW. As wind power fluctuations have been impacting the safe operation of power systems, it is necessary to take online early warning for wind turbines concatenate trip-off so as to keep the power system operating normally.

The electric power system dynamic security assessment (DSA) and early warning system did not consider wind turbine trip-off and its impacts on system operation, so the early warning result is optimistic [1-9]. In this paper a risk assessment model for wind generator trip off (RAMWT) was presented in order to make a dynamic security assessment of the power system and provide early fault warnings. Firstly, the causes for wind farm trip-off were investigated. On the base of wind power filed integration national standard in China, the indices for judging wind turbine trip-off is established, by means of the statistical analysis on Jiuquan Wind Power Base LVRT field test. Secondly, the concept of electrical distance is utilized to sort and scan the anticipated faults. The tripping capacity of wind turbines during power system transients is calculated and the tripping of wind turbines contributes to the fault. The system stability is analyzed, with consideration of wind generator trip off, in order to prevent cascading failure by facilitating accurate decision-making on the part of electrical power system dispatchers.

1 CAUSES OF WIND GENERATOR TRIP-OFF

The concept of the wind turbines common mode trip off is the phenomenon that wind turbines often trip off at the same time during some disturbances in the power systems. This is a fault model that is different from the fault mode of traditional generator. The common mode trip off of wind generators will challenge the safety of power systems, especially in an area with high wind power penetration. The main reasons for cascade trip-off are summarized as follows [10-12].

1）Overvoltage protection of wind generators.

2）Overcurrent protection of wind generators.

3）High-frequency protection of wind generators.

4）Three phase unbalance.

5）Lack of low voltage ride through.

6）Lack of high voltage ride through.

7）Faults at wind turbines, transformers, lines and so on in the wind farm.

8）Turbines with LVRT may trip off due to software and hardware faults when the voltage is low.

2 FAULT SELECTION

2.1 Index of Wind Generator Trip-off

An online early warning model for wind turbine trip-off is put forward. The model is based on Power System Analysis Software, integrating online data, filtrating the anticipate faults which may cause wind turbines trip-off, taking an online transient simulation analysis every 15 minutes, calculating the wind power trip-off capacity caused by faults, analyzing system stability situation. The model formulation is shown in Fig. 1.

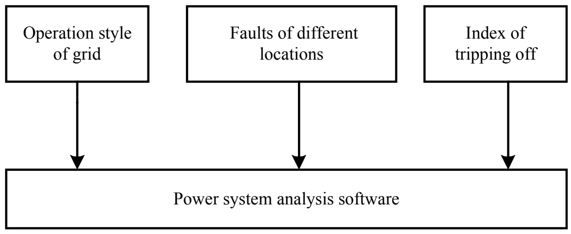

图 1　风电脱网在线预警模型结构图

Fig. 1　Diagram of early warning model for Wind turbines trip-off

Wind turbine trip-off is mainly caused by generator terminal voltage dropping and surging [10-12]. The grid voltage range where wind turbines should trip has been defined all over the world and is taken as the index for wind turbines tripping. But some turbines tripped off before terminal voltage dropped to the allowed range. Therefore, the trip-off index needs to be improved. In December 2012, in the LVRT field test at Jiuquan Wind Power Base, most of the turbines with LVRT came into LVRT mode as the grid voltage dropped, but some tripped due to the faults of themselves. Therefore, in this paper, the indexes for wind turbine trip-offs is combined with the newest The guide rule of wind power integration in China [13] and actual wind power trip-off test are established.

1）Traditional index of wind power trip-off.

China has issued the Wind Power Integration Rule. It stipulates the acceptable voltage range beyond which wind turbines should be removed from grid. The index of wind generator trip-off is as follows.

①Wind turbines without LVRT:

$$U \le 0.9U_n, t \ge 100\ \text{ms};\quad g_1 = 100\% \tag{1}$$

②Wind turbines with LVRT:

$$\begin{cases} U \le 0.2U_n \\ U < (0.509t - 0.118)U_n, \ 0.625 \text{ s} \le t \le 2 \text{ s} \\ U < 0.9U_n, t > 2 \text{ s}; \ g_2 = 100\% \end{cases} \quad (2)$$

③ All types of wind turbines, high voltage trip-off:

$$U \ge 1.1U_n, t \ge 100 \text{ ms}; \ g_3 = 100\% \quad (3)$$

where U is the voltage of connection point of wind turbines; Un is the grid nominal voltage; g_i (i=1,2,3) is the probability of trip-off.

2）Index taking the equipment failure into account.

Three hundred wind generators were tested during the LVRT field test at Jiuquan Wind Power Base in December 2012; 16 wind generators tripped off. The cause of tripping off are shown in Tab. 1.

表 1 风电机组故障脱网统计

Tab. 1 Reason statistics of wind generators trip-off grid

Causes	Over current	Yew failure	Generator over speed	LVRT failure	Protection hardware failure and malfunction
Number	2	3	1	3	7

Based on these results, a statistical method is adopted to calculate wind turbine trip-off probability. Let the generators trip-off obey (0-1) distribution. Now, calculate the confidence interval when the confidence coefficient is 95%.

The sample size h is very large since there were 300 wind turbines in the test. According to central limit law, the turbines trip-off approximately following a normal distribution. The confidence coefficient giving the probability of trip-off g is 0.95 and the confidence interval is (g_1, g_2). The formula is as following:

$$\begin{cases} g_1 = (-b - \sqrt{b^2 - 4ac}) / 2a \\ g_2 = (-b + \sqrt{b^2 - 4ac}) / 2a \end{cases} \quad (4)$$

Where $a = h + z_{a/2}^2, b = -(2h\bar{X} + z_{a/2}^2), c = h(\bar{X})^2$, and h=300, $\bar{X}$=16/300=0.053, $z_{a/2}$=1.96.

According to Eq. (4), the interval of probability g_4 is (3.3%, 8.5%) when one of the confidence coefficients is 0.95. It means that the probability g_4 of the wind trip-off entering LVRT is (3.3%, 8.5%), the reliability is 95%. Therefore, the trip-off index of turbines faults is:

$$\begin{cases} 0.2U_n \le U < 0.9U_n \\ 0 \le t < 0.625 \\ (0.509t - 0.118)U_n < U < 0.9U_n \\ 0.625 \text{ s} \le t \le 2 \text{ s} \\ g_4 \in [3.3\%, 8.5\%] \end{cases} \quad (5)$$

In conclusion, according to the index of wind turbine trip-off, the minimum and maximum trip-off capacity in the process of grid faults is $T_{\min}$, $T_{\max}$:

$$T_{\min} = M_1 \cdot g_1 + M_2 \cdot g_2 + M_3 \cdot g_3 + M_4 \cdot g_{4(\min)} \quad (6)$$

$$T_{\max} = M_1 \cdot g_1 + M_2 \cdot g_2 + M_3 \cdot g_3 + M_4 \cdot g_{4(\max)} \quad (7)$$

where M_i(i=1,2,3,4) is real time wind power correspondingly the 4 index; $g_{4(\min)}$, $g_{4(\max)}$ are minimum and maximum probability of faults trip-off.

2.2 Anticipating Transient Stability Fault Filtration

It is impossible to calculate all of the possible faults online because of the explosion of faults and calculation time consumption. Results are usually filtered faults according to the anticipated severity of accidents [14-18], and warn of the contingencies according to the queue of probability. In this paper the probability of anticipated trip-off faults is queued according to the wind generator trip-off index.

The anticipated fault set (C_S) is all of the faults corresponding to all of the elements in the grid. The anticipated faults set of early warning wind power trip-off consists of 2 parts: interior power grid faults occur on wind farms C_1 and external faults occur on the grid and affect wind farms C_2. C_S is the sum of C_1 and C_2.

Wind farms are generally located in harsh environments with a large number of low voltage feeders and terminal blocks，which may cause short circuits easily. The accuracy of single-phase fault line selection device is low. Single-phase fault easily develops into a three phase short circuit if it is not promptly removed. A three phase fault at a wind farms can not only lead to a serious voltage drop, but also force the adjacent wind farms off-grid. Therefore, data on 3 phase short circuit faults, at the low voltage side of the main transformers, are used to create the fault set C_1.

3.3 Scanning External Faults Based on Electrical Distance

1）Scanning index.

The voltage at the grid connection point for the wind farm is used as the indicator for wind generator trip off. The node voltage sag in the power system is relative to two factors; they are the electrical distance between this node and the point of fault, and support capacity of reactive power in this node. The reactive power support capacity is fixed for a wind farm. Therefore, the electrical distance is used to sort and filter faults.

There are two methods to calculate the electrical distance; one is the impedance method, the other is the sensitivity method. The first method is used to calculate the electrical distance in this paper since it can measure the influence of different short circuits on the wind farm voltage [16-20].

2）Calculation of the electrical distance.

The impedance between two nodes is used as the parameter for measuring the electrical distance between two nodes in a complex network. The input impedance $Z_{ij.\mathrm{in}}$ of a two-terminal network: the equivalent impedance which assembled by any two network nodes of ungrounded ports. The physical meaning is shown in Fig. 2.

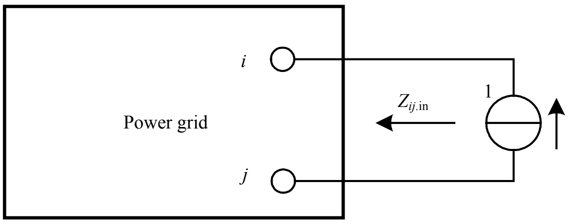

图 2　二端网络的输入阻抗

Fig. 2　Input impedance of two terminal network

The potential drop across the node pair (i, j) is equal to the self-impedance of the node when the unit current flows through the port which is consisted by the node pair.

$$Z_{ij,\mathrm{in}} = M_{ij}^{\mathrm{T}} Z M_{ij} = Z_{ii} + Z_{jj} - 2Z_{ij} \tag{8}$$

where, $M_{ij}=[1,-1]^{\mathrm{T}}$, Z_{ii}, Z_{jj} are self-impedance of node i, j in the node array of impedance. Z_{ij} is the mutual impedance of node i, j. The matrix of nodal impedance is the inverse of the node admittance matrix which is obtained by adding the admittance branch of each bus one by one.

3）Malfunction scanning.

Eq. (8) shows that the input impedance of a two-terminal network is closely related to the elements in the impedance matrix of nodes. The impedance matrix is decided by network structure. The parameters of the network element include real-time topology information of the grid. Therefore, the input impedance of a two-terminal network also reflects the whole network topology information in real time. The equivalent impedance between pairs of nodes represents input impedance of a two-terminal network. If the value of input impedance is smaller, the electrical distance between two nodes is less. The shorter the electrical distance, the more serious the voltage drop at one node when a short circuit occurs at the other node.

The fault set for on-line warming considers three phase short circuit faults on lines and transformers. The malfunction is located in their buses to ensure strict checking. Thus the diverse influence of malfunction on wind farms is represented by the electrical distance between the bus fault point and wind farm.

Wind farms are usually have a few step-up transformers to concentrate power to the grid. The Jiuquan Wind Power Base is intensively integrated into the Northwest Power Grid through the Dunhuang 330 kV and Yumen 330 kV pooled power substation. Thus, the tripping risk indicator P_{I} for wind turbines is characterized by summing the electrical distance between each system bus and the high voltage bus of the pooled power substations.

$$P_{\mathrm{I}} = Z_{\mathrm{a}j.\mathrm{in}} + Z_{\mathrm{b}j.\mathrm{in}}, \quad j = 1,2,3,\cdots,N \tag{9}$$

Where $Z_{\mathrm{a}j.\mathrm{in}}$ and $Z_{\mathrm{b}j.\mathrm{in}}$ are the electrical distances between the two pooled substations and other nodes on the power system. N is the number of nodes in the transmission network.

The faults of top nth on order of P_{I} are selected. The n is determined by the actual size of the grid and the computing capabilities of the risk assessment system. Anticipated failures are assigned to compute nodes of warning systems by a unified platform scheduling server. Transient calculation takes the indicator of wind power tripping into account. If scanned failures of top nth also make wind generator tripping off, the scanning failure process continues according to P_{I} until no fault causes wind power tripping off power system, and then terminates simulation. The scanning model is shown in Fig. 3.

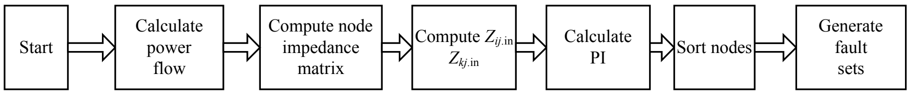

图3 基于电气距离的故障筛选过程

Fig. 3 Fault filtering process based on electrical distance

3 EARLY WARNING OF WIND GENERATOR TRIPPING OFF BY RAMWT

Wind generator trip-off is not considered in existed warning models [21-25], but its impacts on power system operation should not be neglected anymore.

The RAMGT presented in this paper is used for the early warning of wind generator trip-off. It reads the real-time measurement data from the power grid (via a WAMS) every 15 minutes, and integrates the offline data and date from SCADA. On this basis it calculates power flow and generates effective forecasting fault set. Through the transient stability simulation, the model calculates trip-off capacity of wind power under each expected failure. Then adds the trip-off capacity to the process of the accident as a disturbance and analyses the stability of power system caused by cascading failures. RSM provides the accurate decision-making support to electric power dispatcher in order to prevent cascading failures. The model is proposed as Fig. 4.

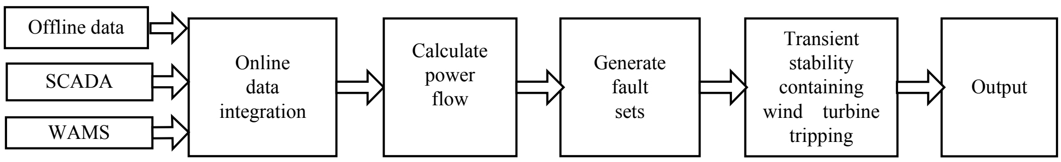

图4 风电脱网在线预警模型

Fig .4 Model of RAMWT for wind turbines trip-off grid

4 SIMULATING ANALYSIS AND CASE STUDY

Gansu Power System is located in Northwest China and wind farms are concentrated in the region of Jiuquan. Nearly 7 GW of wind power connected to the main grid of Gansu via Dunhuang and Yumen power substation. As exposed in Fig. 5.

The electricity generated by these wind farms is transmitted nearly 1 000 km to terminal users over 750 kV lines. The transmission line is a typical large power, long distance line with weak power grid structure, as shown in Fig. 5. Online data from Gansu Power Grid at 04:50 April 17, 2011 was taken in order to validate the effectiveness of the off-grid wind power risk assessment system proposed in this paper. The scale of the power grid at this time is as follows: 5317 transmission lines, 2618 transformers, total wind power output 1 826 MW. 97 wind turbines are used for the online equivalent model of the wind farm; these wind turbines lack LVRT capabilities at this time.

The number of anticipated faults on the power grid is over 10,000. System faults were sorted and filtered according to the algorithm proposed in this paper. The first 500 anticipated faults were simulated in detail; along with an additional 97 faults originating in wind farms. The results indicate that 597 of these faults would cause wind turbine trip-off. The remaining redacted faults do not needed to be simulated. The calculation time is 11 minutes and 26 seconds which is satisfactory given online computing needs. The simulation results of anticipated faults are shown in Tab.2.

The capacity for LVRT fault is 0, because no wind turbine in wind farm has this capacity at this time. The low-voltage there-phase short circuit in GanXi2 line caused the tripping accident on April 17, 2011. The state of the power grid during the fault was: the minimum voltage was 283 kV on the 330 kV bus of 750 Dunhuang transformer and the maximum value was 366 kV. This leads to 943.2 MW of LV wind power and 63 MW of HV wind power being tripped. The results given by the risk assessment model

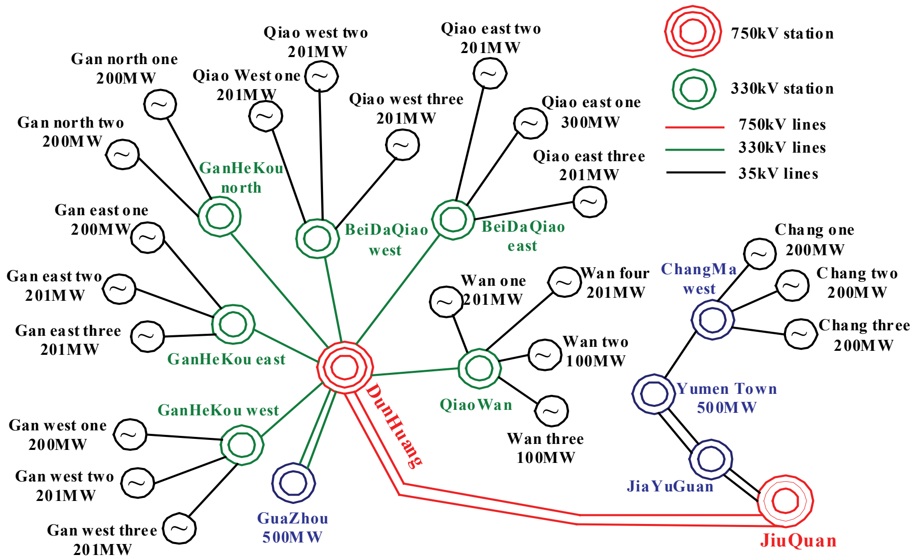

图 5　某风电基地风电并网接线图

Fig. 5　Wind power connection diagram

表 2　预想故障计算结果

Tab. 2　Computed results of anticipated failure

Fault location	Dunhuang minimum voltage/kV	Dunhuang maximum voltage/kV	Tripping capacity of low voltage/MW	Tripping capacity of high voltage/MW	Tripping capacity of fault/MW	Total tripping capacity/MW	Maximum power angle/(°)
Dunhuang transformer	3.1	382	1 826	0	0	1 826	183
Dunjiu line71	3.6	382	1 826	0	0	1 826	183
Dunha line71	3.6	382	1 826	0	0	1 826	182
Yumen Transformer	272.7	367	1 170	550	0	1 720	165
Yujia line31	275	367	1 170	550	0	1 720	165
Jiuhe line71	74.3	384	1 826	0	0	1 826	181
……	……	……	……	……	……	……	……
Ganxi2	280.6	377	1 011	69	0	1 080	175
……	……	……	……	……	……	……	……
Lingong31 line	306.1	329	0	0	0	0	155

indicate that the LV tripping capacity is 68.5 MW higher than the standard model suggests while HV tripping is 6 MW higher. The cause of the additional tripping is that wind farms are equaled into several wind units in online data. As the error is within 10% it meets engineering needs. The minimum voltage is 2.4 kV lower than the actual and the maximum voltage is 11.1 kV higher than the actual, since reactive power compensation equipment is disconnected in actual in the transient process. But they were considered in the online simulation process.

5　CONCLUSION

A risk assessment model for wind generator tripping off is presented. This model puts forward an accurate and comprehensive index of wind turbine trip-off. It generates a sorted and filtered anticipated fault set based on electrical distance. Finally, the established wind turbine trip-off Risk Assessment Model can calculate trip-off capacity of wind power and measure system stability. Both the correctness of the proposed method and the effectiveness of the proposed risk assessment model are verified by simulation results from Gansu Power Grid online data.

参考文献

[1] Lvan M，Alan R．Online security analysis of power grids with high wind penetration[J]．IEEE Power & energy magazine，2012，10(2)：62-70．

[2] Han Z，Cao Y．Analysis on and precautions against large-scale wind turbines off-grid[C]//IEEE the International Conference on Advanced Power System Automation and Protection．Beijing，China：IEEE，2011：1974-1980．

[3] Sun H，Zhang Z．Analysis on serious wind turbine generators tripping accident in Northwest China Power Grid in 2011 and its lessons[J]．Power System Technology，2012，36(10)：76-80．

[4] 陈树勇，朱琳，丁剑，等．风电场并网对孤网高频切机的影响研究[J]．电网技术，2012，36(1)：58-64．
Chen Shuyong，Zhu Lin，Ding Jian．Impact of grid-connected wind farms on high frequency generator tripping in isolated power grid[J]．Power System Technology，2012，36(1)：58-64(in Chinese)．

[5] Chen S，Gao N．Affect analysis of power grid energy quality for coastal wind power access[J]．Energy Procedia，2011，12：752-760．

[6] 严剑锋，于之虹，田芳，等．电力系统在线动态安全评估和预警系统[J]．中国电机工程学报，2008，28(34)：87-93．
Yan Jianfeng，Yu Zhihong，Tian Fang，et al．Dynamic security assessment & early warning system of power system[J]．Proceedings of the CSEE，2008，28(34)：87-93(in Chinese)．

[7] Su F，Zhou X．Development and application of on-line wind power risk assessment system[C]//2011 International Conference on Advanced Power System Automation and Protection(APAP2011)．Beijing，China：Tsinghua University，2011：2061-2065．

[8] 贺益康，胡家兵．双馈异步风力发电机并网运行中的几个热点问题[J].中国电机工程学报，2012，32(27)：21-26．
He Yikang，Hu Jiabing．Several hot-spot issues associated with the grid-connected operations of wind-turbine driven doubly fed induction generators[J]．Proceedings of the CSEE，2012，32(27)：21-26(in Chinese)．

[9] Martinez M I，TapiaG，Susperregui A，et al．DFIG power generation capability and feasibility regions under unbalanced grid voltage conditions[J]．IEEE Transactions on Energy Conversion，2011 26(4)，1051-1062．

[10] Chen Q，Littler T．Large-scale wind generator cascaded tripping[C]//2013 IEEE International Conference on Computer Science and Automation Engineering．Guangzhou，China：IEEE，2013，919-923．

[11] Naresh A，Liu C C．Tripping of wind turbines during a system fault[C]//IEEE Power and Energy Society General Meeting Conversion and Delivery of Electrical Energy in the 21st Century．Pittsburgh，PA：IEEE，2008：2654-2660．

[12] Chen Q，Littler T，Wang H．Tripping control for transient stability in coordinated hydro and wind generation[C]//IET International Conference on Renewable Power Generation Conference 2013．China：IET，2013：1-4．

[13] State Grid Corporation of China．GB/Z19963-2009 The guide rule of wind power integration in China[S]．Beijing：State Grid Corporation of China，2009．

[14] Chen Q，Littler T，Wang H．Application of PMUs to coordinate hydroelectric and wind power plant operation[C]//International Conference on Sustainable Power Generation and Supply．Hangzhou，China：IEEE，2012：1-6．

[15] 蔡建壮，白同朔，侯志俭．电力系统偶然事故选择中异常数据的鉴别与处理[J]．中国电机工程学报，2002，22(8)：26-30．
Cai Jianzhuang，Bai Tongshuo，Hou Zhijian．Outliers' detection and assessment in power system contingency selection[J]．Proceedings of the CSEE，2002，22(8)：26-30(in Chinese)．

[16] Li G，Steven M．Integral square generator angle index for stability ranking and control[J]．IEEE Transactions on Power Systems，2005，12(2)，926- 934．

[17] 王海霞，刘娆，赵彩虹，等．考虑节点间电气距离的潮流追踪损耗分摊方法[J]．电网技术，2008，32(2)：196-201．
Wang Haixia，Liu Rao，Zhao Caihong，et al．Power loss allocation based on power flow tracing with consideration of the electrical distance between buses[J]．Power System Technology，2008，32(2)：196-201(in Chinese)．

[18] 陈树勇，王聪，申洪，等．基于聚类算法的风电场动态等值[J]．中国电机工程学报，2012，32(4)：11-19．
Chen Shuyong，Wong Cong，Shen Hong，et al．Dynamic equivalence for wind farms based on clustering algorithm [J]．Proceedings of the CSEE，2012，32(4)：11-19(in Chinese)．

[19] Liu Hong．A new method about calculating electrical distance[C]//Power Engineering and Automation Conference．Wuhan，China：IEEE，2011：2016-2021．

[20] Blumsack S，Hines P．Defining power network zones from measures of electrical distance[J]．IEEE Transactions on Power Systems，2005，12(1)：52-60．

[21] 杨秀媛，董征，唐宝，等．基于模糊聚类分析的无功电压控制分区[J].中国电机工程学报，2006，26(22)：6-10．
Yang Xiuyuan，Dong Zheng，Tang Bao，et al．Power network partitioning based on fuzzy clustering analysis[J]．Proceedings of the CSEE，2006，26(22)：6-10(in Chinese)．

[22] Morren J，Haan S W H．Short-circuit current of wind turbines with doubly fed induction generator[J]．IEEE Transactions on Energy Conversion，2007，22(1)：174-180．

[23] Quan Q，Zhang H．Research and development of the comprehensive platform for analysis and warning of power grid[C]//2012 Innovative Smart Grid Technologies-Asia．Tianjin：IEEE，2012：1087-1093．

[24] Ren H，Hui X．Early warning mechanism for power system large cascading failures[C]//IEEE International Conference on Power System Technology．Hangzhou，China：IEEE，2012：1065-1071：

[25] Hsiao T Y，Lu C N．Network congestion warning indices [J]．IEEE Transactions on Power Systems，2008，23(3)：1527-1528．

陈麒宇

收稿日期：2014-08-11。

作者简介：

陈麒宇(1986)，男，博士研究生，研究方向为新能源接入下的电力系统运行与控制，Qchen05@qub.ac.uk。

(编辑 李泽荣)