

PAPER • OPEN ACCESS

System protection related technologies of power grid with high proportion of external ultra HVDC power

To cite this article: Qi Lyu *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **227** 032024

View the [article online](#) for updates and enhancements.

You may also like

- [Study on risk assessment of trans-regional transmission lines tripping disaster induced by wildfire](#)
Changkun Chen, Tong Xu, Sai Cao et al.
- [Correlation between single-wire and multi-wire tripping of the flow past a circular cylinder](#)
Antrix Joshi and Alis Ekmekci
- [Topologically protected loop flows in high voltage AC power grids](#)
T Coletta, R Delabays, I Adagideli et al.



ECS
The
Electrochemical
Society
Advancing solid state &
electrochemical science & technology

DISCOVER
how sustainability
intersects with
electrochemistry & solid
state science research

System protection related technologies of power grid with high proportion of external ultra HVDC power

Qi Lyu¹, Kaiyuan Hou² and Da Feng^{3,4}

¹ Electric Engineering Department, Columbia University, New York, NY 10027 USA;

² Northeast Branch, State Grid Corporation of China, Shenyang, 110180 China;

³ Dept. of Electrical Engineering, Tsinghua University, Beijing 100084, China.

⁴ Email: fengda985@163.com

Abstract. High power DC blocking causes the high and low frequency problems respectively in the sending and receiving end grid. Considering the Ultra HVDC without direct corresponding power supply construction, the system protection with simple-reliable structure and real-time communication is set up against the frequency risk of sending end grid, and the global optimal strategy and precise control of generator tripping are realized. Covering the wind, hydro and thermal power of whole sending end grid, the system protection with double-layer structure is designed, multi-object oriented real-time communication multiplexing technique is studied, and the calculation method of frequency characteristic and precise generator tripping strategy is proposed. According to the characteristics of different types of power and its influence on the safe operation of power grid, the DC modulation and optimal control strategy of wind, hydro and thermal power are presented. The simulation results show that the system protection is effective and practical.

1. Introduction

With the rapid development of the Ultra-high voltage (UHV) interconnected power grid and the significant increase in cross-regional power transmission, the security and stability characteristics of power grid have changed greatly. Frequency stability problems, caused by the high proportion of transmission power in sending and receiving side, have posed a serious threat to the safe and stable operation of power system [1-4]. When the proportion of UHV DC transmission power in sending and receiving side is too high, once faults such as UHV DC blocking occurs, serious over-frequency or under-frequency stability problems will arise in the sending and receiving power systems [5-7].

At present, most UHV DC projects generally have a certain number of corresponding power supplies that are synchronously put into production. When DC blocking occurs, the corresponding power supplies are tripped first. Then consider tripping a small number of other controlled power supplies [8-9]. The research mainly focuses on the following areas. One is discretely configuring measures according to frequency and tripping generators by ordered rounds. The other one is the research on coordination and optimization of generator grid-related protection [10-13]. ZHANG Zhiqiang et al proposed the system protection configuration principle including that the corresponding supporting power sources for UHVDC projects have top priority to be switched off [14]. YANG Qi et al made the research on the optimization of the over-speed protection setting and over-frequency generator tripping and a coordinated strategy is carried out and the application result is good [15]. In the literature [16], a system over-frequency suppression method is proposed, which combines



generator primary frequency modulation, generator tripping and generator over-speed protection. LI Xiaojun et al studied the coordination of the over-speed protection settings between units for regional power grids [17]. In the literature [18], the analytic formula of regional grid frequency deviation is derived, and the frequency variation characteristics are mastered. A method for quickly configuring over-frequency generator tripping scheme based on single-machine model is proposed. However, the research and engineering application on selecting controlled objects such as DC modulation, wind, hydro, and thermal power of large power-delivery grids, is lack of investigating.

A cross-regional UHV DC project will be put into operation in China, of which the rated transmission power has reached more than 20% of the regional grid load at the sending end. The capacity of generation tripping required for DC bipolar blocking is about 15% of the total generated power. However, this DC project does not have a corresponding supporting power supply. Power supplies within the regional power grid are selected as the controlled tripping objects. The number of controlled objects is nearly one hundred with various types including wind, hydro, thermal power stations.

This paper designs a high-reliability system protection covering nearly a hundred power stations. Multi-object real-time communication multiplexing technology has also been studied. Based on the different characteristics of power stations and their impact on the safety operation of power system, a global optimization control strategy for DC modulation and wind, hydro, and thermal power stations is put forward. Simulation results show the effectiveness and practicality of the proposed system protection.

2. System protection structure

For over-frequency problems in the sending grid caused by UHVDC bipolar blocking, singly generator tripping plan will become extremely complicated when controlled power sites (including DC modulation) are too many, scattered and involving various types of power plants. If the control plan is not proper, it may cause generator frequency protection (including unit OPC disorderly operation), large-scale wind turbine disconnection, cross-section flow off-limit, abnormal voltage etc. In addition, it will lead to frequency oscillation and even frequency instability of whole system and result in power load loss and even system disintegration. Therefore, the system protection design must meet the requirements of simple structure, reliable operation, global optimization, and precise control.

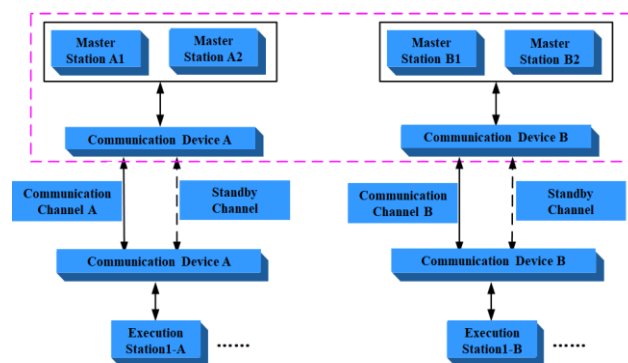


Figure 1. Schematic diagram of system protection structure.

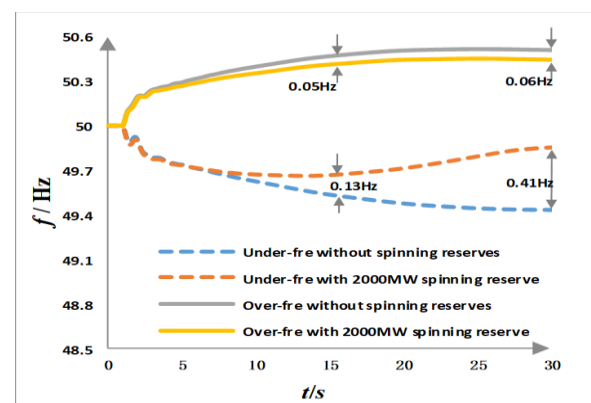


Figure 2. Frequency simulation curves under different spinning reserves.

Study in this paper follows the principles: 1) simplifying the system structure and control strategy as much as possible, 2) improving the reliability and stability of communications, 3) reducing the risk of mal-operation and miss trip. We propose the double-layer structure of system protection against over-frequency risk at the sending end. The master station directly communicates with the execution stations in real-time. The master station detects the system operation scale, the controlled generators'

operation information online and judges the UHV DC blocking and commutation failure, etc. After online precise calculation of the generator tripping capacity, the master station directly and sequentially delivers the modulation and tripping commands to each execution station. The execution station collects the real-time operating information and upload it to the main station. It also receives and discriminates the tripping commands from the master station. It has frequency and voltage judging and control functions as the third line of defense for system safety. The schematic diagram of system protection in the double-layer structure is shown in Figure 1.

This system protection adopts the dual configuration of different hardware platforms of the master station. Each master station is configured redundantly to minimize the risk of device miss tripping. Each device adopts a dual-communication channel with dedicated automatic switching and independent routing, which improves the reliability of information communication and transmission control commands.

3. Basis of optimization control strategy

3.1. Boundary conditions

The optimization principle includes ensuring the frequency and voltage stability of the sending end grid and the following boundary conditions should be met.

(1) Make full use of the system's own frequency adjustment capability. The amount of generator tripping needs to be as small as possible under the premise of satisfying the frequency deviation control.

(2) Don't cause other safety and stability problems or chain reactions, such as frequency oscillation, line overload, voltage over-limit, over safety quota and so on.

(3) Ensure the coordination between generator tripping control and the DC restart. Generator tripping and DC power increasing must not occur at the same time.

(4) Measure order should follow the principle of minimizing the impact on the system security. The order is as follows: modulating DC line within the area, modulating other inter-area DC lines, tripping near wind power, tripping remote wind power, tripping hydropower, and finally tripping thermal power.

3.2. Total generator tripping capacity

When UHV DC line is blocked, the total capacity of generator tripping power at the sending end can be calculated. The total capacity quantity is decomposed and then sent down to each execution station after online optimization. The transmission power of UHV DC before blocking is P_D , the total capacity of generator tripping power after DC blocking is P_S . Then P_S is formulated as follows.

$$P_S = P_D - K_G \cdot (P_Z / f_0) \cdot \Delta f_0 - P_M \quad (1)$$

where, f_0 is the rated frequency of the sending power system, Δf_0 is the allowable frequency deviation of sending power system after recovers, P_Z is the total generated power of sending power system, P_M is the modulatable amount of other operating DC lines; K_G is the frequency characteristic coefficient of the system, and K_G can be expressed as:

$$K_G = \frac{\Delta P / P_Z}{\Delta f / f_0} \quad (2)$$

where, ΔP is the increased power at the sending power system, Δf is the corresponding frequency increment caused by ΔP .

3.3. Frequency characteristic coefficient estimation method

K_G in formula (1) is the key parameter for calculating the total tripping capacity after bipolar locking. It relates to the system load scale, the adjustment characteristics of generator and load, the system maximum and minimum rotation reserve, and wind power proportion. Fixed value of K_G cannot meet the engineering requirement as the above factors are changing all the time. However, it is very difficult to obtain a real time and accurate value of K_G of an actual system. This paper proposes a method for

estimating the frequency characteristic coefficient considering the system scale and the proportion of wind power. This method is suitable for calculating the frequency characteristic coefficient of the system in the case of over-frequency, which can effectively improve the accuracy of generator tripping capacity calculation and meet the actual system precise control.

According to the system frequency characteristics and a large number of simulation calculations, it is verified that the spinning reserve has less influence on the frequency characteristic coefficient when the system is over-frequency, while has greater influence when the system is under-frequency. Taking a regional power system as an example, the total generated power is 53,000 MW. In the case of 0 MW and 2000 MW of spinning reserve capacity, the frequency simulation curves when the unbalanced power are ± 2000 MW respectively are shown in Figure 2.

In Figure 2, the impact of system spinning reserve on under-frequency problem is significantly greater than that on over-frequency problem. The frequency deviation in the over-frequency and under-frequency conditions at 15s is 0.05 Hz and 0.13 Hz respectively and at 30s is 0.06Hz and 0.41Hz respectively. Therefore, when estimating the frequency characteristic coefficient of the over-frequency system in the practical engineering application, the influence of spinning reserve can be ignored. The frequency characteristic coefficient is expressed as follows:

$$K_G = f(P_Z(t), P_w(t)) \quad (3)$$

where, $P_Z(t)$ is the daily power generation curve of the system, $P_w(t)$ is the daily wind power generation curve of the system, $t=0\sim 24$ h.

K_G is estimated by real-time acquisition of $P_Z(t)$ and $P_w(t)$ at system protection master station. The relationship between K_G and $P_Z(t)$, $P_w(t)$ is calculated in two ways. One way is by the combination of historical measured data and off-line simulations, which are stored in the strategy table of the master station in advance. The other way is by the online data of stability control devices and the historical big data intelligence analysis.

4. Proposed optimization control algorithm

4.1. Control algorithm

Assume that the regional power grid can be divided into m regions according to the safety and stability characteristics. The power output P_k in each region can be expressed as:

$$P_k = P_{wk} + P_{hk} + P_{tk} + P_{tk\min} \quad k=1,2,\dots,m \quad (4)$$

where, P_{wk} is the output of wind power in the k -th region, P_{hk} is the output of hydropower in the k -th region, $P_{tk\min}$ is the minimum thermal power output in the k -th region to ensure safe and stable operation, P_{tk} is the remaining thermal power output.

Therefore, the tripping power capacity in each region is formulated as:

$$P_{Ck} = P_{wk} + P_{hk} + P_{tk} \quad k=1,2,\dots,m \quad (5)$$

The total tripping power capacity is formulated as:

$$P_C = \sum_{k=1}^m P_{Ck} \quad (6)$$

The total tripping power capacity of wind, hydro and thermal are as follows respectively.

$$P_w = \sum_{k=1}^m P_{wk}, \quad P_h = \sum_{k=1}^m P_{hk}, \quad P_t = \sum_{k=1}^m P_{tk} \quad (7)$$

Obviously, to ensure frequency control requirements, it is necessary to arrange enough controlled power stations to satisfy $P_C > P_S$. Considering tripping-restart cost and effect to the system, the tripping sequence is as follows:

(1) Trip wind power. To minimize power flow fluctuations and taking into account the off-grid problems that wind power instability may cause, wind power tripping sequence should be from near to far in accordance with the electrical distance between wind farm and fault UHVDC.

(2) Trip hydropower. Considering that the hydropower is conducive to enhance the short-circuit ratio of the direct current near region, the hydropower tripping sequence should be from near to far in accordance with electrical distance between the hydropower plants and DC line and load centre.

(3) Trip thermal power. The thermal power tripping sequence should be from near to far in according with the electrical distance between the thermal power plant and the DC line and load centre. The heating unit cannot be tripped during the heating period.

4.2. System protection control process

According to the previous research results, the optimization control strategy of system protection can be designed, which is shown in Figure 3. When the device sending a generator tripping command, it also sends a DC-restart and power in-creasing command, which effectively avoids the under-frequency problem at the sending end.

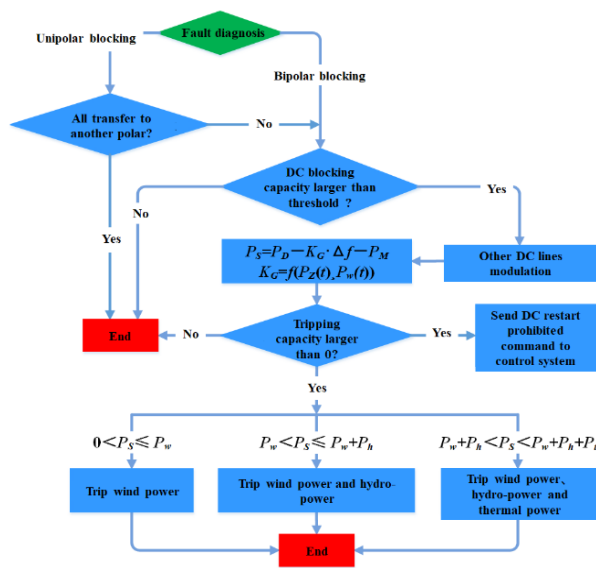


Figure 3. Flow charts of system protection optimization control.

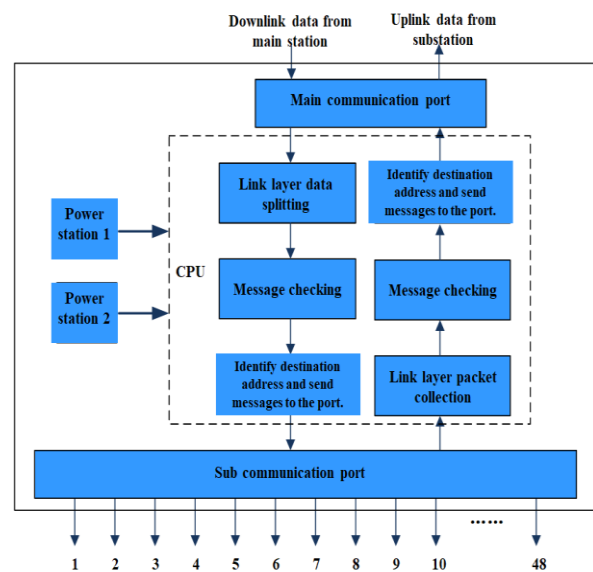


Figure 4. Multi-object oriented real-time communication multiplexing equipment.

5. Multi-object oriented real-time communication multiplexing technology application

The protection structure of the double-layer system is simple and reliable. Due to the limited bandwidth capacity of traditional 2M packets, it is unable to support one master station to communicate with tens or even hundreds of execution stations at the same time. Study in this paper combines the large-capacity nature of Ethernet communications with the real-time nature of 2M communications. It also proposes a multi-object oriented real-time communications multiplexing technology. A dedicated multiplexing communication device with one master station channel interface and 48 executive station channel interfaces is developed. The device uses Ethernet technology and E1's 2M protocol technology to solve the communication problem of the master station facing multiple execution sub-stations through the conversion between protocols. The multiplexing communication device is shown in Figure 4.

The device uses a standard 4U 19-inch full-length chassis and consists of dual power modules, main control modules, and multiple 2M interface modules. Each 2M interface module can collect the data of nine substations and send them to the main control module through the high-speed communication bus. The main control module collects the data from multiple 2M interface modules and communicates with the stability control main station through the external SFP optical port.

When processing uplink data, the 2M interface module encapsulates the 2M packet into an Ethernet packet after receiving it and sends the packet to the main control module through a custom protocol between modules. The main control module then replaces the protocol with a protocol for communication with the master station and forwarding the packet to the port connected to master station. When dealing with the downlink data, the Ethernet interface connected to master station on the main control module receives the Ethernet packet sent from main station, and then unpacks according to the protocol with main station. Packets sending to the same 2M module are packed within an Ethernet packet according to the inter-module communication format. Then the packet is sent to the corresponding 2M module. After receiving the Ethernet packet, the 2M module unpacks the packet and extracts the packet data. The module then sends the data to the corresponding 2M port.

Through the application of above technologies, the multiplexing communication device can meet the requirements for direct communication between the main station and multiple execution stations. It has a large technical advantage in terms of operational reliability, real-time data, and transmission stability. The advantages are shown as follows.

(1) The main station configures one device above which can communicate with 48 execution stations at the same time. The communication rate can reach millisecond level.

(2) Ethernet communication between the master station and the multiplexing communication device can ensure large-capacity communication bandwidth and avoid message data loss.

(3) Multiple 2M messages are transmitted to the master through an Ethernet message. The communication frequency between the master station and the communication multiplexing device is greatly reduced, and the load of the stable control master station is reduced either.

(4) The method of real-time reception and temporary buffering between the communication multiplex device and the substation guarantees the real-time and stability of communication. It can ensure the communication of all 2M packets and that all 2M packets can reach the master station within a millisecond delay.

(5) Without increasing the space occupied, four communications multiplexing devices can be installed in one communication cubicle.

(6) Double network connection is used to connect with the safety automatic device. The operating channel can automatically switch to the standby channel instantaneously when the channel is operating abnormally without affecting the normal operation of the device.

The experimental test proves that the communication device has high reliability of operation and high communication transmission speed. It can meet the real-time requirements of security and stability control of system protection.

6. Application simulation

A regional power grid is about to put a UHV DC line into operation with a rated transmission capacity of 10,000 MW. System protection related technologies proposed in this paper have been designed to protect against over-frequency risks in the regional power grid.

The regional power grid is now transmitting power to another regional power grid by a UHV DC line with rated power transmission capacity of 3000 MW. The new UHV DC project to be put into production will also transmit power to the same regional power grid, as shown in Figure 5.

According to (1) and (2), the system frequency characteristic coefficient K_G can be calculated, as shown in Table 1. The value of K_G is proportional to the total generated power, and inversely proportional to the proportion of wind power (i.e. the frequency stability of the system increases as the system scale increases but decreases as the wind power proportion increases).

K_G is stored in the master station's strategy table in advance. When an UHV DC blocking occurs, the master station takes control measures according to the flow in Figure 3. When the DC modulation fails to meet the frequency control requirements, the tripping power capacity is calculated by (1) firstly, and then the tripping commands are issued to each execution station through the calculation method above.

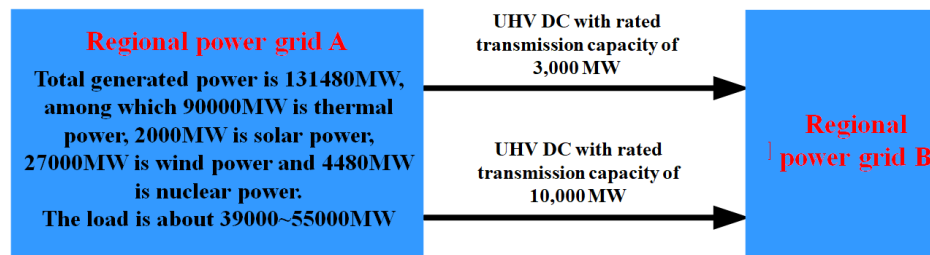


Figure 5. Schematic diagram of a regional power grid.

The generator tripping capacity when the DC power blocked at 5000 MW is shown in Table 2. When the proportion of wind power changes, the amount of generator tripping capacity is not much different, about 100 MW. However, when the load level changes, the tripping capacity at peaking and valley has a large difference, reaching more than 500 MW. Simulation shows that the variable K_G corresponding to different load levels achieves accurate control of the generator tripping capacity.

Table 1. Coefficient of frequency characteristics (p.u.).

Total generated power (MW)	Wind power proportion(%)				
	5	10	15	20	30
39000	6.70	6.62	6.54	6.45	6.29
41000	6.73	6.65	6.57	6.49	6.33
43000	6.76	6.68	6.60	6.52	6.37
45000	6.79	6.71	6.64	6.56	6.41
47000	6.82	6.74	6.67	6.59	6.45
49000	6.84	6.77	6.70	6.63	6.49
51000	6.86	6.79	6.73	6.66	6.53
53000	6.89	6.82	6.76	6.69	6.56
55000	6.90	6.84	6.77	6.71	6.59

Table 2. Capacity of generator tripping (MW).

Total generated power (MW)	Wind power proportion(%)	
	5	30
39000	3740	3820
41000	3680	3760
43000	3620	3700
45000	3560	3640
47000	3500	3580
49000	3440	3520
51000	3380	3460
53000	3320	3400
55000	3260	3340

7. Conclusions

This paper studies the system protection related technologies of high-proportional UHV DC transmission grids against frequency risk. For UHV DC sending power systems with no auxiliary power supplies, a high-reliability dual-layer structure system protection covering the wind, hydro, and thermal power supplies is designed. The multi-objective real-time information and communication multiplexing technology is studied. A method for calculating the frequency characteristics of the system considering the power system scale and the proportion of wind power is put forward. An accurate strategy algorithm for generator tripping when the system is over-frequency is proposed. According to the characteristics of different types of power supplies and the impact on the safe operation of the power system, a global optimization control strategy of DC modulation and wind, hydro, thermal power is proposed.

The simulation results verify the validity of the frequency characteristic coefficient estimation method. The calculated generator tripping capacity can meet the requirements of precise control. The optimization control algorithm considers the characteristics of various power sources and their different impacts on the operation of the power system. The control strategy ensures the safe and stable operation of the power system with minimum cost.

References

- [1] Liu Zhenya and Zhang Qiping 2013 Study on the development mode of national power grid of China[J] *Proceedings of the CSEE* **33(7)** 1-10
- [2] Jin Weigang, Li Yong, Yin Yonghua, et al. 2016 Optimum Scheme and Its Probabilistic Sensitivity Analysis for Wind Power Transmitted Through UHV Transmission Corridors Bundled with Thermal Power[J] *Automation of Electric Power Systems* **40(6)** 126-133
- [3] Guo Xiaojian, Ma Shiyang, Shen Hong, et al. 2012 HVDC Grid Connection Schemes and System Stability Control Strategies for Large-scale Wind Power [J] *Automation of Electric Power Systems* **36(15)** 107-115
- [4] Chen Yun, Chen Dezhi, Wang Yi, et al. 2015 Studies and simulations on over frequency generator tripping principles for wind-PV-thermal-bundled power system [J] *Renewable Energy Resources* **33(10)** 1492-1498
- [5] Han Bing, Sun Shiming, Zhao Jiaqing, et al. 2016 Key Technologies for High Speed Batch Control of Load Dispatching Adapt to Block Fault Disposal of UHVDC Transmission System [J] *Automation of Electric Power Systems* **40(17)** 177-183
- [6] Liu Xiaoming, Liu Yutian, Qiu Xizhao 2012 Emergency load shedding after Yindong 660 kV DC block fault [J] *Electric Power Automation Equipment* **32(4)** 96-99; 116
- [7] Zhao Qiang, Xu Jing, Wang Qi, et al. 2012 Research on power grid stability control strategies for Ningdong DC line on Shandong side [J] *Electric Power* **45(4)** 5-9
- [8] Li Desheng, Luo Jianbo 2016 Typical Design of Security and Stability Control System for UHVDC Transmission [J] *Automation of Electric Power Systems* **40(14)** 151-157
- [9] Zhang Zhiqiang, Yuan Rongxiang, XU Youping, et al. 2016 Optimization of Over-frequency Generator-tripping Scheme in Sichuan Power Grid Adaptable to Multi-UHVDC Transmission Project[J] *Automation of Electric Power Systems* **40(2)** 141-146
- [10] Zhou Lei, Zhang Dan, Liu Fusuo, et al. 2016 Frequency Characteristics of Yunnan Power Grid and Corresponding Over-Frequency Generator Tripping Scheme after Asynchronous Interconnection [J] *Southern Power System Technology* **10(7)** 17-23
- [11] Chen Tao, Feng Li, Lv Yazhou, 2015 et al. Optimization and Coordination of High Frequency Generator Tripping in Isolated Power Grid Based on the Risk Quantification [J] *Power System and Clean Energy* **31(5)** 8-15
- [12] Sun Huadong, Wang Xuedong, Ma Shiyang, et al. 2008 Measures to Improve System Security and Stability for Isolated Operation of Guizhou Main Power Grid and Its Regional Power Networks [J] *Power System Technology* **32(17)** 35-39
- [13] Zhang Zhen, Li Xingyuan, Huang Zongjun 2008 Simulation and Analysis of Over Frequency Generator Tripping for Guizhou Isolated Power System [J] *Modern Electric Power* **25(4)** 31-34
- [14] Zhang Z, Yuan R, Xu Y, et al. 2016 Optimization of over-frequency generator-tripping scheme in sichuan power grid adaptable to multi-UHVDC transmission project[J] *Automation of Electric Power Systems*
- [15] Yang Qi 2013 An Optimal Allocation Scheme for Relay Setting Related to Power Grid and Over Frequency Generator Tripping Measures [J] *Automation of Electric Power Systems* **37(20)** 127-131
- [16] Xiaojun L I, Zhang Z, Lihua W U, et al. 2013 Further Research on Setting Values of Over-Speed Protection Controller for Fossil Power Generation Units in Regional Power Grid[J] *Power System Technology* **37(9)** 2521-2526
- [17] Zhang Zhiqiang, Xu Youping, Yuan Rongxiang, et al. 2015 Frequency Characteristics of Power Grid at Sending End of Split Large-Scale Interconnected Regional Power Grid and Corresponding Over-Frequency Generator-Tripping Scheme[J] *Power System Technology* **39(1)** 288- 293
- [18] Wang Y, Ma S, Wang Q, et al. 2012 Present status and developing trend of research on over frequency in isolated power grid[J] *Power System Technology* **36(12)** 165-169