

A method of emergency frequency control based on Multi-resources coordination

SHEN Hongming¹, YAO Yuhai², DU Na¹, LI Tiechen¹, CHEN Wei¹, ZHANG Xianglong¹, and ZOU Ge¹

¹State Power Economic Research Institute Co.,LTD, Beijing 102209

²State Grid Beijing Electric Research Institute, Beijing, 100075

shen198806@126.com

Abstract. The first system protection demonstration project-Eastern China emergency frequency control system is introduced in detail. Then, the specialty of flywheel energy storage in frequency control is researched, and the analysis result show that the flywheel energy storage can be used in emergency frequency control. In addition, mathematical model of frequency estimation is proposed based on the frequency characteristics of generator and load. Thus, the frequency response can be calculated after power loss that caused by DC block. At last, a method of emergency frequency control with Multi-resources coordination is proposed based on the curve of frequency response.

1. Instruction

With the construction of UHVDC project, China's power grid is in the period of "strong HVDC and weak AC". During the transitional period, the small disturbance of the AC system causes a significant change in the DC transmission power, which in turn has a significant impact on the safe and stable operation of the AC system [1]. Thus, it is difficult to ensure the safety and stability of the power system based on the traditional control measures. Therefore, the grid company put forward a new idea—system protection at the end of 2015, in order to enhance the security and stability of large power grid.

In July 2016, East China Power Grid successfully put into operation China's first system protection demonstration project - East China Power Grid frequency emergency coordination control system. It is expected that by the end of 2018, with the operation of Jinbei, Xitai and Zhundong DC, the single DC receiving capacity of East China Power Grid has been raised to 12 million kilowatts. The East China Power Grid is facing severe frequency stability problems when single / multiple DC blocking occurs. A set of frequency emergency coordination control system, and in August 2016 binjin DC blocking event played a good control role.

Based on the emergency coordination and control system of East China Power Grid, this paper introduces the existing emergency frequency control measures in detail and further analyzes the function of flywheel energy storage technology in emergency frequency control. Furthermore, through the mathematical modeling of generator and load, the purpose of fast calculation of frequency response characteristic after UHVDC blocking is achieved. And the DC modulation, cutting pump, precision load control and flywheel storage are given through the frequency characteristic response curve. Can work together to control the program.



2. East China Power Grid frequency emergency coordination control system

September 19, 2015, Jin Su direct current bipolar latch, East China Power Grid emergency drop in frequency, the minimum frequency of 49.58Hz, the upcoming low-frequency low-cycle load shedding device, the frequency of defensive system has been a major challenge, the frequency curve shown in Figure 1 Show. East China Power Grid is a multi-DC feeding area. Only once the first closure of Jin-Su DC leads to serious frequency problem. If multiple DCs are locked at the same time or in succession, it will cause more serious frequency stability problems. At the same time, the DC system contains a large amount of Power electronics, severe inertia in the system, frequency drop accelerated, may trigger a serious system of cascading failures. Therefore, in order to ensure the safety and stability of the AC system during DC blocking, passive FM can not be taken blindly and more proactive emergency frequency control methods need to be studied.

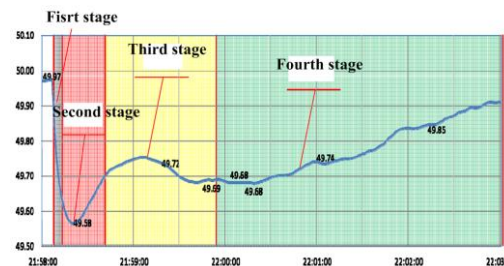


Fig.1 The frequency curve of Eastern China grid during JIN-SU DC block

China's first system protection demonstration project - East China Power Grid frequency emergency coordination control system was successfully put into operation in July 2016. The system consists of a central control station, three control stations and a number of sub-stations. Control stations have three control measures: Multi-DC coordination, fast cutting off interruptible load and cutting pump. The control structure is shown in Figure 2.

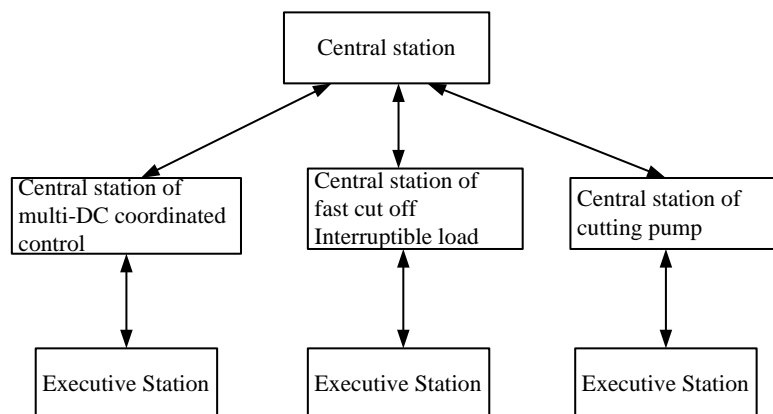


Fig.2 The structure of Eastern China grid emergency frequency control

Multi-DC coordinated control: For the receiving system, the main purpose is to make use of the short-time overloading capability of the DC link. For the sending system, the emergency descending power of the DC link is mainly used to achieve the purpose of emergency frequency control.

Cutting pump: The pumping power plant can be seen as a heavy load in the pumping conditions, thus, the purpose of emergency frequency control can be achieved by cutting pump.

Fast cut off Interruptible load (precision load control): By contracting with large local users, priority is given to removing it quickly and urgently when the grid needs emergency control [11].

The three kinds of frequency emergency control measures have a certain priority: the highest priority is the multi-DC coordination control, the second is the pumping and cutting, and the quick cutting can interrupt the load. At the same time, the three control measures are coordinated with each other. After the DC blocking, the master control station calculates the power shortage and determines

the specific promotion/removal amount of each control strategy according to the adjustable amount collected by each substation.

Binjin DC pole 1 was blocked on August 4, 2016, which causes the system frequency to drop to 49.882 Hz. The frequency emergency coordination control system worked. The system frequency was promptly restored by sending a frequency increase instruction to each substation. Through calculation, if the system does not operate, the frequency will drop to 49.835 Hz. It should be pointed out that multi-DC coordinated control is used in this case, and the cutting pump and cutting off the interruptible load did not operate.

3. Research on the application of flywheel energy storage technology in emergency frequency control

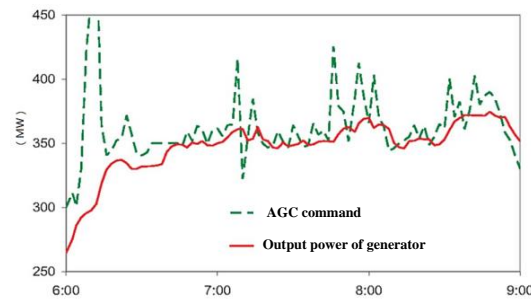
At present, there are mainly three methods for emergency control of frequency, such as DC coordination control, cutting pump and cutting load. Generally, the system frequency can not change fast in a large-scale grid. Traditional coal-fired gas generators generally have a large moment of inertia, thus, the system frequency will not decrease too fast when power shortage occurs. However, the moment of inertia of wind power and solar power are both much smaller than that of conventional power generators. As the proportion of new energy increases, the equivalent moment of inertia of the system will be greatly reduced, which is unfavorable to the short-term frequency stability. Therefore, there is an urgent need to enrich the emergency frequency control measures to meet the challenges of the future power grid.

Table 1 compares the flywheel energy storage with other energy storage technologies. It can be seen from Table 1 that the flywheel energy storage has greater advantages in terms of efficiency, specific energy, specific power, cycle life and discharge time.

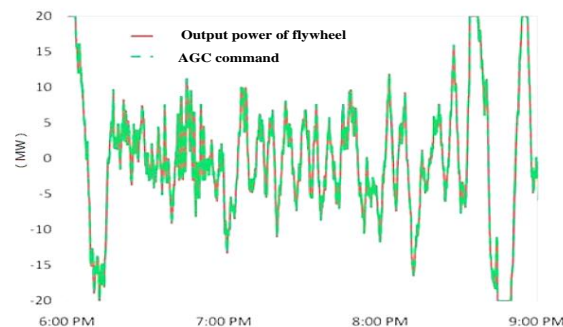
Tab.1 The index list for different storage technologies [7]

Energy storage technology	Pumped storage	Super-conduction energy storage	Chemical battery	Flywheel energy storage	Super capacitor
efficiency (%)	75	90	85	90	90
Proportional energy ($\text{Wh}\cdot\text{kg}^{-1}$)	/	/	5~100	15~150	5~30
Proportional power ($\text{W}\cdot\text{kg}^{-1}$)	low	high	low	high	high
Cycle life	long	long	short	long	long
Discharge time	hours	seconds	hours	minutes	seconds

Power system frequency mainly depends on the active power, so the frequency response faster, the better of the frequency. Figure 4 shows the actual power output curve of ordinary thermal power units and flywheel energy storage. As can be seen from Figure 3, the actual output of thermal power plant can not keep up with the AGC FM command due to the fast response speed of the thermal power unit, resulting in an increase of the acceleration area and poor frequency control effect. The output change curve of the flywheel energy storage can be almost complete tracking of AGC control commands gives the flywheel energy storage very fast response to emergency frequency control requirements.



a) Curves of AGC command and output power of generator



b) Curves of AGC command and output power of flywheel

Fig.3 The AGC response comparison between generator and flywheel

At the same time flywheel energy storage discharge time up to a few minutes, the duration of its continuous support depends on the size of the discharge power, such as discharge power, the duration is short, whereas the long duration. The emergency frequency control time requirements within 1s, so flywheel energy storage in a very short period of time with great power support power shortage, play a fast, a large number of support emergency frequency control purposes.

4. Frequency characteristics after DC blocking

At this stage, the frequency response prediction after DC blocking is mainly achieved by building the electromagnetic/electromechanical model of the regional power grid. For the regional power grid, if you want to get a more credible simulation results, you need to build a higher degree of sophistication of the model, the calculation speed may be slower. Therefore, the main use of offline computing results to make a large number of strategy table, and then match the strategy table after the DC blocking.

In order to achieve fast estimation/calculation of frequency response, this dissertation establishes a mathematic simulation model of regional power grid to accelerate the calculation speed by researching short-term frequency response characteristics such as generator and load, and finally realizes the goal of real-time calculation.

4.1 Synchronous generator short - term frequency mathematical model

After the DC blocking causes the power shortage, the kinetic energy of the synchronous generator spindle is released to meet the load demand, so the reduction of the rotation frequency has a certain inertia. Assuming that there is no transmission congestion in the grid of the whole area, the whole network frequency will be a unified value. In this case, the single-plane equivalent model can be used to characterize the relationship between the whole network frequency and the power shortage, as shown in the following formula [2, 3]:

$$\Delta P / (2H) = d(\Delta f) / dt \quad (1)$$

In formula (1), ΔP is the power shortage caused by the DC blocking fault, Δf is the system frequency offset function, and H^* is the per unit of the equivalent moment of inertia of all generators.

The larger the moment of inertia, the lower the grid frequency SLOW. The formula for the inertia parameter is as follows:

$$H^* = (\sum H_g^* \times S_g) / (\sum S_g) \quad (2)$$

In equation (2), $\sum H_g^*$ is the moment of inertia of a certain generator in the system (this data is provided by the manufacturer), and S_g corresponds to the rated capacity of the generator. The weighted inertia of all the generators in the studied regional power system is weighted to the rated capacity of the generator, and the equivalent moment of inertia of the system can be obtained.

During the actual operation of the power system, the unit input in the system may change in real time, which requires timely identification of the generator in operation and obtaining the real-time system moment of inertia. At present, the PMU of wide area measurement system in our country is the largest in the world. It is preparing to deploy a phasor measurement unit (PMU) in the main grid and the main power plant in the network of 330kV and above to achieve wide-area phasor measurement at the national, regional and provincial levels System, and the PMU device can measure the switch condition of the power plant unit. Therefore, the moment of inertia of the future regional power grid can be obtained accurately and in real time through wide-area measurement.

In addition, the primary frequency modulation of the generator is realized through the built-in governor. The transfer function of the governor and the prime mover can be equivalent to the first-order inertial link in terms of frequency response, while the two first-order inertia links in series can ignore the second term, is directly equivalent to a first-order inertia, the transfer function is as follows:

$$\Delta P_{Gen} = - \sum \frac{K_{3n}}{T_{2n}s+1} \Delta f \quad (3)$$

In formula (3), ΔP_{Gen} is the power increment of all the generators of the system under the action of primary frequency modulation. K_{3n} is the primary frequency modulation coefficient of the n th generator in the system. T_{2n} is the equivalent time constant of the n th generator in the system, and its value is the sum of the time constant of the governor and prime mover. The effect of a frequency modulation is mainly determined by the coefficient of variation and the time constant. According to the scene data of the blocking frequency accident of the Longzheng DC line in 2006, only 51.96% of the units operated at the accident. Therefore, the key to the accuracy of the generator model parameters is to monitor their conditions in real-time.

4.2 Load short-term frequency mathematical model

Over the years, domestic and foreign experts and scholars carried out a wide range of in-depth study of the load model [3-5], proposed and validated a variety of load models. According to whether the load model reflects the load dynamic characteristics, it can be divided into static model and dynamic model. According to the different models derived from the model, it can be divided into mechanism model and non-mechanism model. According to whether the model is linearized, it can be divided into Linearization model and non-linearization model. According to whether the model is related to frequency, it can be divided into frequency-dependent model and frequency-independent model [6]. In studying the short-term frequency characteristics of load, it is often necessary to pay attention to its transient process, and the dynamic load model should be selected. However, in the field of short-term frequency control of the system, the main concern is the relationship between load absorbed power and grid frequency. Therefore, single input / single output transfer function model can be selected.

In recent years, in order to simplify the analysis of the problem, the common practice at home and abroad is to locally linearize the "frequency-absorbed active power" curve of the load model near the power frequency. The load frequency factor D is used as the active power variation and the frequency variation The ratio between the coefficients. In fact, in different seasons and even at different times of the same day, the load frequency factor will vary with the nature of the load. General motor load ratio is high, the load frequency factor is large, and the motor load ratio is low, the load frequency factor may be greatly reduced. On the other hand, the load response has certain dynamic characteristics, and

in some cases, the load frequency factor changes greatly during the whole process. Therefore, the frequency response of the load is often difficult to predict. The researches at home and abroad only stay on the level of ex-post simulation, model assumptions and experimental measurement parameters. The parameters of the load-frequency response model can not be obtained in real time. The introduction of wide area monitoring system makes the load parameter identification become possible, which the system frequency response estimation accuracy will be greatly enhanced. In this paper, considering the dynamic characteristics of load response, the dynamic load model in [4] is as follows:

$$\Delta P_{Load} = \frac{k_{pf} + T_{pf}s}{T_2s+1} \Delta f \quad (4)$$

In formula (4), when the grid frequency is Δf , the load absorbs the change of active power. k_{pf} and T_{pf} are the active power damping coefficients [5], T_2 is the load time constant. For ease of description, the above formula can also be as follows:

$$\Delta P_{Load} = (k_1 + \frac{k_2}{T_1s+1}) \Delta f \quad (5)$$

In equation (5), k_1 is the static frequency response parameter of the load, and k_2 is the dynamic frequency response parameter of the load, which represents the proportion of the induction motor load in the system. T_1 is the time constant, which can be regarded as the equivalent inertia time constant of the induction motor.

4.3 Short-term frequency dynamic model

The mathematical model of the above power system components is integrated into a complex frequency domain model, and the short-term frequency dynamic model of the power system is obtained. In order to simplify the discussion, ignore the frequency of a dead zone and the limit (simulation results show that due to the rapid decline in system frequency early, the frequency of the dead zone has little effect on a FM; and the frequency deviation is not too large, the first FM Will not be limited, such as the Longzheng DC blocking incident once there is no frequency limiting FM [9,10]). The simplified model is shown in Figure 4.

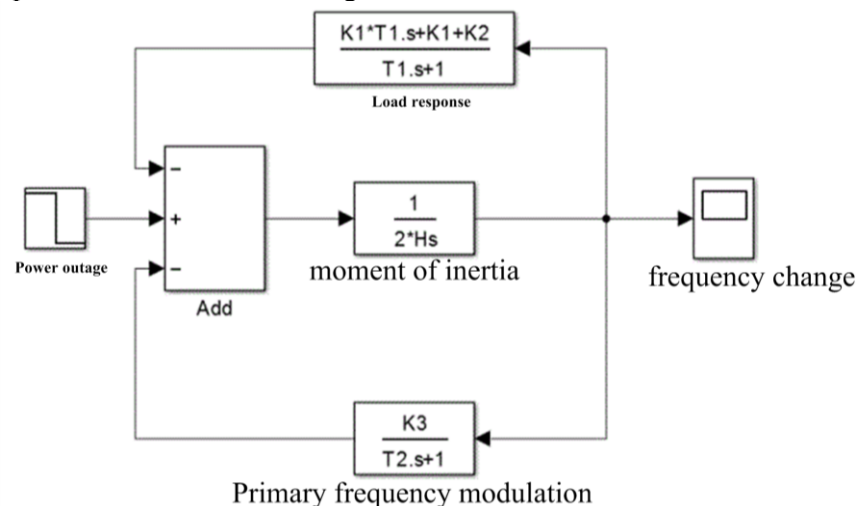


Fig.4 The sampled short frequency dynamic mathematic model

4.4 Frequency dynamic analysis

Based on the analysis results in Section 4.3, a typical frequency dynamic curve is obtained, as shown in Figure 5 (assuming a power deficit of 7GW). As can be seen from Figure 5, after the DC blocking causes a large amount of power shortfall, the system frequency drops and falls to the lowest frequency after a period of time, and then the frequency starts to rise to a steady-state frequency under the action of a frequency modulation.

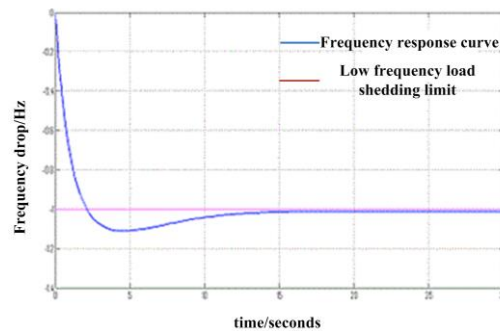


Fig.5 The typical frequency curve

It can be seen from Figure 5 that there are two key points in system frequency after DC blocking: 1 is the lowest frequency and 2 is the steady-state frequency. If the lowest frequency point is lower than the low-frequency load shedding line, the third-round low-frequency load shedder will still take action even if the steady state frequency value is higher than the low-frequency load shedding line, resulting in a large amount of load loss. Therefore, it is necessary to coordinate different emergency frequency control resources, raise the lowest frequency point so that the lowest frequency point is not lower than the LFL limit, and the system frequency is ensured to be stable.

4.5 Multi-resource coordination control scheme

Considering the changing characteristics of frequency after DC blocking, it is necessary to integrate the characteristics of the control methods in multi-DC modulation, flywheel energy storage, cutting pump and precision load control to achieve the purpose of emergency frequency control.

After the DC blocking happens, not only the power system of the terminal is affected, but also the power transmission system of the sending terminal faces the cutting machine. The improvement of the DC emergency power can not only reduce the power shortage of the power receiving terminal but also reduce the cutting capacity of the power transmission network. Therefore, Preferred. At the same time, DC modulation also need to leave a number of lines to achieve the function of raising the lowest frequency of the system. When the capacity is constant, the power support provided by flywheel energy storage is inversely proportional to the support time, which determines that this method is suitable for the lifting of the lowest frequency point of the system. And the marginal cost of flywheel energy storage is small, so the priority is second only to DC modulation. The pumped storage power plant has little effect on the power grid after its operation, but the emergency cutting pump has some damage to the service life of the equipment, so its priority is after the flywheel energy storage; finally, the quick cutoff can interrupt the load and prevent a large-scale unplanned power outage.

According to the above coordinated control scheme, not only the purpose of emergency frequency control but also the cutting of the least load can be guaranteed, and the load can be removed without any interruption, thus minimizing the safety, stability and social impact of the DC blocking on the power grid.

5. Conclusion

(1) Flywheel energy storage technology is more suitable for emergency frequency control due to its fast response time and longer duration.

(2) According to the characteristics of different control methods and the characteristics of the frequency curve after DC blocking, the multi-DC coordination scheme is proposed: multi-DC modulation is the top priority, and flywheel energy storage takes the second place, followed by cutting pump, the end priority is the precision load control.

The new multi-resource coordination control scheme can not only achieve the purpose of emergency control of frequency after DC blocking, but also ensure a minimum loss of load and has a good application scenario.

Acknowledgments

This work is supported by the independent project of State Power Economic Research Institute Co.,LTD .

References

- [1] GONG Hong, JIANG Wei, WANG Yuhong, et al. Transactions of china electrotechnical society, 2017,32(6):67-75.
- [2] T. Shekari, F. Aminifar and M. Sanaye-Pasand. "An Analytical Adaptive Load Shedding Scheme Against Severe Combinational Disturbances," in IEEE Transactions on Power Systems, vol. 31, no. 5, pp. 4135-4143, Sept. 2016.
- [3] W. Tan. "Load frequency control: Problems and solutions," Control Conference (CCC), 2011 30th Chinese, Yantai, 2011, pp. 6281-6286.
- [4] J. W. O'Sullivan and M. J. O'Malley, "Identification and validation of dynamic global load model parameters for use in power system frequency simulations," in IEEE Transactions on Power Systems, vol. 11, no. 2, pp. 851-857, May 1996.
- [5] E. Welfonder, H. Weber and B. Hall. "Investigations of the frequency and voltage dependence of load part systems using a digital self-acting measuring and identification system," in IEEE Transactions on Power Systems, vol. 4, no. 1, pp. 19-25, Feb 1989.
- [6] ZHAO Liang, LI Dan, ZHANG Wenchao, et al. Simulation research on dynamic load model of north china power grid[J]. Power system technology, 2007,(05):11-16.
- [7] K. Samarakoon, J. Ekanayake and N. Jenkins. "Investigation of Domestic Load Control to Provide Primary Frequency Response Using Smart Meters," in IEEE Transactions on Smart Grid, vol. 3, no. 1, pp. 282-292, March 2012.
- [8] QIU Wenxiang, LI Daxing, XIA Gefei, et al. A low cost permanent magnet biased bearing used in flywheel energy storage system[J]. Transactions of china electrotechnical society, 2015,30:58-62.
- [9] GAO Xiang, GAO Fuying, YANG Zenghui. Frequency accident analysis in east china grid due to DC line fault[J]. Automation of electric power systems, 2006,(12):102-107.
- [10] YAO Liang, CHEN Luan, ZHENG Bin, et al. Research on area frequency control strategy of wind-fire hybrid power generation system[J]. Power System Protection and Control, 2016,44(11):46-52.
- [11] LUO Jianyu, LI Haifeng, JIANG Yefeng, et al. Source network load friendly interactive and precise load control system based on stability control technology[J]. Electric power engineering technology, 2017,36 (1): 25-29.