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Power Grid Cascading Failure Blackouts Analysis

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Abstract. In this paper, several typical blackout events at domestic and overseas are introduced, and the processes of blackout and the causes of the blackout are briefly analyzed. Then, the blackout caused by cascading fault is explained from accident principle and occurrence mechanism. On this basis, the model method based on complex system theory is further discussed. Finally, according to the common problems of blackout at domestic and overseas, the prevention and emergency measures of power grid cascading failure are put forward from multiaspects aspects.

Key words: Blackout; Cascading Failure; Model Method; Measures.

INTRODUCTION

With the rapid development of the global economy, large-scale interconnection of power grid has become an inevitable trend of the development of power system. Power network has become one of the most complex networks in the world. The formation of the complex network not only improves the operation efficiency of the system, but also increases the uncertainty of the system operation, a wider range of system disturbances and more serious consequences of system accidents. At the same time, power grid interconnection also brings a series of technical problems, such as voltage control, low frequency oscillation, stability, fault chain reaction and so on[1]. In the large-scale interconnected power network, when the power network failure occurs, the system will redistribute the power flow, if not treated, the overload lines or transformers will be removed, which may cause a series of chain reactions, or even system collapse, resulting in power grid blackout. This paper studies the blackout accident of power network, summarizes and analyzes the commonness and difference of the blackout accident in the world, then introduces the analysis model of the blackout accident, and puts forward the corresponding prevention and emergency measures. Power grid blackout is often a chain reaction process, first of all, a single component failure or a number of failures accumulated, due to improper emergency or not timely, and ultimately lead to deterioration of the fault, unable to control; eventually, there was a blackout. In the past ten years, blackouts have occurred frequently in the world, which have a great impact on the social and economic development of the accident areas. These accidents also show the characteristics of cascading failures.

INTRODUCTION TO POWER GRID BLACKOUTS

US and Canada "8.14" Blackouts

US and Canada lost tens of billions of dollars in direct economic losses, the outage involved the entire eastern US power grid. At least 21 power plants were shut down in the accident. The outage lasted for 29 hours and the load 61800MW was lost. About 50 million people were affected, covering an area of about 24000 square kilometers, with 80 per cent of power outages in New York [2].

The immediate cause of the accident was that three UHV transmission lines were too close to the branches, resulting in short-circuit tripping. Secondly, because the alarm system of the first Energy Company of the United

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States was not working properly, the monitoring equipment was lacking, and the workers were operating improperly, no further measures were taken, which aggravated the impact of the blackout caused by the accident.

Blackouts in Hainan, China

On September 26, 2005, No. 18 Typhoon "Davy" caused serious damage to power facilities in Hainan, causing part of the power plants to continuously trip the train, the final system all disintegrated, resulting in a rare province-wide blackout. Hainan "9.26" blackout has two obvious characteristics, one is that the blackout affects a wide range of power plants, and the scope of blackout involves the whole island; the other is that the time from normal state to complete collapse is short, and only the power network around 4min is black [3].

Overall analysis shows that bad weather is the direct cause of the blackout across Hainan. However, the low level of grid design, isolated operation, serious aging of equipment, large machine and small network and weak connection of the grid structure are the deep causes of the "9.26" blackout in Hainan.

PRINCIPLE ANALYSIS OF GRID CASCADING FAILURE

From the above examples, it can be seen that the occurrence of blackout is not only the occurrence of a simple event, but also the comprehensive development result of a series of events and multiaspects accidental factors. Because the power system is generally equipped with appropriate protection and control measures, it can ensure the security in a moderately credible event, and will not lead to a large area power outage [2]. Fig. 1 is a schematic diagram of the factors leading to power system blackouts and their development.

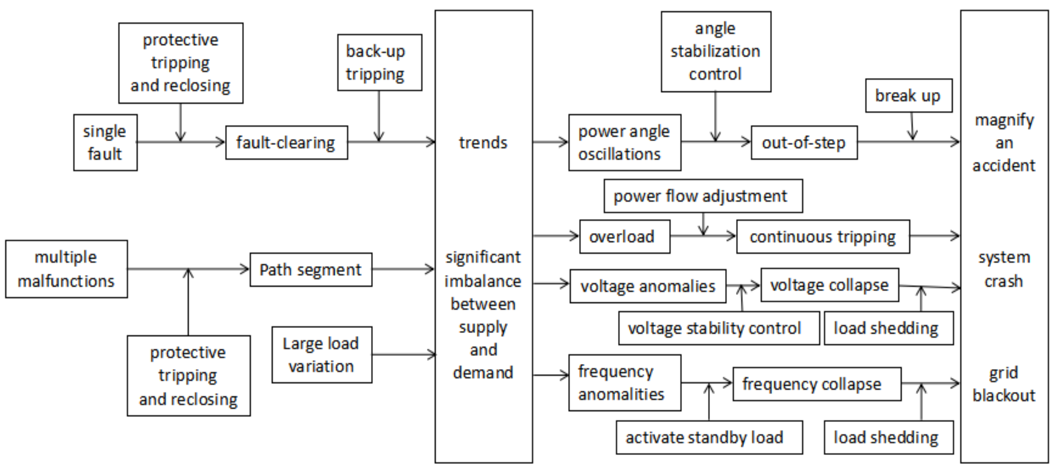

FIGURE 1. Schematic diagram of grid cascading failure

It can be seen from the diagram that the four main factors leading to the system blackout are: (1) power angle stability failure, (2) system out of step; (2) overload chain reaction; (3) voltage collapse; (4) frequency collapse. Such events and their interactions have great fortuitousness and are difficult to predict in advance. For example, the voltage fluctuation caused by the system out of step may further cause the generator to trip out of order, which will cause the system voltage and frequency to deteriorate and finally collapse; The power imbalance is further aggravated after the system is out of step, which causes the overload cascading trip and finally leads to the collapse of the system.

GRID CASCADING FAILURE ANALYSIS METHOD

At present, most of the research on cascading failures at domestic and overseas consider the development mode of cascading failures as follows: after initial fault removal, power grid due to the transfer of heavy load caused by the relay protection has jumped off the power grid components "this mode." The concrete research involves to the physical

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process simulation, the abstract macroscopic dynamic simulation and so on multiaspects stratification planes [4-6]. This paper mainly introduces the model method based on complex system theory.

Model Method Based on Complex System Theory

Self-Organized Criticality of Large Blackouts

Self-organization theory is one of the representative achievements in the research of complex system theory in recent years. Self-organization theory holds that the chain reaction caused by small events can affect any number of components in the system in the critical state, and the chain reaction in all scales is the constitution of its dynamic characteristics. In the macroscopic performance, a series of uniform small disturbances will make the system take place the "avalanche" events large and small. If these avalanche events exhibit fractal structure in space and 1 / f noise in time, that is, power law distribution in time and space, it indicates that the system is self-organized criticality.

Using the complex system theory, American scholars Dobson and Cameras analyzed the blackouts in American power system from 1984 to 1999[1]. The results show that the power law relationship between the scale and frequency of blackouts is as follows:

$$\log N(Q) = a - b\log(Q + c)$$

Q denotes the scale of the blackouts, (Q) is the probability of blackouts, a, b, c are Constant.

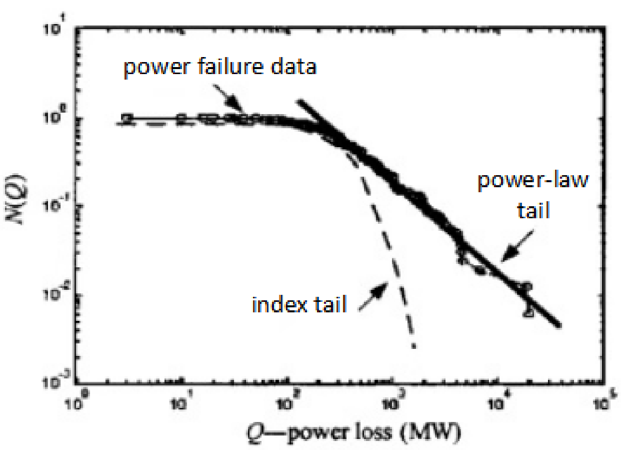

FIGURE 2. Power-rate relationship for a large power outage

The sand pile model can intuitively demonstrate the self-organized critical state. Imagine that a pile of sand is piled up on a platform by adding sand at random, one grain at a time. With the increase of the sand pile, its slope gradually increases. Once the slope between the adjacent positions of the sand pile reaches a certain closed value, a collapse will occur [7]. If the increase of the power load is similar to the falling sand in the sand pile model, when the load increases to a certain level, the power system will enter the critical state, just as the sand grains will slide when the slope of the sand pile is too steep. Caused by the size of the avalanche the critical state of the power system is bound to occur in varying sizes of blackouts.

TABLE 1. Analogy between power system and sand pile

Type	System state	Applied force	Reactive force	Event
Power system	Load level	Load demand of the user	System improvement	Load limit or trip
Sand model	Sand slope	Add the sand	Interaction of grains of sand	Sand collapse

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The self-organized criticality of the power grid can be further explained in the following ways: the increase of load will lead to the decrease of the system operating margin and the increase of the probability of accidents; On the other hand, people continue to maintain the power grid, building new power plants and transmission lines, so as to improve the load capacity of the entire grid and reduce the probability of accidents. These two opposing forces will eventually reach a state of equilibrium, which is the dominant self-organization process of power network evolution.

OPA model

OPA model classifies the dynamic behavior of power system into slow time scale and fast time scale to explain the power law behavior of power system blackout [5]. The slow time scale dynamics behavior is a kind of self-organized action process and leads to the critical point of the system, while the fast time scale dynamics behavior is the cascading failure and leads to the occurrence of power outage. The dynamical behaviors of these two kinds of time scales are coupled with each other. The dynamic behavior of slow time scale is reflected by the interaction process of increasing load demand and increasing power supply capacity of the system. When the load of the system increases slowly, the operating pressure and the probability of outage (fast time scale dynamic behavior) increase, in order to meet the needs of power supply. The system engineer will take a series of measures to avoid the occurrence of the same kind of failure and finally realize the increase of the power supply capacity of the system.

(1) Dynamic behavior at slow time scales

The dynamic behavior of slow time scale is characterized by the increase of load and the improvement of transmission line capacity [4]:

Let P_{ik} be the power injection of each node on the kth day, where the power injection of the generator node is positive and the power injection of the load nodal point is negative. The injection of all the nodes each day forms a vector:

$$P_{ik} = (P_{1k}, P_{2k}, P_{3k} \cdots, P_{nk})^T$$

There are m transmission lines in the system and P_{jk} is the active power of the first j line on the k day. Then the active power vector on the k-day grid line is:

$$F_{jk} = (F_{1k}, F_{2k}, F_{3k} \cdots, F_{nk})^T$$

There is a linear relationship between the line power and the injection power when the DC power flow model is used in the simulation process. On the k day, there is a relationship between the line power and the injection power:

$$F_k = AP_k$$

The matrix A represents the constraints of the network. The slow increase in load is expressed as:

$$P_k = P_0 \prod_{l=1}^{k} \lambda_l$$

Where λ_l is a group of independent and identical random variables, and its mean value is slightly more than 1. Thus, the transmission power on the line after the load increase can be obtained as follows:

$$F_k = AP_k = AP_0 \prod_{l=1}^{k} \lambda_l$$

(2) Dynamic behavior at fast time scales

The fast process of OPA model mainly reflects the cascading fault performance of the system after the initial event, that is to say, the fast process is mainly aimed at the chain reaction process [8].

The basic algorithm of the OPA model is carried out according to the following iterative steps: step 1, the initialization power flow is calculated according to the power injection of the day of the system, step 2, the initial line

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fault events are determined according to the known probability; Step 3, if the line or generator power limit, or a line has been broken, the system must re-adjust the power, the adjustment method in accordance with the standard linear programming method, if the optimization results are not feasible; The iteration is stopped and the overload lines that occur during the optimization process are recorded; Step 4, for the overload lines appearing in step 3, determine whether the lines will trip and stop operation according to the known probability; step 5, if there is a line outage, turn to step 3, otherwise stop iteration. It can be seen from the above that the OPA model gives a quantitative description of the blackout caused by cascading failures to a certain extent. From a long-term point of view, this kind of explanation accords with people's intuitive experience to a certain extent. For example, the increase of load demand and the resulting increase of the operating pressure of the system, which may make the system in some cases due to the initial disturbance and cause blackout cascading failure.

PREVENTION AND EMERGENCY MEASURES FOR CASCADING FAILURES

In order to prevent and deal with the cascading failures, it is necessary to understand the occurrence and development process of cascading failures and the main factors to promote the transmission of cascading failures. The research shows that the cascading failure in the large power grid from the initial event to the failure cascading end of the blackout will take a long period of time. In the process, the speed of the chain reaction will pick up gradually-the interval between failures will be reduced from the first minute to the second, and eventually after a critical failure. The system loses a large number of components in a very short period of time, and the system blackout occurs [2]. Figure 4 below is a typical power grid cascading failure, including the start, development, climax and collapse of the four phases. The analysis of previous large-scale cascading faults at domestic and overseas shows that the main factors promoting the fault propagation in the development stage of cascading failures include large-scale power flow transfer, inappropriate action of protection and insufficient reactive power support of the receiving end power network.

In view of the above analysis, combined with the common problems of blackout at domestic and overseas, this paper puts forward the prevention and emergency measures of power grid cascading failure from multiaspects aspects. (1) Increase the construction and investment of electric power to avoid the problem of shortage of electric power supply. In recent years, the deep-seated causes of blackouts in the world are often caused by such factors as overload, balance of power flow distribution, and so on. (2) Reasonable planning of power network and setting of relay protection. Only by ensuring a strong grid framework, complete and accurate relay protection, can we avoid the risk to the maximum extent. (3) Adhere to the unified scheduling mechanism. The lack of coordination capacity, machine network, transmission and distribution network coordination often lead to small accidents cannot be dealt with in time, but to expand the scope of the accident, resulting in serious consequences. (4) Strengthen the research of basic technology and the training of operators. Cascading fault is a dynamic development process in the blackout accident. As long as the operator finds out the problem in time and takes the correct emergency measures, the further deterioration of the accident can be effectively controlled.

CONCLUSION

A blackout is usually the result of a succession of accidents rather than a simple failure. This evolution process is related to a variety of factors, such as accident type, operation mode, power network structure and so on. It is difficult to predict accurately in advance because of the ever-changing process. However, it still has a general rule, which is caused by the accidental failure, and then evolves into the process of blackout. It can be divided into slow successive events, rapid successive failure interruption, oscillation, collapse and long recovery stages. In the slow successive events, if the relay protection can quickly clear the fault, take preventive control measures in time, start the reserve or cut off some load, adjust the power flow, it is possible to prevent the future development of the accident. In the stage of rapid successive outage and possible system stability failure, the use of preventive control is too late to eliminate the risk, and emergency control can only be used to avoid stability damage and prevent system collapse.

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