Analysis on Several Blackouts Caused by Extreme Weather and its Enlightenment

Ying Wang*, Jiechen Wu, Haiqiong Yi
State Power Economic Research Institute, Beijing 102209, China
wangying@chinasperi.sgcc.com.cn

Abstract. In recent years, blackouts caused by extreme weather show a trend of frequent occurrence. This paper analyses the external causes of blackouts, summarizes the evolution process of blackouts, discusses the internal causes of blackouts in power system, analyses the challenges faced by power system under the superposition of extreme weather and renewable energy, and finally puts forward some suggestions for the planning of high proportion renewable energy power system.

1. Introduction

As the planet warms further, heat-waves and other weather extremes that today occur once in hundreds of years, if ever, would become the "new climate normal," creating a world of increased risks and instability. In recent years, blackouts caused by extreme weather happened increasingly. Although the probability of such blackouts is quiet low, but the consequences are extremely serious. It is particularly important to find out the process of blackouts caused by extreme weather, analyze the weakness of power systems, and explore the enlightenment. On the other hand, in order to achieve the goal of carbon neutrality, all countries have clearly proposed that there will be a high proportion of renewable energy resource in the future power supply. Since the output of wind and solar power generation is strongly correlated with the weather, therefore, it is of great significance to study the challenges brought by extreme weather to the power system with a high proportion of renewable energy.

2. Statistical analysis of the external cause of blackouts

In the early development of the power industry, the power system is small and independent, and the scope of single accident is limited. With the gradual expansion and complexity of the power system in major countries, the scope of single accident is significantly expanded, and the continuous improvement of electrification also makes the impact of blackout more serious. According to the external causes, the blackouts since 1990s can be divided into five kinds of extreme weather, improper operation of personnel, equipment failure, network attack and other [1]. Take the United States as example, the proportion of blackouts caused by extreme weather increased from 27% in 1992 to 73% in 2020 (as shown in Figure 1). This is because with the increasing maturity of the power system structure and the continuous improvement of the operation and maintenance level, the proportion of blackouts caused by improper personnel operation, equipment failure and other factors is on the decline. On the contrary, blackouts caused by extreme weather are gradually frequent, which has become the main external cause of blackouts.
3. Overview of evolution process of blackouts

The influence range of extreme weather in the power system can be divided into two kinds, local and regional. The evolution process of blackouts can be correspondently summarized as the cascading failure type from local to regional and the direct cause of regional supply and demand imbalance.

3.1. The cascading failure type of blackouts

The cascading failures, which usually start from local and short-term extreme weather, cause a series of cascading failures due to the weakness of the power system itself, promote the continuous expansion of fault scope, and eventually lead to regional imbalance of supply and demand, leading to large-scale blackouts.

Australian local time on September 28, 2016, in South Australia, due to extreme weather such as typhoon and rainstorm, six faults occurred on the transmission lines in a short period of time, resulting in a sharp drop in voltage, causing a total of 505 MW of wind turbines off the grid, and then a tidal current transfer occurred, resulting in the only connection between South Australia and the outside world. The overload disconnection of the AC tie line Heywood (525 MW power flow before the line fault) eventually led to the power outage in South Australia. The blackout lasted for 50 hours (80% - 90% of the load power supply was restored after 7.5 hours of blackout), and 1.7 million people in South Australia were affected. This event is the first blackout in the world caused by extreme weather[2].

On August 9, 2019, UK local time, multiple circuit line faults caused by lightning strike successively caused the superposition and disconnection of horn offshore wind farm, little Barford gas power station and distributed generation. Among them, horn wind farm lost 737mw, little Barford gas turbine lost 641mw and distributed generation lost 500MW, resulting in the system frequency as low as 48.8hz and low trigger frequency load shedding action. The total power lost in this incident reached 1878mw (6.5% of the total load), which exceeded the fortification standard of the British power grid, resulting in blackouts in parts of England and Wales for about 1.5 hours, affecting 1 million people [3].

3.2. The regional supply and demand imbalance blackouts

The blackout accidents that directly lead to the imbalance of regional supply and demand usually start from the regional and long-term extreme weather. The initial impact scope of the blackout accidents is
directly regional. The regional power system is facing the problems such as the sharp rise of power demand, the damage and outage of generator units, the interruption of power grid interconnection and so on. To solve this problem, a large-scale power cut will be triggered.

California, USA (hereinafter referred to as California) experienced the first power outage in turn since the 2001 energy crisis from August 14 to 15, 2020 local time. During the event, California suffered the most serious heat wave since 1985, which led to a surge in power demand. Meanwhile, 470MW gas-fired units tripped, the output of wind power photovoltaic units decreased sharply (the maximum output of wind power decreased by 1200mW, the maximum output of photovoltaic units decreased by 1900mW), and the output of gas-fired units lost 250MW due to disoperation. California independent system operators started "three-level emergency state", took load shedding measures for many times, accumulated 1748mw, and called demand side response, a total of 1691mw. The longest time of power outage is 150 minutes, affecting more than 420000 users, and the largest power shortage is about 4400mw during peak period [4].

Texas (hereinafter referred to as Texas) local time February 14-19, 2021, due to the extremely cold weather once in 30 years, resulting in a sharp increase in power demand and unexpected outage of generating units in Texas, eventually resulting in a large-scale continuous blackout in turn. During the period of power rationing, the state power reliability Commission issued the highest level of "three-level emergency", with the maximum power rationing load as high as 16500mw (accounting for 1 / 4 of the expected load). At the most serious time, a total of 46000mw generating units (accounting for about 1 / 3 of the total installed capacity) were shut down. In this event, more than 4.5 million households were affected by the power outage.

4. Analysis of internal causes of power system blackout

Extreme weather is unavoidable external causes, but the internal weak links exposed by power outage are the root of the problem.

4.1. The equipment components

The generator set, transmission line and other equipment components in the power system should have the ability to resist external interference, but often because of equipment aging and loss, the tolerance is reduced, or there are some problems such as the design standard of disaster prevention is not consistent with the actual meteorological conditions, not considered and so on.

Typical cases: in South Australia power failure event, multiple circuit lines trip repeatedly within two minutes; in Texas power failure event, natural gas pipe network ice blocking caused the interruption of gas unit supply, blade icing caused the shutdown of wind turbine, low temperature solidification of diesel engine system caused the decrease of thermal power unit output, etc.

4.2. The supply capacity

The sudden rise of power demand caused by bad weather is inevitable, which requires a reasonable margin for power supply. In addition to the factors of power unit damage leading to reduced output or even outage, if the reserve margin is too low and the overall adequacy is not enough during normal operation of power system, it will more easily lead to imbalance between supply and demand under fault conditions.

Typical case: a blackout occurred in California in July 2020. Before the blackout, the total installed capacity of California power grid was 48550mw, the peak power demand was 46780mw, and the reserve capacity was only 1770mw. In the extreme hot weather, the power demand is further increasing, which makes it difficult for California power grid to maintain the balance of supply and demand.

4.3. The power grid structure

Power grid should play the role of optimal allocation of resources and mutual support under fault in power system, but there is often a phenomenon that the interconnection capacity between power grids
is insufficient or even close to isolated grid operation, or the interconnected power grids do not have complementary benefits of resources.

Typical case: the scale of interconnection between Texas power grid and other power grids in the United States is only 1250MW, accounting for only 1.7% of the maximum load, which is close to the isolated grid. Due to the characteristics of the power grid, other states cannot provide support during the period of power rationing.

In the power failure accident in Mexico in December, 2004, due to the long-term close to full load operation of four transmission lines in the north and South important transmission sections, the fault of one transmission line caused the other lines to exceed the limit, which further led to the imbalance of supply and demand in the north and South regions.

During the blackout in California, the power grid interconnected with California has the characteristics of similar resource characteristics and similar peak hours. Under the influence of large-scale extreme high temperature, the power grids of neighbouring states interconnected with California are faced with severe power shortage situation, and the power grids cannot support each other.

5. Test of power system brought by extreme weather and new energy
However, it is imperative to introduce new energy sources into the grid, which will bring more uncertainties to the development of power system. The existing stock risk of power system to resist extreme weather and natural conditions will inevitably add up the incremental risk brought by the rising proportion of new energy in the future, or even become the main power supply body, thus bringing more severe test to the power system.

5.1. The strong uncertainty
The reverse peak regulation of new energy output will change the peak valley characteristics, and put forward new requirements for short-term rapid balance of supply and demand. The higher the proportion of new energy in the power system, the more obvious the "duck curve" will be. On the one hand, it changes the traditional peak valley period, further aggravates the peak valley difference, and brings greater challenges to power generation adequacy. On the other hand, the power load drops rapidly in the early peak period and rises rapidly in the late peak period, which puts forward higher requirements for other units to quickly climb and power system real-time balance in a short time.

The random fluctuation of new energy output will bring diversified operation modes and probabilistic demand for supply and demand balance analysis. In addition, a large number of new energy sources are connected to the distribution network, which brings greater randomness to both the source and load sides. The "boundary conditions" of the power system will be more diversified, and the future power grid structure needs to have a larger "feasible region" to meet the security of the whole system. In the balance of power and electricity, the role of renewable energy will be changed from "icing on the cake" to "equal share" with conventional energy. The traditional deterministic forecasting, planning and operation methods will be difficult to apply. The concepts and methods of power balance and capacity adequacy need to be transformed from deterministic thinking to probabilistic thinking.

The vulnerability of new energy output will make the power system face internal and external pressure in extreme weather. Bad weather is often the first and most likely to affect the new energy units, prone to sudden drop in output, the phenomenon of units lying in the nest. Even in the period of insufficient wind and solar resources, such as cloudy and rainy days, the equivalent capacity of new energy units connected to the system is less than the actual rated capacity, which is easy to cause the occurrence of power supply shortage. With the synchronous units in the system being replaced by wind turbine units, the problem of power supply reliability will become more prominent.

5.2. Safe and stable operation
New energy itself has poor anti disturbance performance, which is easy to cause cascading failure due to large area off grid. The frequency and voltage withstand standard of new energy power generation
equipment is low, and it has low immunity. When the system accident causes a great change in
dynamic characteristics, the new energy power generation unit is easy to be large-scale off grid,
causing cascading failure.

The "zero contribution" of new energy to the moment of inertia forces the power system to face
more severe traditional stability problems. The new energy does not have the mechanical moment of
inertia of the traditional generator set. The new energy unit squeezes the conventional unit, which
reduces the total moment of inertia of the online unit and the ability to maintain the system stability.
The dynamic characteristics of the power system change significantly, which has a significant impact
on the traditional angle stability, voltage stability and frequency stability.

A large number of new energy grid connected promote the development of high power electronic
system, and cause new stability problems. In highly electronic power system, the interaction among
power generation equipment, transmission network and power load will cause instability oscillation in
the frequency range of several Hz to several thousand Hz, and cause stability problems such as sub or
super synchronous oscillation and harmonic resonance, resulting in unit trip and even equipment
damage, endangering the safe and stable operation of power system.

6. Enlightenment on the construction of power system with high proportion of new energy
access
The new power system with new energy as the main body should continuously ensure safe, reliable
and flexible power supply, and have the ability to withstand extreme weather. In the process of
drawing the blueprint of the new power system, we should face up to the frequent trend of extreme
weather, pay attention to preventing major risks from the planning source, and fully make strategic
planning and tactical plans.

6.1. Equipment immunity
First, comprehensively improve the grid related performance of new energy power generation, and
promote the active support and control ability of new energy. According to the requirements of the
main power supply, research and improve the fault voltage ride through technology of new energy
station, promote the new energy unit to achieve the support capacity of inertia, primary frequency
regulation, damping and active voltage regulation by retaining active power reserve or configuring
energy storage equipment and using corresponding control system or installing independent control
device.

The second is to improve the standard of equipment design. In order to improve the design standard
of disaster prevention, it is necessary to evaluate the weakness and defects of equipment components
in each link of power system, strengthen the depth of differential planning and design of important
lines and substations, and strengthen the precision of environmental condition evaluation in local areas,
especially in micro terrain and micro meteorological areas. According to the requirements of the three
lines of defence, we should strengthen the carding and accurately formulate the planning measures and
plans.

The third is to strengthen the storage, transportation and emergency response capacity of coal and
gas. Strengthen the analysis of the impact of extreme weather on coal and gas transportation,
investigate the key weak points of the supply chain, eliminate the key constraints of the supply chain,
strengthen the prediction and early warning and emergency plan, form the whole chain and industry
emergency coordination mechanism, and constantly improve the quality and safety guarantee ability
of energy supply.

6.2. Power adequacy
One is to consider the quarterly volatility of new energy and carry out short-term power planning.
After new energy occupies the dominant position of power generation, the power system will be more
sensitive to the seasonal changes of resources. In order to effectively deal with the seasonal random
fluctuations of large-scale new energy, it is necessary to consider the medium and short-term power planning based on quarterly or even monthly power investment decisions.

Second, considering the anti-peak regulation characteristics of new energy, we should carry out flexible resource planning. Considering the anti-peak regulation characteristics of new energy, it is necessary to judge the adequacy of flexible adjustment resources based on the net power demand curve, so as to reserve sufficient margin for the peak of net power demand; it is necessary to conduct minute level operation simulation for typical periods (such as morning peak and sunset in the evening), verify the short-time climbing ability of the system, and carry out flexible adjustment combined with the system operation flexibility requirements under finer time resolution with making flexible regulation of resource planning.

Third, considering the randomness of new energy, probabilistic power balance analysis is carried out. In view of the strong randomness of new energy, it is necessary to explore the description method of new energy and load randomness under different time and space scales, establish the evaluation standard and threshold standard reflecting the probability adequacy, and study the power and electricity balance analysis method based on interval prediction and probability prediction. Furthermore, the influence of meteorological conditions on the uncertainty of both sides of the source load can be considered to carry out probabilistic data modelling and power balance analysis on both sides of the source network based on power meteorological information.

6.3. Interconnection of power grid

First, the power grid needs to continuously ensure safe and stable operation. We should deepen the construction of a strong power grid, strictly implement the "guidelines for power system security and stability", ensure the stable operation of the backbone grid, and build a mutual support and structural coordination of the upper and lower power grids.

The second is to give further play to the benefits of cross regional interconnection. The new energy output has a regional smoothing effect, and the volatility decreases with the expansion of the spatial scope. Expanding the balance area can reduce the demand for the total peak shaving resources to a certain extent. We should improve the level of new energy consumption by cross time and space mutual aid, scientifically plan the new trans regional transmission channel, ensure the smooth trans regional transmission of new energy, expand and improve the main AC grid, build the optimal allocation platform of hydro thermal and wind power resources, and support the safe and efficient operation of trans regional DC.

The third is to carry out collaborative flexible planning to adapt to the uncertainty of development. The traditional power system planning can be evaluated by several typical operation scenarios, while the future power system operation mode will be diversified, decentralized and complicated under the strong uncertainty environment. It is necessary to consider the uncertainties in the planning process and establish a flexible planning method based on robust planning theory and stochastic planning theory, so as to find a more flexible and more adaptive flexible planning scheme.

6.4. Electricity market

The first is to design the relevant market mechanism to ensure the adequacy of power generation capacity. There is insufficient generation capacity in both Texas and California. In view of the adverse impact of insufficient generation capacity on power system reliability, we should improve the cost recovery mechanism of traditional energy units, release the power investment signal, effectively guide the healthy development of power supply structure of power grid, ensure the supporting role of thermal power units in extreme cases, and ensure the abundant generation capacity of the whole system.

The second is to introduce uncertainty punishment mechanism in combination with energy policy development. In view of the uncertainty of the output of high proportion of new energy, we should give consideration to both "guaranteed quantity" and "guaranteed price", and study the design of
punishment mechanism for new energy with different levels, magnitudes and characteristics to participate in market-oriented operation.

Third, actively cultivate new flexible resources to participate in the power market. In the face of the increasing demand of power system for flexibility, we should actively mobilize the source storage resources to participate in the auxiliary service market, which is not limited to the flexible transformation of generating units, generalized energy storage resources and conventional power users. We should further explore the demand response mechanism, introduce innovative technologies such as blockchain, moderately carry out bilateral and multilateral transactions, and establish a multi-level power market. It is necessary to explore the resource flexibility of the system.

Fourth, it is clear to carry out the emergency circuit breaker mechanism in the power market. In view of the problem that the power system is in the extreme operation state, which leads to the release of wrong signals in the power market and further aggravates the development of the situation, the participating users should be allowed to actively withdraw from the market operation, and the necessary administrative intervention measures should be introduced.

7. Conclusion
Extreme weather is an unavoidable external challenge of power system. In order to avoid blackouts, we should pay more attention to the analysis of the internal problems of power system. In addition to strengthening the anti-interference ability of equipment and components, improving the adequacy of power supply and strengthening the interconnection of power grid, the power system should attach importance to the more severe tests in dealing with the strong uncertainty of new energy and ensuring the safe and stable operation in the future under the development trend of the rising proportion of new energy.

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