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REVIEW

Review of Black Start on New Power System Based on Energy Storage Technology

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ABSTRACT

With the continuous development of new energy generation technology and the increasingly complex power grid environment, the traditional black start scheme cannot meet the requirements of today's power grid in order to ensure the stable operation of the power system can be restored quickly in the face of large power outages, so a more complete black start scheme needs to be developed to cope with the new power system. With the development of energy storage technology, the limitations of the traditional black-start scheme can be solved by new energy farms with energy storage configuration. Therefore, this paper investigates the problems faced by black-start, the key technologies of energy storage assisted new energy black-start, and introduces the research related to new energy black-start technology to provide reference for future research and application of new energy black-start.

KEYWORDS

New energy; black start; energy storage; rapid recovery

1 Introduction

The construction of new energy-led power system is a further overall deployment for China's "double carbon" target in September 2020. With the in-depth research on new energy power generation, the penetration rate of renewable energy power generation is increasing, and the inherent randomness, intermittency and volatility of new energy power generation make the network structure and dynamics become increasingly complex, and once events such as extreme weather or human-operated faults occur, it is likely to cause large-scale off-grid of new energy sources, thus causing the entire power system to fail and causing major power outages, which brings great challenges to the safe and stable operation of the power system. For example, on August 20, 2021, due to extreme cold weather, wind turbines in Texas, USA were forced to shut down because their blades were frozen, and natural gas facilities experienced reduced production due to freezing wells and equipment malfunctions. During this event, power outages in Texas lasted up to 4 days, with a peak load of 20 GW, leaving over 4.5 million residents without power. The accident caused direct and indirect economic losses estimated at up to $80 to $130 billion [1]. It can be seen that the impact of contemporary power grid outages is becoming more and more serious, not only for society and people's livelihoods, but also for national security and economic development. Therefore, it is necessary to develop a black start plan in advance so that the system can be restored in an orderly manner in case of a major accident. In early November 2021, a power outage in the eastern region of India caused severe damage to the power system in Kashmir, leading to a long period of power outages affecting hundreds of thousands of users. However, the Indian Power Company quickly restored the power supply using black start technology, significantly reducing the duration of power outages for users. The successful black start operation brought great convenience and help to the local residents by restoring the power supply quickly.

At this stage, the black start power supply is mainly undertaken by hydroelectric power units and gas units, while the penetration rate of new energy generation is increasing, the limitations of the traditional black start scheme due to its more serious impact by geographic resources and other issues are gradually revealed. For example, water resources are scarce in the northwest of China and Inner Mongolia Region, so the distribution of hydroelectric power plants is relatively sparse, and once a lumping power outage occurs, relying only on hydroelectric power plants to restore the process will lead to a very slow response, which will cause a lot of economic losses, but in those areas are very rich in scenery resources, therefore it is particularly important to take different research on new energy black start solutions for different areas according to local conditions.

The development of energy storage technology has greatly promoted the process of black start development. Energy storage, as a relatively new industry in recent years, has received sufficient attention both at home and abroad, so has a relatively rapid development, and there is no small-scale development in the power system of various regions in China. At present, the new energy storage type electric field configured with energy storage system at home and abroad has been put into operation. Due to the configuration of the energy storage system, the new energy storage field has stronger controllability than the traditional type of power field, and its in-depth study can be used as a black-start power supply to help the grid to quickly restore power after a major power outage, which can improve the speed of grid recovery and reduce economic losses.

This paper will briefly introduce the concept of energy storage assisted new energy black start, briefly discuss the problems faced by new energy black start technology, and present the analysis of each problem and the prospect of energy storage assisted new energy black start for the subsequent research.

2 Black Start Principle Analysis

Black start is the process of gradually restoring the entire power system by restoring the power supply capability of power plants that do not have self-start capability in the power system under the premise that only power plants with self-start capability and available power sources within the power system are used to provide power [2]. It can be divided into three stages according to the different roles assumed by the black start in the grid restoration process at different time stages.

(1) Phase 1: mainly through the power plant with self-start capability as a black start power source, so that it forms a subsystem with other power plants in the system that do not have self-start capability, after meeting the plant load and supplying power to them, so that the generating units that do not have self-start capability start. This stage takes about 45∼60 min.

(2) Phase 2: In this stage, mainly through the division of the surrounding load level, the power plant has been restored and the restoration of the higher priority of the load to form a small system

of isolated weakness, priority for the important load to restore power supply. The process takes about 3∼4 h.

(3) Phase 3: This phase is to expand the small system to the entire outage system, through the gradual recovery of some of the load will gradually stabilize the entire system, improve the system recovery capacity, will restore power supply to all loads, this phase because the need to restore the entire system, so for the system voltage and frequency monitoring, while restoring the previous relay protection devices to prevent black start failure. This phase takes 7∼9 h.

The three main phases of the black start process are shown in Fig. 1:

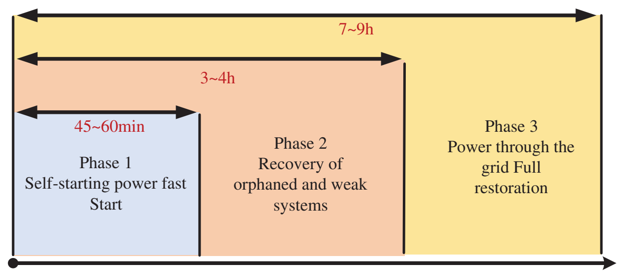

Figure 1: Schematic diagram of the main black start process

The traditional black start power sources are hydroelectric units and gas engines, as well as large diesel generators and thermal power units that can switch loads quickly. The new energy black start power supply is mainly undertaken by photovoltaic power plants and wind power plants. According to Table 1, it can be seen that at this stage of the blackout, hydroelectric units are mainly used, while in today's vigorous development of new energy sources, photovoltaic power plants and wind power plants are involved in the black start process, which has become the trend of black start development.

Table 1: Current black start methods for large power outages

Time	Region	Outage duration	Black start power
2019.6.16	Argentina	2 h	Hydroelectric units
2019.3.7	Venezuela	24 h	Hydroelectric units
2018.3.21	Brazil	6 h	Hydroelectric units
2015.3.31	Turkey	6.5 h	Hydroelectric units
2012.7.30	India	2 days	Hydroelectric units
2009.11.10	Brazil	4 h	Hydroelectric units

As the new energy black-start power supply uses photovoltaic or wind power generation is subject to greater weather and geographical conditions, the areas where the new energy black-start mode can be used are generally located in areas with rich photovoltaic or wind power generation resources and do not have more hydraulic resources. Due to the inherent strong randomness, intermittency and volatility of renewable energy generation, and the new energy power station itself does not have the ability to self-start, so it is necessary to assist the new energy power station to complete the self-start, and then the new energy power station to complete other black start tasks, energy storage battery because of its high charging and discharging conversion efficiency and mode conversion flexibility, short response time and more stored energy and other characteristics, can help new energy system to complete self-start.

The combination of energy storage system and new energy unit to realize black start can effectively supplement the amount of black start power and make it possible for parallel recovery of black start, which can effectively improve the black start response efficiency and reduce power outage time. Due to the advantages of fast response speed and high energy density, the absorption ratio of wind power can be effectively increased by configuring large-capacity battery energy storage systems for wind farms and building them into energy storage wind farms [3]. Therefore, it is of great theoretical value and practical significance for the cited research on the configuration of energy storage systems into new energy farms.

3 Problems Faced by Black Start Technology

3.1 Traditional Black Start Problem

Power system black start was first proposed by American scholars in the 1980s [4], and in 1998, China's Ministry of Science and Technology listed the power system restoration program as one of the sub-topics of the research project [5], which marked the official start of black start research in China. With the official start of the research, whether it has black start capability has also become one of the important indicators for grid safety assessment. In the initial stage of the technology, black start process is mainly undertaken by thermal power units and hydroelectric power units to assume the role of black start power, among the completed project tests at home and abroad, references [6–9] are the study of the experiment of using hydroelectric power units and gas units as black start power. Reference [10] described the process of the Swedish blackout in 1983 to start the southern nuclear power plant through the northern hydroelectric power plant, and reference [11] described a research program proposed by the state of Nebraska in the United States in 1990 to restore thermal gas units through hydroelectric power plants to complete the black start task, and reference [12] studied the first black start test successfully completed in China, the black start task was accomplished on May 05, 2000 in the North China grid through a pumped storage power plant. The traditional black-start scheme can indeed be achieved by setting the black-start power source to pumped storage power plants and thermal gas units with self-starting capability, but due to the rich land resources in China, the unbalanced distribution of hydropower units in different regions, and the high penetration rate of new energy generation in some regions, some hydropower units and thermal units as black-start power sources are not widely used. Therefore, we have to look for a better and more economical black-start power source. As the installed capacity of wind and photovoltaic grows year by year, in areas rich in light and wind resources, we can choose to play their own geographical advantages of the black start power, this makes it inevitable for other new energy sources to participate in the black start.

3.2 New Energy Black Start Energy Storage Requirements

Energy storage systems are important for the operation and implementation of new energy black starts, compared with the traditional black start method without energy storage system, the Reference [3] pointed out that the deployment of energy storage system can make the system start faster, have stronger regulation ability and more flexible equipment deployment, and can well solve the negative impact of high grid penetration of renewable energy on the black start system. Reference [13] found that the configuration of energy storage system can provide a good solution to the problems of peak shaving, frequency regulation and new energy utilization after the power system restoration; References [14,15] used battery storage system to smooth out the active power fluctuations of wind farms. References [16,17] used new energy storage systems to improve energy utilisation and control the frequency regulation of the grid through the joint operation of new energy and energy storage systems; Reference [18] used energy storage system as a strategy to change the stability of wind farm injection current according to the problems such as the outgoing frequency of wind farms cannot be continuously constant and stable. From the above references, it can be seen that the energy storage technology has a strong potential, and its analysis and research can make it possible to assist in the black start task. Therefore for new energy black start for the selection of energy storage, is also very important.

For the type of energy storage, the energy storage technology can be distinguished according to different ways of electrical energy conversion and can be divided into: electrochemical energy storage, chemical energy storage, mechanical energy storage, thermal energy storage, electromagnetic energy storage and mechanical energy storage. Reference [19] showed that the largest scale of energy storage in the current application accounts for the highest proportion of electrochemical energy storage, because its deployment is more flexible, and the restrictions on the external environment are little, and can be directly charged and discharged, which is now one of the more important development directions in energy storage technology. Reference [20] verified the possibility of wind farms configured with vanadium liquid flow energy storage equipment as a black start power source; reference [21] analyzed the physical characteristics of various batteries and different ways of constructing energy storage systems at this stage; reference [22] listed the following more mature electrochemical energy storage technologies according to the current research results and their performance is shown in Table 2. The reference [23] analyses the multi-hour operation of multi-energy microgrids and optimises the energy storage control strategy.

Table 2: Comparison of various electrochemical energy storage technologies

Energy storage method	Lead-acid batteries	Sodium-sulfur batteries	Liquid flow batteries	Lithium batteries
Energy density (WH/kg)	30∼50	150∼240	10∼30 Wh/L	75∼200
Power density (W/kg)	75∼300	150∼230	16∼33 W/L	150∼315
Power rating (MW)	0∼40	0∼15	0∼50	0∼50
Response time	<s	<s	S	<s
Charge and discharge efficiency (%)	60∼70	70∼80	75∼85	80∼90
Cycle life (year)	5∼15	10∼15	5∼10	8∼20
Number of cycles	500∼1000	2500	12000+	1000∼10000+
Development stage	Mature	Business	Demonstration-business	Business
Whether with black start capability	Yes	No	No	Yes

For the research on energy storage capacity and start-up time, reference [24] introduced the first phase of China's scenic storage demonstration project for 98.5 MW wind power and 40 MW PV power generation with 20 WM hybrid energy storage device; Reference [25] analyses the optimal capacity and cost of hybrid energy storage systems in standalone DC micro-grids. The Reference [26] proposed an optimization method based on the asymmetric Copula function to establish a binary joint probability distribution to accurately describe the power allocation capacity configuration of energy storage. The reference [27] used the Copulas function to obtain the relationship between the output power of wind farms and photovoltaic power plants, and found the main influencing factors affecting the cost of hybrid energy storage systems in wind and solar power systems. The above literature mainly describes the research on energy storage capacity allocation.

4 Energy Storage Assisted New Energy to Achieve Black Start Key Technology

4.1 New Energy Black Start Feasibility Assessment Study

In the preparation stage of black start, the first thing is to make a reasonable assessment and judgment of the black start power supply. The first thing is to ensure the reliability of power supply when a new energy power station is used as a black start power supply. According to China's "Technical Specification for the Preparation and Implementation of Black Start Program for Power Systems (for Trial Implementation)", a power generation system must meet the following conditions to be used as a black start power source: the unit must have self-starting capability, power can be flexibly regulated and in-phase operation capability in the state of total blackness of the power grid [28]. The Reference [29] makes a corresponding real-time scheduling strategy considering the coordinated scheduling of distributed energy sources and verifies its effectiveness. The Reference [30] establishes a system frequency response model under the joint action of synchronous generator, wind farm and low-frequency load shedding device to analyse the effect of wind farm output power on the system frequency response. An accurate prediction method of wind turbine rotor speed based on piecewise fitting and Bernoulli equation is proposed. Reference [31] pointed out that the volatility of wind power and photovoltaic output can lead to the inability to accurately respond to the lack of complementarity of scenery output in some cases; reference [32] was pointed out about the impacts caused by randomness of wind power. It can be seen that new energy black start feasibility assessment is necessary due to the impact of scenery power characteristics. In the following studies on the feasibility assessment of new energy sources, reference [3] assessed the feasibility of new energy black start in terms of environmental conditions and wind farm/photovoltaic plant capacity; Reference [33] suggested that the feasibility of new energy black start is mainly assessed in terms of the self-starting capability of the unit and the output reliability of the unit. This paper also mainly lists the evaluation methods for these two aspects.

4.1.1 New Energy Black Start Self-Start Capability Assessment

One of the conditions for a new energy power plant to be a black-start power source is that it has its own black-start capability. Take doubly-fed wind turbines as an example, although doubly-fed wind turbines can seamlessly connect off-grid to grid-connected, they do not have black-start capability by themselves. When the grid is down, doubly-fed wind turbines cannot rely on themselves to connect the units to the grid. Energy storage system is needed to provide plant voltage and frequency, and auxiliary power supply for wind turbines, so that self-starting can be realized. The following studies are about self-starting, reference [34] configured energy storage devices in doubly-fed asynchronous wind turbines to provide current during self-starting; reference [35] designed a control strategy for alternate control of rotor-side and grid-side converters to improve the starting speed and stability of wind turbines; reference [36] added energy storage devices on the outlet side of wind turbines to realize self-starting of wind farms and designed a control strategy to maintain the system frequency control strategy.

And based on the previous paper has been selected to complete the storage battery, the location of energy storage is also very important for the black start capability, the reference [37] points out that energy storage, as a bidirectional power component, its connection position in the power system directly affects the flow direction of the system, changes the line load, affects network losses, and even affects the system voltage level. Reference [38] proposed that the selection of multiple energy storage systems with participation in the black start process can improve the above problems will be well improved due to the distance causing the storage power plant for the operation of voltage adjustment difficulties to increase. Therefore, for the location of energy storage, it needs to be calculated and analyzed.

Energy storage power plants usually have four locations to choose from: power side, grid side, distribution network side, and user side. To assist the new energy plant to participate in the black start, energy storage is usually constructed at the new energy side. Reference [39] compared two options of configuring energy storage at the PV plant bus and for PV units. But reference [33] presented four black-start energy storage siting options as shown in Fig. 2 below, using wind farms as an example.

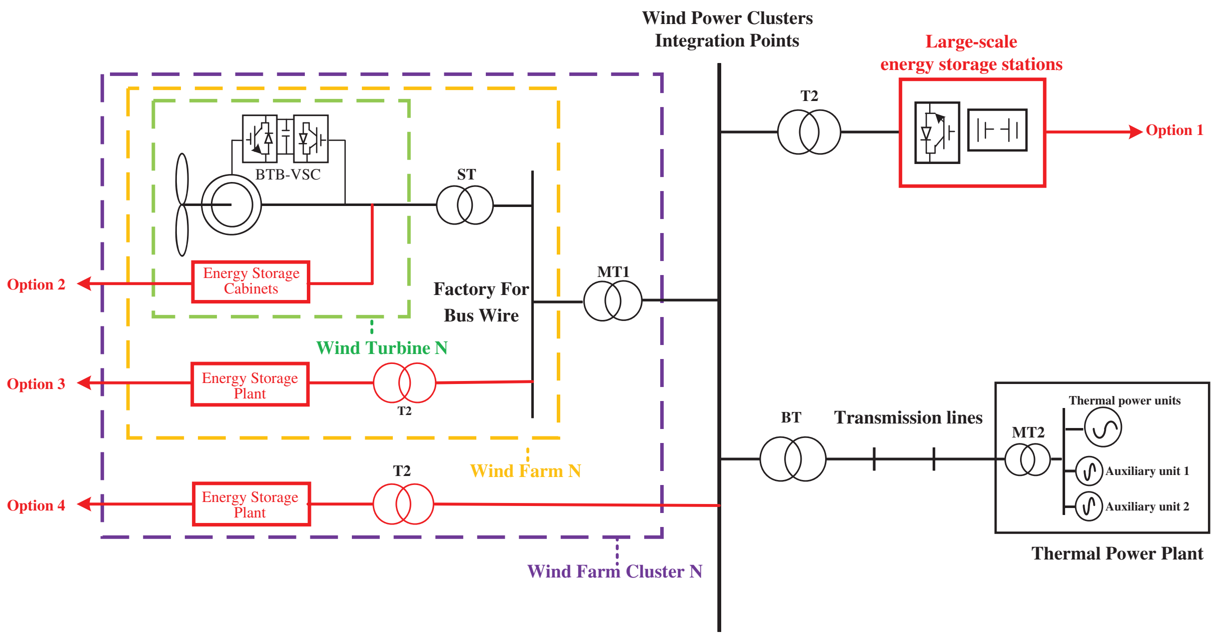

Figure 2: Black start energy storage location scheme

Different reference schemes can be proposed according to the different locations and different capacities of energy storage power plants. The four options is proposed in the figure above are: a large energy storage plant at the wind power cluster grid, a medium-sized energy storage plant at the wind farm cluster aggregation bus, a small energy storage plant at the wind farm plant bus, and a small energy storage cabinet at the wind turbine side. According to different programs to analyze their charging and discharging distance, the functions that can be achieved, as well as advantages and disadvantages, according to the actual situation in reality to analyze and compare the optimal program, that can ensure the self-starting ability of new energy black start.

4.1.2 Credibility Assessment of New Energy Black Start Output

Another very important issue for the realization of the new energy black start process is to ensure the reliability of the black start power supply. Due to the randomness and uncertainty of the new energy power plant, judging whether it has the ability to continuously produce power is necessary to meet the required power to supply the black start load. Reference [30] mainly considered the start-up power and start-up time of thermal power units, the sustained probability of wind speed of wind farms and the number of wind turbine start-up units, and conducted data sampling to count the sustained probability of different wind speed of wind farms; reference [33] counted the annual PV output of a PV power station in Inner Mongolia, and the cumulative probability of output is shown in Table 3. It can be seen that the availability can mostly meet the black start required power output confidence. Reference [40] argued the feasibility of wind power/PV black start from the calculation of the continuous effective output probability.

Table 3: Cumulative probability of annual photovoltaic output of a photovoltaic power station

Output (%)	Cumulative probability
>90	17.3
70	46.8
50	56.4
30	77
10	95.1
<10	4.9

The black start power output credibility is mainly evaluated by two aspects, on the one hand, the power output prediction of the black start power, and on the other hand the evaluation index of the power output. According to the prediction and evaluation of the output power of the wind and photovoltaic power plants, the predicted reference value of the output power of the wind and photovoltaic power plants is obtained, in order that according to the obtained reference data, the black start load demand power can be obtained and compared with the output power of the wind power plants and photovoltaic power plants for black start feasibility assessment, so as to determine whether the black start work can be completed.

Reference [41] summarized the principle of the feasibility assessment method in Fig. 3 below. The horizontal axis of the figure below is the time t, while the assessment time is generally one hour of the black start process, and by advancing backward by one hour, the black start feasibility for the next few hours can be derived by assessing, the time period in which the black start can be executed can also be derived.

For wind farms and photovoltaic stations due to the different influencing factors they need to consider, the processing methods for the data are also different. In reference [33], for photovoltaic power prediction, the article pointed out the need to consider the season, weather type, solar irradiance, temperature and other influencing factors, but the text does not consider the season, wind speed, weather type and other influencing factors, so the prediction accuracy can be improved by considering the above factors. Reference [20] evaluated the feasibility of wind storage as a black start power source for various weather conditions based on historical conditions in simulation experiments for various cases; the factors can be compared with various aspects of the required prediction period based on a large amount of historical data to find the highest similarity as a sample. With the selected sample, and the various aspects of the required time period to be sought, a prediction model can be built to predict the output power by the least squares method. Finally, the predicted output power is then compared with the power evaluation index that can satisfy the black start, so as to evaluate whether the predicted time period can satisfy the black start requirement. The flow of the new energy black start power output confidence evaluation is shown in Fig. 4 below.

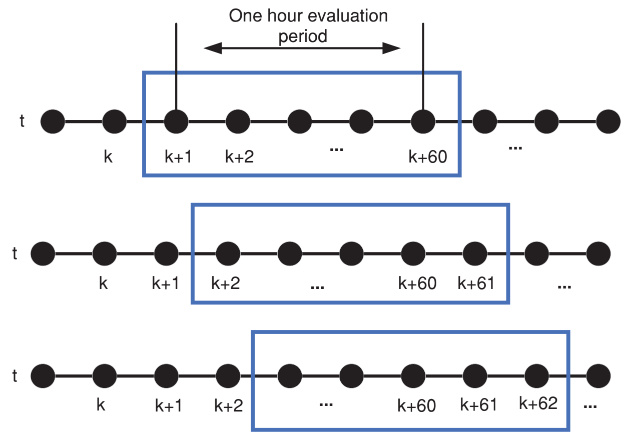

Figure 3: Principle of feasibility assessment method

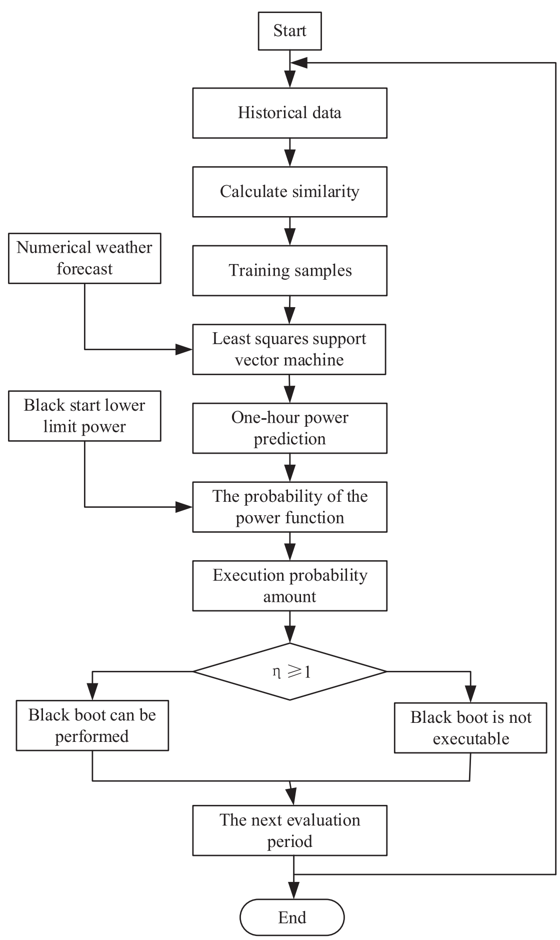

Figure 4: Flow chart of black start output reliability evaluation

4.2 New Energy Black Start Energy Storage Configuration

4.2.1 Independent Energy Storage Auxiliary New Energy Black Start Energy Storage Configuration

When energy storage-assisted wind farms participate in the black start as black start power supply, research on capacity configuration methods and schemes of the energy storage system can effectively reduce the configuration cost of battery energy storage, which is of great significance.

In order to solve the problem of black-start power fluctuation of new energy sources, reference [42] based on a wind storage system as the black-start power source, considering the fluctuation of wind power output, puts forward the optimal allocation strategy of energy storage capacity, determines the new energy black-start power source based on the minimum wind speed probability density and the optimal wind speed probability inclination, and determines the energy storage allocation participating in black-start based on the wind power prediction combined with SOFM and LSSVM. At the same time, for the problem of wind power output smoothing, a method based on the asymmetric Copula function to fit the joint probability distribution was proposed in reference [26] to minimize the cost consumption and consider the correlation between power allocation and capacity allocation of the energy storage system, so as to improve the accuracy of fitting the joint probability distribution and reduce the cost of energy storage allocation. Reference [43] aimed to minimize energy storage cost and maximize the SOC range of initial energy storage by configuring auxiliary wind farms to participate in the black start and using the linear weighted sum method to determine the optimal rated power.

The above documents all adopt energy storage systems to assist wind farms to compose wind storage systems as black start power sources, and wind power has the advantages of small starting power and fast starting speed. If wind farms are safely and stably introduced in the early stage of black start, the system recovery process will be effectively accelerated. Reference [27] took the maximum fluctuation that can be suppressed by the system in the initial recovery period as the output amplitude limiting target of wind power and considers the starting time of auxiliary units of thermal power units to determine the capacity configuration of the energy storage system.

4.2.2 Multi-Energy Storage Assisted New Energy Black Start Energy Storage Configuration

For areas with more wind and less water or areas with water shortage but sufficient light, hydropower cannot be used as the black start power source to carry out the black start process. Although this problem can be solved by wind power and photovoltaic power generation, new energy as the black start power source still has major problems: The unit itself has no self-starting ability and the new energy power generation power has great volatility. These problems affect the realization of the new energy as the black start power supply problem, and all need to be effectively solved.

In the process of power grid restoration after a power outage, the role of the energy storage system is to assist the new energy source to complete the self-start, balance the power and stabilize the voltage frequency of the system. It is important to configure the appropriate capacity for this process, as shown in Fig. 5 below.

The auxiliary wind power of the energy storage system supplies power to the auxiliary units of thermal power units. When the wind power is less than that of thermal power auxiliary units (B1, B2 zones), the power deficit will be made up by the energy storage system. The power of wind power is greater than that of thermal power auxiliary units (A1, A2, A3 zones), and part of the power of the system overflows. However, considering the cost of the energy storage system, if all the power overflows are absorbed by energy storage, the energy storage capacity will be too large, which does not meet the economic requirements.

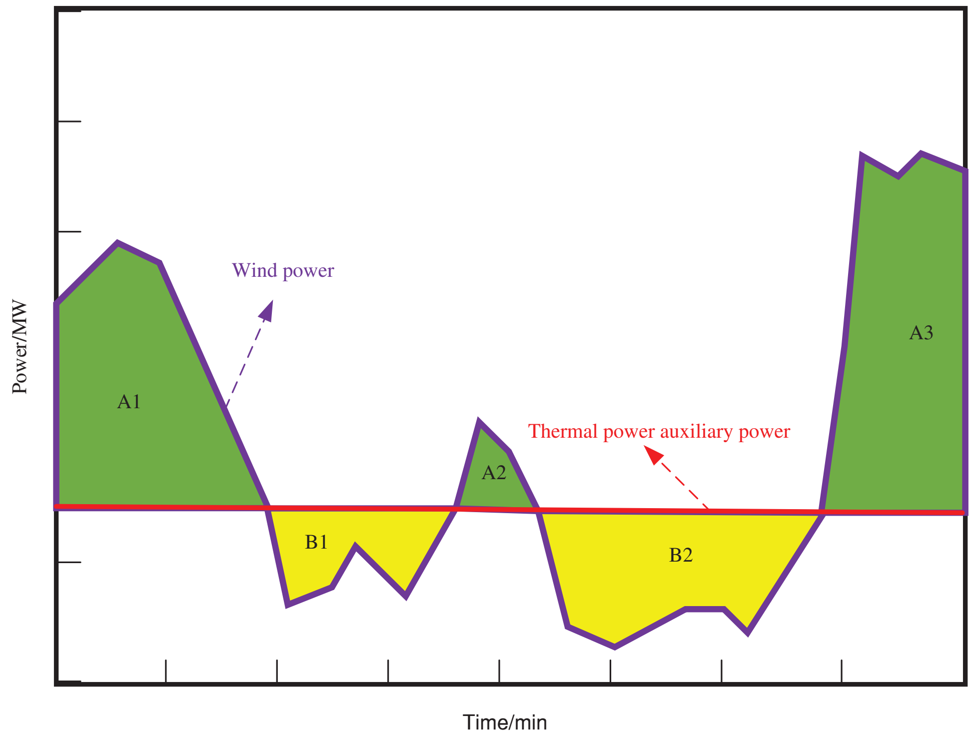

Figure 5: Black start energy storage capacity demand diagram

In recent years, the development of energy storage technology has greatly promoted the process of black start, meanwhile, a large number of encouraging policies of energy storage technology in our country [44,45]. The National Energy Administration and National Development and Reform Commission have issued a series of encouraging policies in succession, thus greatly pushing the process of energy storage in our country. In particular, several energy storage demonstration projects in Henan, Jiangsu, and other places have been put into operation [46,47] and the energy storage situation has taken shape (Table 4). Since the energy storage technology can improve the stability of the system during normal operation [48–51], when the system has a major power failure, the energy storage technology can assist the new energy power to complete the self-start operation and other subsequent recovery operations, greatly speeding up the process of power grid restoration. Energy storage technology combined with new energy can form three kinds of black start power supply: wind storage black start power supply [52] and optical storage black start power supply [53,54]. And black start power supply of micro grid [55], improving the capability of new energy black start. A large number of scholars at home and abroad have done a lot of research on energy storage capacity allocation. Reference [56] used the improved wavelet analysis algorithm to divide the hybrid energy storage system into different energy storage units, and each energy storage unit is responsible for different wind power fluctuations, which effectively improves the effect of fluctuation suppression. However, the proposed method is not very reasonable in terms of economy. To solve this problem, fuzzy control theory can be used to establish the function for the economic optimization of energy storage technology [57], which considers the economic benefits and the efficiency of fluctuation suppression. Reference [58] has reduced the energy storage cost of fluctuation suppression by handing the tasks of new energy fluctuation suppression to the hybrid energy storage system, respectively. Reference [59] put forward two methods to complete the operation of peak trimming and valley filling and smooth the fluctuation of wind power respectively, which meet the goals of integrating micro-grid with new energy and minimizing the energy storage capacity. The effect is shown in Fig. 6.

Table 4: Energy storage power stations have been built and are under construction

Place	Energy storage type	The magnitude of energy storage capacity (kWh)	Energy storage purpose
Shahekou, Dalian	Fluid flow battery	200 MW	Peak shaving
Henan Province	Electrochemical energy storage	100.8 MW/125.8 MWh	New energy utilization, frequency modulation, peak regulation
Gansu Province	Lithium iron phosphate battery	720 MWh	New energy utilization, peak regulation
Zhenjiang, Jiangsu Province	Lithium iron phosphate battery	202 MWh	Peak regulation, frequency modulation, black start
Inner Mongolia	Multiple forms of energy storage	3000 MW	New energy utilization, peak regulation

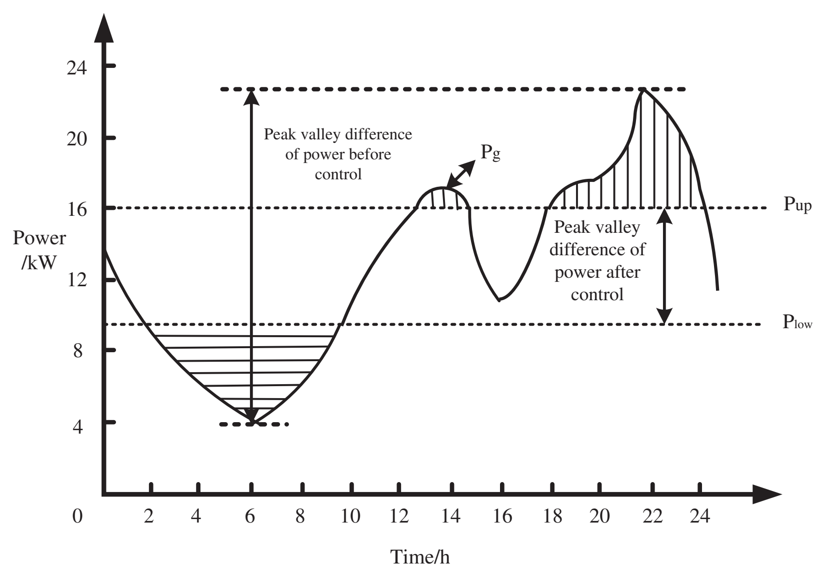

Figure 6: Schematic diagram of peak shaving and valley filling control strategy

Reference [60] comprehensively considered the three aspects of calming efficiency, energy storage life, and economy, and verifies that the hybrid energy storage mode is superior to the single energy storage mode in calming wind power fluctuation. However, when the energy storage capacity configuration and optimization are carried out, it is one-sided to consider a single factor or a single algorithm. Considering the different conditions separately, the obtained capacity configuration will also be quite different. The objectives of references [57–61] for the optimal allocation of energy storage include reliability objectives such as the effect of energy storage technology to smooth the fluctuation and the demand of integrating wind power into the power grid, economic objectives such as minimum equipment investment cost or minimum energy storage capacity, and wind power utilization rate. For the existing research on energy storage configuration, most of them are related to how to smooth the fluctuation after the new energy is connected to the grid. However, regarding the energy storage assisting the new energy black start power supply to complete the self-start process and the auxiliary black start power supply to power the auxiliary units of thermal power units, there is still a lack of research on the configuration of the energy storage system in this process.

4.3 Energy Storage Assisted Black Start Control Strategy

4.3.1 Optimization Strategy of New Energy Black Start Assisted by Energy Storage

The participation of energy storage technology in the black start of new energy can help the black start power supply complete the self-start operation and maintain the stability of the system voltage and frequency. Reference [62] proposed a black start control strategy based on hierarchical control for optical storage microgrids. By screening the current state of the energy storage system, the main power supply is selected to carry out hierarchical black start, so that the optical storage micro-grid can complete the black start operation safely and effectively, and also provide a certain reference for the actual micro-grid black start project. For the light-storage microgrid, reference [63] proposed a voltage control strategy based on improved micro-source droop characteristics to ensure that the output voltage increases from zero to maintain the stability of the voltage and frequency of the system to make the black-start power supply provide better voltage and frequency support. For wind farms and photovoltaic power stations as a black start power source is combined with an energy storage system, the process of black start, its power output volatility, because there are power storage systems and SOC constraints [64–66], may cause the energy storage system to charge or discharge, making energy storage system may not continue to adopt references [67,68], resulting in black start operation fails. With the continuous recovery of the system, the continuous input of the black start load makes the power fluctuation gradually increase, so the coordination control in the recovery process becomes particularly complicated. The success of the black start operation directly depends on the coordination degree of the new energy power station and energy storage technology and depends on whether sufficient load supply can be guaranteed. Reference [69] proposed a power coordination control strategy for energy-storage wind farms. Establish active power controller and reactive power controller respectively: adjust the active power output and reactive power output of the wind farm through the SOC of the energy storage system and the actual reactive power output, so as to keep the state of the energy storage system within a reasonable setting range. Reference [70] put forward a photovoltaic system control strategy suitable for power grid black start and verifies that the changes in energy storage configuration and the environment will affect the voltage, frequency, and recovery time of the system during the black start to a certain extent. Therefore, reasonable control of photovoltaic output power will effectively improve the black-start capability of the system. In reference [71], energy storage was used as the main power source and a photovoltaic power generation control strategy is proposed by combining tracking load and maximum power. Effectively control the photovoltaic output power and complete the black start operation.

4.3.2 Coordinated Control Strategy of Multi-Energy Storage

For the wind storage system with single energy storage control, if the SOC of the energy storage system exceeds the limit value and causes the energy storage to be over-charged or over-discharged, the power balance in the system will be difficult to guarantee, and the energy storage system may also be disconnected and the black start operation fails. For the above problems, experts and scholars around the world have shifted their attention to the coordinated control strategy of multi-energy storage power stations. Fig. 7 below illustrates the hybrid energy storage system architecture for microgrids.

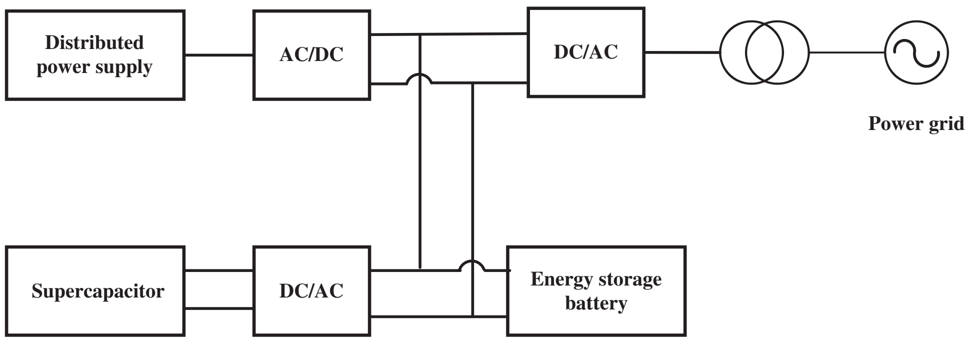

Figure 7: System structure diagram of hybrid energy storage

For multiple energy storage systems to participate in the black start, it is necessary to keep all energy storage SOC within the prescribed reasonable range. Because the traditional droop control is difficult to ensure the balance of each energy storage SOC. For this purpose, the sagging control strategy was introduced in references [72,73] to improve the unbalanced distribution of multi-storage power. Reference [74] proposed a new droop control strategy for DC microgrids to ensure that distributed energy storage and power distribution of adaptive regulatory load can be coordinated under normal communication and no communication conditions. The control strategy can be smoothly switched under the two working conditions, and the distributed energy storage SOC balance and load power dynamic distribution (coordination and distribution between multiple energy storage) can be realized. Overcharge or over-discharge of the energy storage system or frequent charge and discharge will lead to the destruction of system stability. For DC microgrid multi-energy storage units, reference [75] proposed an adaptive hierarchical coordinated control strategy in order to quickly achieve SOC balance among multiple energy storage units and reduce bus voltage deviation. Through power distribution level control and power balance level control, the state of SOC can be balanced. However, there is a problem. If the power of an energy storage unit exceeds the maximum charge-discharge power, the power balance of the system will be destroyed and the stability of the system will be threatened. As shown in Table 5 below, the running state of energy storage is divided into five running states with the SOC of energy storage as a reference.

Table 5: Working state of the energy storage unit

Soc range	Running state
$(Soc_{maxe},1]$	Overcharge (stop)
$(Soc_{max\_stable}, Soc_{max}]$	Critical overcharge
$(Soc_{min\_stable}, Soc_{max\_stable}]$	Stable operation
$(Soc_{min}, Soc_{max\_stable}]$	The critical discharge
$(0, Soc_{min}]$	Overshoot (stop)

In order to optimize and rationally distribute the power of each energy storage station, new strategies are introduced in many literatures. By adding or subtraction the power distribution coefficient constant [76] or controlling the reverse power flow of critical over-charge and over-discharge energy storage [77], the state of charge of the energy storage system can be controlled within a certain range, and the over-charge, over-discharge or frequent charge and discharge of energy storage can also be effectively avoided. In reference [77], the SOC of the energy storage system can be recovered by itself, and the flexible control ability of the DC system is enhanced. At the same time, reference [78] realized the rational distribution of energy storage power by optimizing wind power output. In view of the coordination problem of multi-wind storage joint systems, reference [79] proposed wide area coordination control of various wind storage systems considering the temporal and spatial correlation of wind power. Based on the cooperative game theory, it further proposed the cluster income distribution strategy to enable the wind storage system to participate in the cluster control.

Most of the existing research aims at ensuring the SOC balance of each energy storage unit. Once the power of an energy storage unit exceeds the power limit, the stability of the system will be directly damaged. Most of the research has not given specific solutions to this problem. In addition, since the function of an energy storage power station is to stabilize voltage and frequency, once the energy storage power station fails and stops working, the stability of the system will be directly reduced, and there is relatively little research on the solution to this problem.

4.4 The Prediction Accuracy of New Energy Improves the Credibility of Black Start

New energy as a green energy, its randomness and volatility caused by the impact has been the focus of scientific research, and black start as a power outage recovery measures, in the recovery phase, for the voltage, frequency and power and other evaluation indexes have more stringent requirements, once the stability can not meet the standard, it is likely to make the unit to be started to start the failure of the whole process of black start failure, or even cause a larger-scale blackout. Therefore, to predict the power of new energy power station in advance, and improve the prediction accuracy is a new energy black start at this stage needs to be studied in depth in a direction. At this stage, the combination of mathematical model and multi-scale new energy prediction method is used to improve the prediction accuracy. Reference [80] summarized the more commonly used photovoltaic prediction methods at this stage and briefly describes the principle and its advantages and disadvantages. Reference [81] proposed a prediction algorithm based on the combination of tracking behavior of the artificial fish swarm algorithm and BP neural network algorithm, and incorporates the prediction data into the influencing factors to improve the speed and accuracy of prediction. Reference [82] based on the framework of model predictive control, constructed the evaluation index of wind and solar storage system participating in black start, proposes the prediction model and rolling optimization model of wind and solar storage power generation system, and smooth the fluctuating characteristics of wind and solar through storage. Reference [83] proposed a short-term PV prediction method based on the optimized wavelet neural network based on the cuckoo algorithm, and combines the type of weather as well as the type of season to improve the prediction of short-term forecasts, which improves the prediction accuracy of short-term forecasting. The above literature mainly improves the prediction accuracy by improving the intelligent algorithm or increasing the influencing factors in two ways, while optimizing the algorithm to improve the prediction accuracy, the use of photovoltaic storage, wind storage power plant in the storage power plant to make up for the prediction of the error generated in the subsequent research can also be used as a new research direction.

5 Research Prospects

With the continuous research and development of new energy and energy storage technology, new energy black start-ups will be paid more attention. In the future, the research should be more focused on the following aspects.

5.1 Black Start Energy Storage Policy

With the continuous improvement of energy storage black Start technology, the policy of black Start is increasing. Since the implementation of the Implementation Rules for the Management of Grid-Connected Operation of Power Plants in the South and the Implementation Rules for the Management of Auxiliary Services of Grid-Connected Power Plants in the South (2017 edition), the number of unplanned outages of units has decreased significantly, the availability rate of AGC and the primary frequency modulation operation rate have increased significantly, and the safe and stable operation of the system has been effectively guaranteed. In order to further mobilize power generation enterprises to actively participate in power auxiliary services, the Southern Energy Regulatory Bureau will revise the "two detailed rules" to improve the compensation standard for the black starters. In the Implementation Rules for the Management of Auxiliary Services of Grid-Connected Power Plants in Central China and the Implementation Rules for the Management of Grid-Connected Power Plants in Central China published in September 2020, it is pointed out that energy storage is a kind of service, and energy storage is included in the scope of power plants. In the two detailed rules, "energy storage service" has been attached importance, and black start, as a type of paid auxiliary service, implements the rule of payment according to the effect and generates the efficiency evaluation mechanism of the energy storage system, to solve the problems existing in the compensation mechanism of electric power auxiliary service. According to the data collected and analyzed by Polaris Energy Storage Network, the "black start" auxiliary service market in the Guangdong region is gradually emerging. Since January 2019, more than 160 power plants have paid black start compensation fees, and the average fee has gradually increased from more than 1,900 yuan in January 2019 to 25,400 yuan in December 2019. It can be seen that energy storage black start is gradually getting the attention of the country and society.

5.2 Energy Storage Configuration

Traditional energy storage configuration has advantages such as high-cost performance, fast response speed, etc. However, with the development of energy storage technology, the supercapacitor has strong advantages in terms of its relatively high power density, capacity, charge-discharge efficiency and service life, etc. It is an energy storage device combined with a traditional capacitor and battery [80]. At the same time, the reversibility of charging and discharging is good. It can charge and discharge hundreds of thousands of times, and the efficiency can reach 80%. Therefore, more and more scholars and research institutions pay attention to it, and it has been applied to a certain extent. It mainly stores electric energy directly based on the principle of a double electric layer and is an energy storage device between the conventional capacitor and battery [80]. Charge and discharge have good reversibility, can be repeatedly stored hundreds of thousands of times, and have energy storage efficiency of up to 70%∼80%. Its advantages are mainly reflected in the large capacity and small volume; Use of a wider range of temperatures; More secure and stable use [81]; And more rapid response [82]. In reference [83], the hybrid energy storage system proposed by battery and supercapacitor can be widely used in wind farms to suppress wind power fluctuations with the aid of the rational design of a two-layer control model and charge-discharge controller. The application of supercapacitors as energy storage in microgrids was introduced in detail in reference [84]. Reference [85] theoretically proved that hybrid energy storage can make full use of the complementary characteristics of battery and supercapacitor to improve the power output capacity of energy storage. Reference [86] proposed a new energy management method for the hybrid system of ultracapacitor and battery based on smooth control and traditional limit management. Thus, although the cost of supercapacitors is relatively high and the cost performance is not as high as that of traditional energy storage configuration, with further research, it is believed that supercapacitors can develop more and more mature.

5.3 Control Method

For coordinated control of multi-energy storage, in order to improve the unbalanced distribution of multi-energy storage power and ensure the balance of SOC of each energy storage, the existing methods mostly adopt the improved droop control strategy, which will affect the stability of the system. If the failure occurs, the system will not be controlled anymore. In addition, the premise of existing studies is that the SOC of energy storage does not exceed the limit, and most studies have not proposed a reasonable solution to the situation where the SOC of energy storage exceeds the limit. Once the power of an energy storage unit exceeds the charging and discharging power limit, the system power imbalance will be directly caused and the stability of the system will be destroyed. It will threaten the power balance of the system and destroy its stability of the system. Most studies have not given specific and reasonable countermeasures. In addition, once the energy storage power station that has stabilized the system voltage frequency stops working, the system stability will be directly reduced.

Most of the studies for energy storage system power allocation, often only consider the energy storage unit charged state, if you can according to the different status of the energy storage power station is given different control instruction, the more energy storage will fully coordinate control and power allocation method for wind the black start service, better implement system restoration after the blackout. In short, there is still much work to be done to address many of these issues.

6 Conclusion

This paper gives a brief overview of the new energy black start, mainly focusing on the feasibility assessment of the new energy black start, energy storage configuration, and control strategy. The main conclusions are as follows:

1) Due to the randomness of wind power generation and photovoltaic power generation, the output power of solar power generation system may not meet the problem of black start load, so the feasibility evaluation of new energy black start is very necessary for the design of black start scheme, and the location and configuration of energy storage power stations should be carefully calculated. For output reliability, the least square method can be used to build a prediction model to achieve the purpose of power prediction, to predict whether the future output of the power station can meet the needs of black start load.

2) New energy storage auxiliary black start, can help since the launch of black start power supply complete operating and maintaining the stability of the system voltage and frequency, the allocation of storage capacity, and optimize the energy storage capacity, consider one factor alone or separately based on a certain algorithm is one-sided sex, considered separately different conditions factors, the capacity allocation will have bigger difference. The optimal energy storage capacity configuration should be obtained by considering the reliability objective, economic objective, and utilization ratio.

3) The coordinated control strategy of multi-energy storage is expected to solve the problem of over-charging or over-discharging of some energy storage caused by disordered charging and discharging of single energy storage control, which leads to the shutdown of energy storage and power

imbalance of the system. However, the unbalanced distribution of multi-energy storage power should be solved to ensure the balance of SOC of each energy storage.

4) By improving the prediction accuracy of new energy, the output power of photovoltaic and wind power can be better controlled, to reduce the instability brought by the volatility and randomness of new energy power generation and improve the success rate of new energy black start-ups.

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