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Research progress and expectation of hybrid energy storage in new power system

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Abstract. With the increasing penetration rate of new energy in the power generation system, the uncertainty of its output brings great challenges to the stable operation of the power system. It is imperative to build an efficient and reliable energy storage system. Hybrid energy storage can satisfy the task of wave calming under the demand of multiple scenarios. This paper focuses on the hybrid energy storage system composed of a supercapacitor and lithium battery, mainly introduces its characteristics and topology, and discusses the key role in calming new energy fluctuations and peak cutting and valley filling. The internal power distribution strategy of hybrid energy storage is sorted out, and it is clear that the optimization goal should balance economy and reliability, and there should be corresponding optimization goals in different scenarios. It points out that a variety of topologies should be built in the future, and calls for the active application of new wide-band gap materials and multi-sided collaborative configuration combined with intelligent optimization algorithms to promote the more efficient and stable application of hybrid energy storage systems in the new power system.

Keywords: new energy, hybrid energy storage, power distribution, optimization strategy

1. Introduction

Nowadays, the human world is faced with two major problems: energy exhaustion and environmental pollution, and the traditional power generation mode is facing a great challenge. In this context, new energy power generation technology has gradually become the object of attention. By the end of August 2024, China's installed capacity for new energy power generation has reached 1.27 billion kilowatts [1]. It accounts for 40.7% of the country's total installed power generation capacity and is still growing. New energy power generation has the advantages of being pollution-free and renewable, but its randomness, intermittency and volatility make it difficult to connect to the grid. In a power system with a high penetration rate of new energy, the uncertainty of its output adds a lot of pressure to the frequency regulation and peak regulation of the power system. In order to reduce the abandonment of wind and light, achieve the maximum utilization of resources and meet its power demand at peak load, the system will be equipped with energy storage devices. The energy storage device can not only act as the output end to relieve the power shortage during the load peak, but also act as the consumption end to consume the new energy when the output is sufficient, reducing the waste of resources and ensuring the stability of the power system output. In this way, the volatility of new energy can be suppressed and the purpose of peak cutting and valley filling can be achieved.

This paper will take the hybrid energy storage represented by supercapacitor and lithium battery to sort out its research in the aspects of calming and peak-cutting and valley filling, power distribution, and capacity configuration. The following hybrid energy storage structures are composed of lithium batteries and supercapacitors. The purpose of this study is to promote the application of hybrid energy storage systems in the new power system more efficient and stable.

2. Overview of the composition and topology of hybrid energy storage

Energy storage devices can usually be divided into power type and energy type. Power type refers to large power density, fast response speed but less storage energy, suitable for instantaneous fluctuation adjustment of power grid, while energy type refers to large energy density, more storage power but slow response speed, suitable for long-term adjustment of the power grid fluctuations [2-3]. The technical parameters of supercapacitors and lithium-ion batteries for energy storage of power devices are shown in Table 1.

Table 1. Energy storage technical parameters of supercapacitors and lithium batteries [4-6]

Performance	Lithium-ion battery	Supercapacitors
Energy density /(W·h/kg)	100~200	4~10
Power density /(W/kg)	250~450	3,000~20,000
Life/year	5~20	—
Cycles/times	2,000~2,500	150,000~500,000
Charging time	30 min to 8 h	≤2 min
Continuous discharge time	30 min to 8 h	1 to 60 s

It can be seen from the chart that the two as a single energy storage device cannot cope with the output of multiple scenarios, and the combination of the two as a hybrid energy storage mode can achieve the characteristics of fast response speed and high energy density.

The topologies of the two are active, semi-active and passive. Because passive can not achieve power distribution and there are shortcomings such as slow response speed, it is not widely used in the field of new energy storage, and this paper will not be detailed. Figure 1 shows the structure diagram of the active energy storage structure connecting to the new energy power generation system. The active energy storage structure is that the lithium battery and the super capacitor are connected to a DC/DC converter in series. In this way, two energy storage devices with different terminal voltages can be connected and regulated respectively, making the energy distribution strategy of the system more flexible. According to the distribution strategy, the capacity configuration of the energy storage system can be further optimized to increase its utilization and reliability [7]. The semi-active structure is shown in Figures 2 and 3.

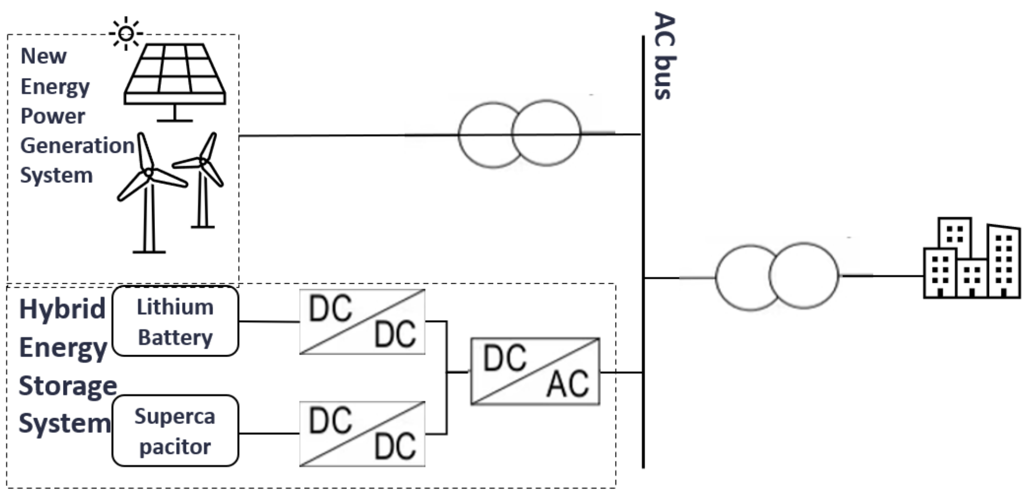

Figure 1. Active topology

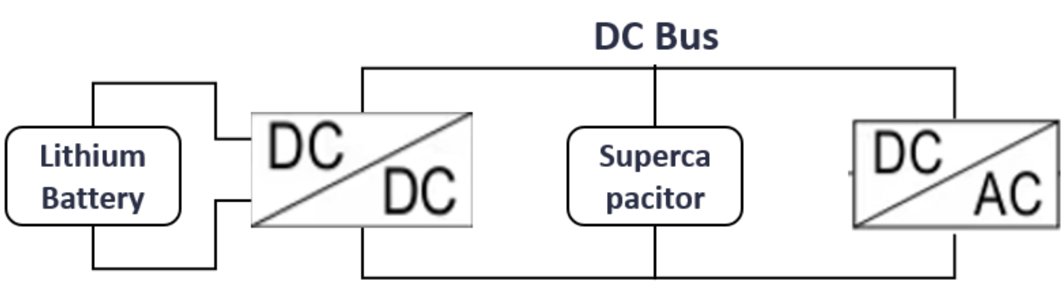

Figure 2. Semi-active topology of lithium battery through DC/DC parallel

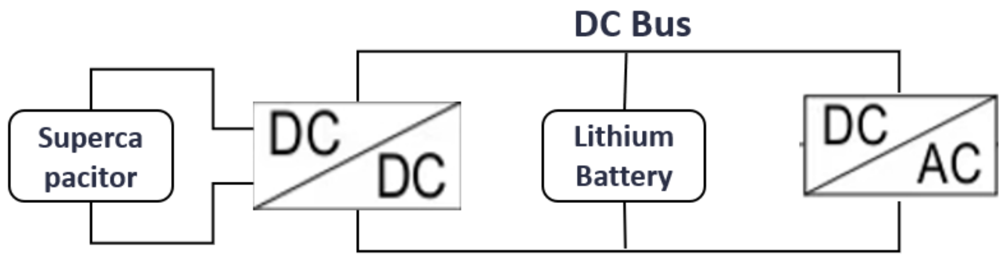

Figure 3. Semi-active topology of supercapacitors passing DC/DC in parallel

Figure 2 shows that the lithium battery is connected to the DC/DC converter, then the power of the lithium battery is controllable, and the service life of the lithium battery can be extended by adopting a reasonable power distribution strategy. The ultracapacitor is directly connected to the DC bus, which can quickly respond to voltage and power fluctuations of the bus [7-9]. Figure 3 shows the opposite positions of the two energy storage devices, which requires the DC/DC converter to have a fast response speed to avoid high-frequency fluctuations on the bus affecting the life of the lithium battery.

3. The key role of hybrid energy storage in calming and peak-cutting and valley filling

The production and use of electric energy are simultaneous. In the new energy power plant, because of its output uncontrollability, it often cannot meet the actual electricity demand, in the peak period electricity, it will cause an unreliable power supply, and in the valley. it will need to abandon the wind, adjust the light angle, and perform other operations, which reduces the energy utilization rate. Therefore, an energy storage device can also play the role of peak cutting and valley filling while carrying out the new energy power suppression and consumption. When the fluctuation of new energy output is greater than the grid-connected standard, the energy storage device can absorb the excess power or release the missing power to meet the grid-connected requirements. The relationship can be expressed as follows:

$$P_{hess} = P_{real} - P_{stand} \tag{1}$$

$$P_{hess} = P_{sc} + P_{bat} \tag{2}$$

P_{hess} represents the charge/discharge power of hybrid energy storage

P_{real} and P_{stand} denote actual renewable power output and grid-compliant reference value respectively

Positive P_{hess} indicates discharging mode, while negative values correspond to charging mode

P_{sc} and P_{bat} represent supercapacitor and lithium battery response power

For the smoothing of the new energy output, many scholars have carried out research on this. Based on the mode decomposition method, some scholars decompose wind power into a power sequence that meets grid-connected standards and a power sequence that requires hybrid energy storage impulse discharge [10]. The strategy combining double sliding window and particle swarm optimization is also used to smooth the wind power output. The two modes can not only ensure the system's ability to follow the sudden change of wind power, but also select an appropriate smoothing window when the wind power is relatively stable to maintain a better smoothing output effect [11]. Some scholars decompose the original signal by wavelet packet to obtain the high-frequency signal and the low-frequency signals, and then decompose the high-frequency signal and the low-frequency signal until the target requirement is reached. Finally, the high-frequency power fluctuation is allocated to the power storage element and the low-frequency power is allocated to the energy storage element [12].

4. Internal power distribution strategy of the energy storage system

After the completion of the new energy power suppression, the reasonable distribution of internal power of the hybrid energy storage system is crucial to improving the performance and reliability of the system. Different distribution strategies also have different requirements for the capacity and cost of the energy storage system. From the above table 1, it can be seen that the charge and discharge times and service life of lithium batteries are smaller than that of supercapacitors, and the response speed of supercapacitors is faster than that of lithium batteries. Therefore, based on its characteristics, the instantaneous fluctuation power of output can be allocated to the ultracapacitor. For the continuous increase or decrease of the fluctuating power, let the lithium battery bear. For the reasonable distribution of power, the low-pass filtering algorithm can be used to screen out the low-frequency component and distribute it to the lithium battery.

$$P_{bat} = \frac{1}{Ts+1} P_{hess} \tag{3}$$

$$P_{sc} = P_{hess} + P_{bat} \tag{4}$$

The algorithm is simple to use with only one-time variable T, and selecting an appropriate time constant T is crucial. The choice of time constant T determines the proportion of supercapacitors and lithium batteries in the energy storage load. The upper and lower bounds of time constant T are first determined based on the characteristics of these two energy storage devices. The golden section method is then applied to narrow down this interval, followed by the parabolic approximation method to obtain the optimal solution when the interval reaches the target range [13]. Considering the longer lifespan and lower cost of supercapacitors compared to lithium batteries, supercapacitors can independently smooth fluctuating power when sufficiently charged, though their energy density limitations must be considered.

Some scholars categorize fluctuating power into three components: spike fluctuations caused by instantaneous power surges, steady fluctuations showing gradual increases/decreases over time, and recurrent fluctuations requiring continuous charge/discharge cycles of energy storage devices [14]. The supercapacitor is designed to handle spike and recurrent fluctuations. For steady fluctuations, the lithium battery intervenes when voltage deviation occurs due to the supercapacitor's low energy density, ensuring the supercapacitor remains responsive to subsequent fluctuations. However, the uncertainty of renewable energy generation introduces additional complexity.

When the SOC parameter of the energy storage system approaches its upper limit, the charging capacity weakens while the discharging capacity strengthens. In such cases, sudden positive increases in P_{hess} cannot be absorbed. Conversely, when SOC approaches the lower limit, energy cannot be discharged to suppress negative P_{hess} increases. Addressing fluctuations under these boundary conditions may lead to battery overcharging/overdischarging and increased cycling frequency, significantly degrading battery lifespan. To prevent this, some strategies sacrifice grid-connection standards by maintaining battery SOC around 0.5 to preserve charge/discharge margins [15]. However, this approach underutilizes the supercapacitor's coordinating role and weakens the system's smoothing capability.

Alternative methods propose state-dependent regulation: during lithium battery charging, supercapacitors maintain high charge levels with lithium batteries dominating charging responses; during discharging, supercapacitors take priority while lithium batteries provide secondary support [16]. This operational logic reverses when lithium batteries enter discharge mode.

5. Optimization goal of hybrid energy storage system

Under the new form of power system, hybrid energy storage greatly helps the regulation and control of new energy power. In order to smooth the output and meet the power supply demand, the cost of the capacity configuration of the energy storage system is also important. As the output end of the power supply system, the higher the capacity configuration, the stronger the reliability and stability of the power supply system. But the size of capacity and economy are mutually exclusive relationships. Therefore, it is necessary to strike a balance between economy and reliability. The chance constraint is more flexible than the rigid constraint of traditional optimization methods. In other words, by violating constraint conditions with a small probability, great harm caused by certain events can be avoided [17]. However, this probability should be limited to maintaining a certain range. The improved adaptive moving average filtering algorithm is adopted to prevent the over-flattening phenomenon in other periods caused by increasing the sliding window due to high-power fluctuations at several moments [18]. While completing the grid-connection requirements, the tracking ability of the wind power generation plan is maintained, which reduces the energy storage burden. These methods make the actual capacity allocation more practical to a certain extent, but only take into account the inherent cost once. Applying the DRO algorithm to energy storage capacity allocation, a model is constructed with curtailment rate as the constraint and minimum investment cost as the goal, and it is finally concluded that this model can be both robust and conservative [19].

For the cost problem, only wind curtailment is taken into consideration. In maintaining the operation of the power system, the cost is not only composed of the energy configuration of the energy storage system, but also includes the operation and maintenance cost and the compensation cost when the energy storage system cannot meet the task of energy storage power when the power fluctuation is large [20]. Some scholars comprehensively consider the influencing factors to construct a set of evaluation indicators for the effect of energy storage configuration: the change of grid-connected wind power, reflecting the change before and after the fluctuation is stabilized; Coefficient of determination, which represents the ability to track the original power generation plan; Charge and discharge time, reflecting the degree of internal heat accumulation; The number of switching of charging and discharging state reflects the degree of aging; Energy storage throughput, representing the price paid to achieve suppression; Energy storage configuration cost represents the economy of the configuration scheme [21]. This evaluation index can reflect the calming ability of the energy storage system and the ability to follow the original wind power, and also take into account the operation and maintenance cost and compensation cost. A hybrid energy storage system can be considered comprehensively and comprehensively.

Considering the optimal configuration on the time scale can also improve the economy of the energy storage system. The power fluctuation in the future will affect the current charging and discharging behavior and the calming ability in the future. Therefore, by predicting the power fluctuation in the future, the output can be adjusted in advance according to the SOC state of the energy storage system and the future charging and discharging demand [22]. An article proposes that by comparing the first-order filter algorithm with the model predictive control algorithm, it can be concluded that the former requires a larger energy storage capacity to meet the grid-connected requirements [23]. In order to eliminate the delay of low-pass filtering, some scholars use short-time power prediction technology to carry out low-pass filtering on the predicted power, and take the filtering result as the target value to smooth the fluctuation [24].

6. Conclusion

The topology mentioned in this paper should be flexibly constructed according to multiple scenarios and different emphases to achieve the target requirements. The electronic devices used in the topology should keep up with the third-generation wide band gap semiconductors represented by Gallium Nitride (GaN) and Silicon Carbide (SiC). For the energy storage system to bring high frequency, high efficiency of excellent characteristics

For grid-connected demand and internal power distribution, not only the calming effect should be considered, but also the SOC parameters of the energy storage system should be fully combined to maintain the ability to follow the original power generation. Comprehensively consider the capacity allocation problem of the energy storage system, and use the multi-objective particle swarm optimization algorithm, genetic algorithm and other emerging intelligent optimization algorithms to achieve the coordination of multiple mutually limited objectives.

The research in this paper is mainly a summary of the simulation model and theoretical research of the supercapacitor and lithium battery, and the discussion of the form of monotone can further explore the collaborative configuration of hydrogen energy storage and compressed air energy storage and other forms, so as to achieve interdisciplinary technology integration. The coping strategy and energy allocation of the output system in extreme weather are not considered, and the research can be carried out on emergency measures.

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