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Review

Review on the Optimal Configuration of Distributed Energy Storage

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Abstract: With the large-scale access of renewable energy, the randomness, fluctuation and intermittency of renewable energy have great influence on the stable operation of a power system. Energy storage is considered to be an important flexible resource to enhance the flexibility of the power grid, absorb a high proportion of new energy and satisfy the dynamic balance between the supply and demand of a system. At present, the cost of energy storage is still high, and how to achieve the optimal energy storage configuration is the primary problem to be solved. Therefore, the current research progress in energy storage application scenarios, modeling method and optimal configuration strategies on the power generation side, grid side and user side are summarized in this paper. On this basis, the shortcomings that still exist of energy storage configuration research are summarized, and the future research direction for energy storage configuration is prospected. This review can provide reference for the latest development and future research and innovation direction for energy storage configuration.

Keywords: renewable energy; energy storage; optimal configuration; latest research status; future research direction

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Citation: Liu, Z.; Su, T.; Quan, Z.; Wu, Q.; Wang, Y. Review on the Optimal Configuration of Distributed Energy Storage. *Energies* **2023**, *16*, 5426. https://doi.org/10.3390/en16145426

Academic Editor: Ahmed Abu-Siada

Received: 23 June 2023
Revised: 12 July 2023
Accepted: 14 July 2023
Published: 17 July 2023

1. Introduction

With the great efforts to combat climate change and a growing consensus for low-carbon energy, more and more countries are actively introducing policies and measurements to promote the development of renewable energy. This renewable energy industry with wind and photovoltaic power generation as major growth drivers is growing rapidly, playing an important role in satisfying the energy demand, improving the energy structure, reducing environmental pollution and promoting economic development [1,2]. However, with the increasing permeability of renewable energy in the modern power system, the inevitable and strong intermittency, volatility and randomness of renewable energy require higher requirements on safe, stable, reliable, efficient and economical operation for a power system [3,4].

To properly address these challenges, energy storage is increasingly seen as an ideal technical and economic solution. Generally, distributed energy storage is equivalent to load and power through charge and discharge, enabling scheduling of electric energy in time and space [5]. Distributed energy storage with the characteristics of fast response, easy control and bidirectional regulation is becoming an important part of improving the flexibility of a power system, absorbing a high proportion of renewable energy and satisfying the dynamic balance between supply and demand of a power system [6,7]. Moreover, distributed energy storage is also a solution to the costly infrastructure construction of delayed power systems, and it plays a key role in improving energy efficiency and reducing carbon emissions, gradually becoming an important mainstay for the development of distributed generation, smart grid and microgrid [8–10]. Therefore, it is clear that distributed energy storage has become an indispensable part of all aspects of a power system, as shown in Figure 1.

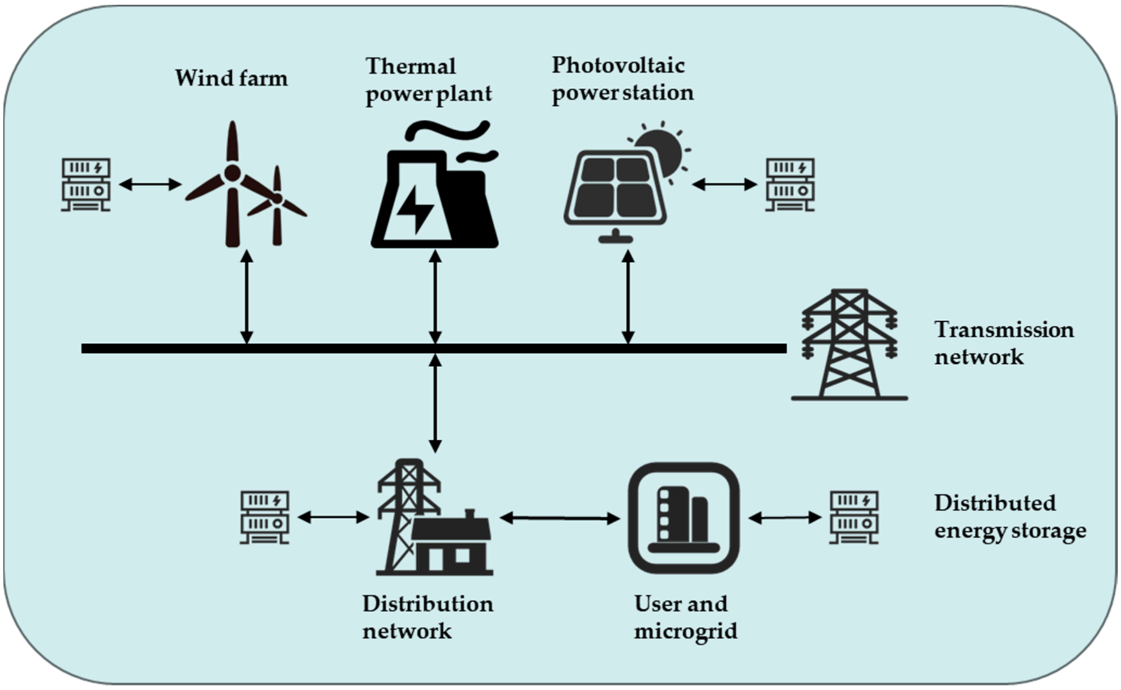

Figure 1. A power system with distributed energy storage.

However, there are still some problems in distributed energy storage while improving the connectivity of renewable energy grids and improving the stability and economy of a power system operation. Energy storage is usually too decentralized to be controlled, and it is difficult to coordinate with conventional devices and complicated to smoothly switch its control strategies. As an important early stage of energy storage application research, the study of optimal configuration of distributed energy storage in different application scenarios is crucial to its efficient and economical application in power systems. The rational planning of an energy storage system can realize full utilization of energy and reduce the reserve capacity of a distribution network, bringing the large-scale convergence effect of distributed energy storage and improving the power supply security and operation efficiency of a renewable energy power system [11–13]. The key issues in the optimal configuration of distributed energy storage are the selection of location, capacity allocation and operation strategy. On this basis, the corresponding optimization objective and configuration algorithm are generally selected according to the requirements of different application scenarios, comprehensively considering both the economic and technical indicators [14,15]. At present, the cost of energy storage is still high, and how to achieve optimal energy storage configuration is the primary problem to be solved. However, considering technical performance and economic performance comprehensively, the research summary and prospect of the optimization method of an energy storage system configuration to achieve a self-balancing ability of the power system through energy storage optimization configuration are still incomplete.

The rest of this paper is organized as follows: the development status and application of distributed energy storage technology for the DG side, grid side and user side are briefly reviewed, the various application scenarios of distributed energy storage in a power system are summarized in Section 2, and the application and development direction of current mainstream technologies are analyzed. On this basis, modeling methods and solving algorithms of energy storage optimization configuration are compared and analyzed in Section 3. Finally, in Section 4, the main contents of this paper are summarized.

2. Application Status of Distributed Energy Storage

With energy storage technology advances, cost reduction and demand side evolving, the widespread application of distributed energy storage in a power system is an inevitable trend in the future power grid and also an important path to break through traditional distribution network planning and operation patterns. Distributed energy storage typically has a power range of kilowatts to megawatts; a short, continuous discharge time; and flexible installation locations compared to centralized energy storage, reducing the line losses and investment pressure of centralized energy storage power stations [16]. Currently, the forms of distributed energy storage are diverse, including energy storage for a new energy power plant, community, electric vehicle, data center, home, mobile, etc. In general, their forms can be classified into electrochemical and physical storage, and various distributed energy storage technologies have been developed with the goal of increasing conversion efficiency, increasing power and energy density and reducing costs. There are substantial developments and progress in energy storage, with cost reduction achieved in electrochemical energy storage, material improvement in physical energy storage and new energy storage technologies updates. From the perspective of the whole-application scale of energy storage, physical energy storage technology is mature in modern energy storage technology, with the largest scale, while electrochemical energy storage technology is the most widely used and has the best development prospects, which is the core content of future global energy storage development [17–19]. With the continuous updating of energy storage technology, the application of energy storage in various aspects of the power system has reached a mature stage of development, with commercial demonstration projects around the world.

Distributed energy storage has corresponding application scenarios in all aspects of the power system, which can effectively eliminate a peak–valley difference, enhance equipment utilization efficiency, promote new energy consumption, regulate voltage and frequency, smooth new energy power fluctuation and participate in demand-side response, etc. [20]. Its main objectives are to support DG grid connectivity, increase the level of DG consumption in load centers and maintain the safe and stable operation of the smart grid and microgrid. In China, energy storage has been used as an important technical support in integrated energy demonstration projects. In the case of PV-storage systems, user-side PV-storage systems are growing rapidly, with massive government subsidies during the early rollout period. In addition, grid-side energy storage continues to evolve from the operational mode, function localization and investment discipline, and gradually matures. Nowadays, a number of battery-energy-storage power stations have been built around the world, as presented in Table 1. From these projects, the key to further development of energy storage technology is how to summarize the experience and make new breakthroughs.

Table 1. Typical MW-level battery-energy-storage power station.

Project	Battery Type	Scale	Application Function
Zhangbei wind–solar energy storage demonstration project in China	Lithium-ion battery	14 MW × 4.5 h	Smooth output fluctuation and correct prediction error
Jiangsu Zhenjiang energy storage power station project in China	Lithium-ion battery	101 MW/202 MW·h	Peak regulation, frequency modulation and emergency power support
Hawaii wind energy storage project in the United States	Lead–acid battery	15 MW/10 MW·h	Frequency modulation and output climb control of wind farm
Primus energy storage power plant project in the United States	Zinc oxide flow battery	25 MW × 3 h	Peak cutting and valley filling for wind farm and photovoltaic power station
Angamos battery energy storage station in Chile	Lithium-ion battery	20 MW × 0.33 h	Frequency modulation and backup power
Sendai substation battery pilot project in Japan	Lithium-ion battery	40 MW/200 MW·h	Improve the power quality of renewable energy

Therefore, different energy storage technologies have different applications and respective roles in various application scenarios. Rational allocation of energy storage in different application scenarios can maximize its technical role, and it is also the most efficient and economical solution. The running state of distributed energy storage is closely related to its application scenario, and current research on the application scenario is mostly combined with optimal configuration modeling of energy storage. The application scenarios of energy storage are distinguished based on environmental conditions, output characteristics of energy storage and configuration methods [21]. However, in this mode, it is difficult to form a systematic understanding of the energy storage configuration of a new power system. Actually, according to the different access locations of energy storage in the power system, the corresponding power levels and application functions are often different, and the selection of location, capacity and operation strategy for optimal configuration of energy storage also needs to be adapted to local conditions. Therefore, according to the access position of distributed energy storage in the power system, this paper mainly divides its application scenarios into the DG side, the grid side and the user side, as shown in Figure 2, and the following contents of this section will analyze the application scenarios of distributed energy storage from the above three perspectives.

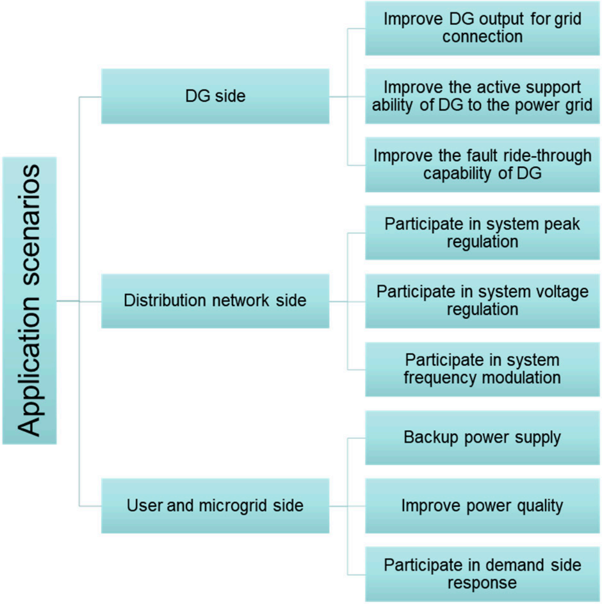

Figure 2. Application scenarios of distributed energy storage on each side of the power system.

2.1. DG Side

2.1.1. Improve DG Output for Grid Connection

Most of the demand for energy storage technology on the new energy side comes from the relevant management regulations, such as the grid-connected operation regulations of new energy power stations and the safety and stability guidelines of power systems [22,23]. The allocation of energy storage based on new energy power stations or bases is the main application scenario to facilitate the consumption of new energy connected to the grid at the DG side. The friendliness of new energy connected to the grid is improved mainly through applications that stabilize the output fluctuations of the new energy, compensate the power prediction errors and reduce the power abandonment rate. By integrating the energy storage characteristics with the self-regulating characteristics of DG, distributed energy storage and DG constitute a set of devices for grid connection, which can restrain the power fluctuation of DG, reduce the impact of DG on the distribution network, improve the controllability and grid-connection ability of DG from the source and also realize the tracking of a production plan. The basic principle of this application mode is that the distributed energy storage must track the output of DG. During the peak or trough period of DG output power, the energy storage stores or releases the electric energy respectively to meet the requirements related to power fluctuation of the connecting point, and the power incorporated into the grid is the sum of DG output and energy storage power [24].

A large number of scholars have carried out research on energy storage configuration to smooth out output fluctuation of new energy power stations, and they proposed to analyze historical data by discrete Fourier transform, first-order low-pass filtering, Kalman filtering and other algorithms, and calculate energy storage capacity combined with technical indicators such as output fluctuation rate, fluctuation frequency band and climbing ability [25–29]. On this basis, some scholars began to comprehensively consider the new energy fluctuation stabilization effect and power prediction error compensation and adopted a multidimensional analysis method to carry out energy storage capacity optimization allocation [30–32]. In addition to technical indicators, economic factors are also gradually taken into consideration in the optimization of multi-objective energy storage allocation. Considering battery energy storage, the economic analysis models are established based on the life loss of energy storage system, the whole life cycle cost and the annual comprehensive cost of energy storage [33–37]. However, different from the relatively fixed service life of conventional power equipment, the service life of battery energy storage is closely related to its charging and discharging depth, frequency and other working conditions. Therefore, when the energy storage scheme is configured, some scholars begin to consider the investment evaluation of energy storage within the whole life cycle, based on the probability and statistical results of charging and discharging depth and charging and discharging frequency of energy storage under specific application conditions [38]. In addition, it is also a relatively new research direction to take into account the multiple cost composition, such as the power abandonment cost of new energy, or to improve the economy of energy storage investment by hybrid energy storage [39–42].

However, in terms of distributed energy storage to improve the power output of DG, the energy storage capacity utilization rate obtained by existing studies is low, and most of the energy storage models are simplified, which is quite different from the reality. Therefore, further research should be carried out on the real-time management of distributed energy storage and the improvement of ultra-short-term prediction accuracy. Moreover, when designing the smooth power fluctuation control algorithm, the correlation between distributed energy storage characteristic parameters should be considered to establish a more scientific large-scale grid-connected model of DG and energy storage, so as to better improve the power output of DG and prolong the energy storage life.

2.1.2. Improve the Active Support Ability of DG for a Power Grid

With the increasing proportion of new energy units with low inertia and weak support in the power grid, the moment of inertia of a power system is greatly reduced, and the supporting and adjusting abilities of key operation indicators are gradually decreased, which means that the safe and stable operation of the system faces great risks. Domestic and foreign scholars use capacity credit to evaluate DG's contribution to system capacity sufficiency, and rational configuration of an energy storage device in DG can effectively increase its capacity credit and enhance its ability to support the capacity margin of a power system [43,44]. Some scholars determine the capacity configuration of energy storage by setting credit level according to the historical output power data of DG, while some others analyzed the effect of improving the capacity credit of DG by adjusting the capacity configuration of energy storage through a posteriori capacity credit evaluation method, so as to find a reasonable energy storage configuration scheme [45–47]. In addition, many scholars have carried out research on the energy storage capacity configuration involved in system inertia support, mainly optimizing the energy storage capacity configuration based on the system frequency response model [48–50]. Some scholars have also proposed a method to configure energy storage according to the ideal dynamic frequency characteristics of the system, such as the inertia coefficient and sagging coefficient [51,52]. The study of energy storage systems in terms of enhancing the active support capability of DG focused on improving capacity credits and participation in inertia support and frequency modulation.

However, most of these studies only focus on DG itself and do not consider the tracking grid scheduling problem, so the active support ability to the power grid is still limited. Besides, since energy storage is not the only means to achieve the active support capacity of DG, the technical effects and economy are still important factors to consider in energy storage configuration.

2.1.3. Improve the Fault Ride-through Capability of DG

The DG provides active support for the power grid, and it is also inevitably affected by the impact of grid-side faults, which brings challenges to the grid-connected operation of DG. The energy storage system as a fault ride-through technology on the DG side often uses SCES or SMES to take advantage of its high power density and fast discharge characteristics. During normal operation, energy storage is used to smooth the power fluctuations of the DG. When a fault occurs in the grid, it is then used to store the power generated by the DG and help to ride through the fault by providing suitable active and reactive power [53]. The supercapacitor energy storage system can maintain the voltage of the DC bus power to achieve LVRT, without affecting the efficiency of the photovoltaic system, but also by sending active power during faults to support the grid [54]. Some scholars have proposed a hybrid energy storage system based on SMES-battery, which can respond more quickly to transient faults, effectively reduce fault current to avoid off-grid and reduce AC power loss [55]. For energy storage configuration, some scholars analyzed the feasibility of an energy storage system configuration based on power constraints and the use of optimization algorithms, aiming at the power and capacity required to configure the energy storage system during the fault period [56,57].

However, although the flexibility of energy storage allows it to improve the desired performance for fault ride-through on the DG side, it requires complex control systems, high investment and maintenance costs, which makes it still not mature for commercial applications. Therefore, it is theoretical and applied value to determine how to find the balance between flexibility and simplicity of energy storage control strategies, and take into account the requirements of technical specifications and investment costs, which are key to the development of energy storage as a fault ride-through technology on DG side.

2.2. Grid Side

2.2.1. Participate in System Peak Regulation

Since the output peak of DG does not coincide with the load peak, the load peak–valley difference increases from year to year, but at the same time, the user's demand for electricity supply reliability gradually increases. When the high-permeability DG is connected to the distribution network, the excess electric energy often cannot be absorbed in time, and some of the DG can only abandon the operation mode of unit power factor or even shut down, which results in serious resource waste such as light abandonment and wind abandonment. By making use of the time–space translation characteristics of an energy storage system to participate in peak regulation, this enables cutting the peak and filling the valley of the load curve, which can effectively optimize the power flow distribution of the distribution network, reduce network loss, alleviate power congestion and slow down the upgrade of transmission and distribution facilities. At present, the commonly used optimization strategy of peak cutting and valley filling is to control load variance [58,59]. Besides, to enable distributed energy storage to better participate in the peak regulation of a system, factors such as the seasonal characteristics, load curve and peak regulation demand of the DG should be considered in modeling, and the appropriate charging and discharging strategies should be adopted to rationally distribute the location and capacity of energy storage units [60,61]. Based on the relationship between capacity and the confidence in meeting demand, some scholars have proposed an exact method to determine the system's energy storage capacity demand. For a power system with high penetration of DG, this clarifies the need for energy storage capacity to improve its peak regulation capability [62].

However, most of the existing research on peak regulation of energy storage participating systems comes from energy storage technology and rarely involves the evaluation model of a peak regulation benefit. To enhance the practicability of energy storage at this stage, it is necessary to investigate how the distributed energy storage can be better combined with the existing peak regulation approaches and also further refine the evaluation models of peak regulation benefits and energy storage capacity demand.

2.2.2. Participate in System Voltage Regulation

When a large number of DG are connected to the power grid, the power flow distribution of the system changes. Meanwhile, due to the uncertainty of DG output, the voltage of some nodes will exceed the limit, which may lead to voltage collapse in severe cases. The coupling degree of active power and voltage in a distribution network is very high, so the influence of this kind of problem on a distribution network is prominent with a domestic distribution network starting late and the regulation capacity of a traditional voltage regulator being limited. The rise of distributed energy storage has gradually become one of the important means of voltage regulation in a distribution network. Energy storage participating in a voltage regulation system can make up for traditional voltage regulation equipment limited by the number of operations and slow response and other problems, which can effectively improve the voltage level of the system. At present, it is the most economical and flexible means to coordinate voltage control with DG and energy storage by fully combining existing reactive compensation equipment, such as an on-load regulating transformer and static reactive compensation device in the network. Traditional voltage regulating equipment is usually used as the main control means, and distributed energy storage and DG with a regulating ability are used as auxiliary measures to relieve the pressure of traditional voltage regulating means and realize voltage regulation of local and other key nodes [63–65].

In terms of coordinated control, voltage control strategies can be formulated according to different time or space scales [66,67]. Since the operation time of different voltage regulation equipment is not consistent, the voltage control strategy is divided into three different coordination optimization modes according to the division principle of the time scale: day-ahead optimization, intraday optimization. In addition, the voltage control strategy can be divided according to different regions where the voltage regulator is located or different feeder branches from the spatial scale. To improve the ability of energy storage in participating in the voltage regulation of a system with large-scale grid-connected DG, it is necessary to further study the problems of layered and zonated automatic voltage regulation control, voltage coordination control between an energy storage system and other reactive power compensation equipment, and smooth switching among control strategies.

2.2.3. Participate in System Frequency Modulation

Distributed energy storage has the characteristics of fast power regulation and high-control precision. In order to ease the frequency modulation pressure of the system, distributed energy storage can be used to assist in frequency modulation of the distribution network. With the further increase of DG permeability, this frequency modulation mode will become an important mode of power frequency modulation [68]. For example, the cooperative frequency modulation mode of thermal power and energy storage has been gradually commercialized, effectively solving the problems of slow climb rate and low adjustment accuracy of thermal power units. In order to improve the frequency modulation ability of DG and prevent the DG from being off-grid due to the unstable system frequency caused by load changes, there are also studies that fully consider the energy storage regulation ability and construct the control strategy of the optimal storage and the wind storage participating in the system frequency modulation [69,70]. For example, the frequency modulation coefficient calculation method is proposed considering the regulation dead zone in the frequency modulation model, so as to optimize the frequency modulation strategy [71]. In terms of the participation of energy storage in AGC, some scholars have established corresponding economic models, including the life and capacity of energy storage, and formulated control methods to help the system to perform frequency modulation, that meet the economic requirements of energy storage while improving the regulation ability of AGC [72].

However, the existing studies have not analyzed the mechanism of large-scale DG affecting the frequency fluctuation characteristics of a power grid or reflected on the potential advantages of an energy storage participation system over traditional frequency modulation power plants from a theoretical level. Therefore, it is necessary to further study the coordination control strategy among various types of energy storage and also between the energy storage and traditional frequency modulation power plants.

2.3. User and Microgrid Side

The forms of load on the user and microgrid side are very diverse, and distributed energy storage with flexibility and distribution plays a variety of roles in this side, as shown in Figure 3. Distributed energy storage connected to industrial and commercial users can improve power quality, increase the permeability of new energy, act as an emergency backup power supply, respond to various disturbances and ensure the safety and stability of power supply for power users. Besides, energy storage is the key to improving the characteristics of microgrid power supply and ensuring the quality of power supply. In microgrid, distributed energy storage can also realize such functions as new energy self-use; reduce electricity cost and local consumption of electric energy; reduce transmission line losses; reduce capacity expansion costs; enhance the disaster resistance of the network as a backup power supply and black start power supply; and supply power to remote areas without power, military bases and other special places [73].

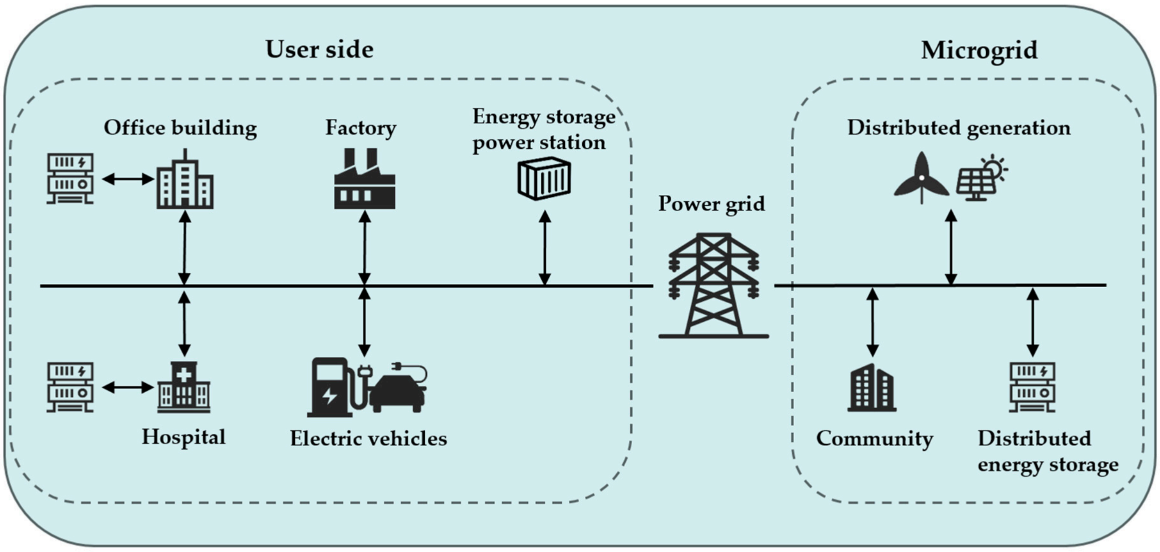

Figure 3. The application of distributed energy storage on the user and microgrid side.

2.3.1. Backup Power Supply

With the development of the social economy and the diversification of public activities, on-site electricity preservation has become a special task of the power sector, and the demand is increasing day by day. Mobile energy storage using electrochemical energy storage is widely used in the backup power mode due to its advantages such as fast response, easy installation, free from regional restrictions and low pollution [74]. Moreover, electrochemical energy storage can realize a millisecond response, and the response time from no load to full load is only a second. When dealing with natural disasters, seasonal loads and other problems, mobile energy storage can be used as a quick backup power supply to the load to avoid major losses caused by power outage. This application mode has been applied in important load users, especially in medicine, advanced electronic manufacturing, data centers, chemical fiber production and other industries, with obvious benefits [75]. In order to minimize load loss during a power outage and guarantee production, life safety and economic property, the joint operation method of mobile energy storage, distributed energy storage resource aggregation technology and post-disaster recovery strategy using mobile energy storage have become new mainstream research directions [76,77]. This also reflects the demand of the current new power system to improve the resilience of the distribution network, that is, the ability to prevent and recover from extreme events.

However, with the advancement of marketization, distributed energy storage belongs to different entities. The traditional analysis methods such as robust and random are difficult to achieve for the distribution of interests among different entities. Therefore, it is necessary to carry out research on the emergency linkage of distributed energy storage and a distribution system under extreme events, and explore the emergency linkage mechanism and multi-agent benefit distribution method, thus providing theoretical support for resiliency improvement of a distribution network.

2.3.2. Improve Power Quality

Due to the application of a large number of power electronic devices in a microgrid, problems such as voltage sag, waveform distortion, high harmonic injection and low power factor will inevitably occur during its operation [78]. The quality of power supply can be significantly improved by installing energy storage on the user and microgrid side. At the same time, energy storage with a fast response speed can smooth the transition of a microgrid in the process of switching operation modes, reduce the transient impact, and maintain voltage stability in the isolated island operation mode, in which the seamless switching control of the microgrid operation state is the difficulty [79]. In the context of the demand for the development of a smart grid, electric vehicles, smart building microgrid and other emerging industries, models will develop rapidly in the future. In order to reduce the influence of new industry development on power supply quality, the flexibility of an energy storage system and electric vehicles can be used to smooth the power fluctuation of a building's microgrid connection line, or the interconnection technology of a vehicle and grid can be used to realize the two-way interaction between electric vehicles and the power grid, so as to save charging costs, reduce power supply pressure of the grid and improve power supply quality [80,81]. Microgrids are highlighted as the technology that can help in providing sustainable and efficient electrical energy solutions. They employ distributed energy resources to efficiently supply local load and increase the reliability of the local network. At the same time, a microgrid is fragile and easy to receive external impact, so there are multiple types of potential problems in power quality [82].

However, the existing research basically proposes corresponding strategies for a single specific problem, and future research should focus on integrated power quality management technology. Besides, the improvement of a grid-connected inverter, power quality regulator topology and control mode should be concerned, and the goal of overall management of various power quality of a microgrid needs to be ultimately achieved.

2.3.3. Participate in the Demand-Side Response

As an important part of a microgrid, demand-side resources can improve the economy of energy storage configuration and increase the benefits of a microgrid by participating in the response of a microgrid reasonably. Distributed energy storage can actively respond to a power grid dispatching during peak load hours, relieve the power grid peak power supply pressure, ensure the supply and demand balance between the power grid source and load to obtain subsidies, and protect the safety and stability of the power system operation [83,84]. User-side energy storage can be charged and discharged in an orderly manner according to the difference of electricity price at different times of the day, so as to gain profits from the price difference. In order to improve the marketization benefits under this mode, relevant studies analyzed the potential benefits of distributed energy storage in various aspects from exploring the rational income mode of user-side energy storage [85,86]. In this application mode, energy storage is generally used as a demand-side response resource to participate in the capacity market. Charging and discharging strategies of energy storage are formulated according to real-time electricity prices, and energy storage power and capacity are determined according to the maximization of economic benefits. On this basis, some scholars innovatively proposed generalized demand-side resources combining the demand response with an energy storage system and constructed a configuration model to obtain scheduling plans [87]. Not only can this kind of research provide a new approach for the formulation of incentive contracts, but they can also play an applicable role in the actual planning and operation of distribution networks in the future.

However, distributed energy storage has the characteristics of scattered spatial distribution and small capacity, so it is difficult to be directly used as a dispatching resource in a power grid. In order to cope with the future participation of a large number of energy storage systems in the power market, the research should focus on the aggregated management of distributed energy storage, the way to participate in peak scheduling and the exploration of demand-side energy storage to participate in power grid operation.

3. Optimal Configuration of Distributed Energy Storage

As mentioned above, distributed energy storage has its corresponding application scenarios in each part of a power system, including source, network and load. In different application scenarios, the capacity determination, location selection and coordinated operation of energy storage have different technical indicators or economic considerations. Therefore, the optimal configuration of distributed energy storage is essentially a multi-objective optimization problem. According to the requirements of different application scenarios of energy storage, appropriate objective functions are selected, the operating characteristics of the system and energy storage are taken as constraints and appropriate algorithms are selected to solve the mathematical model. How to ensure the engineering applicability of energy storage configuration results is a complex problem covering multiple time scales, multiple objectives and multiple constraints. Therefore, the following contents in this section will classify and analyze the configuration model and solving algorithm of energy storage optimal configuration, as shown in Figure 4.

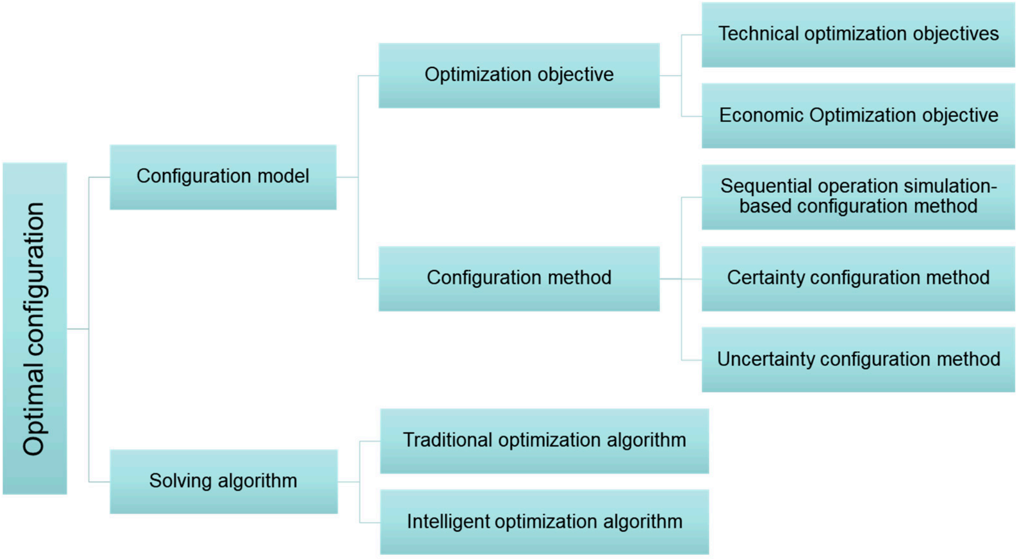

Figure 4. Configuration model and solving algorithm of the energy storage optimal configuration.

3.1. Configuration Model

3.1.1. Optimization Objective

First of all, it is necessary to sort out and summarize the main optimization objectives in each application scenario. The optimization objectives of the power-supply side mainly consider the power comprehensive quality and fluctuation indexes, such as the minimum wind and light discard rate, the ability to smooth the output power of DG, the generation efficiency, the grid-connected voltage quality, the minimum prediction error, etc. [88]. On the power-grid side, technical and economic indicators are mainly considered comprehensively, such as the capacity of peak regulation, voltage regulation and frequency regulation, the process of power grid upgrading and transformation, environmental benefits, the degree of network congestion, network loss, the degree of new energy consumption, etc. [89]. On the user and microgrid side, the main consideration is to improve power quality while making profits for users, which is to mainly control power fluctuation of the link line, reduce electricity cost, improve power supply reliability and participate in the demand-side response [90]. In addition, in order to reduce the number of traditional energy storage configurations and give play to the energy storage characteristics of demand-side resources, some scholars have built a generalized energy storage capacity configuration model based on electric vehicles and demand-side flexible loads that can be reduced or transferred [91]. On this basis, joint planning of distributed power supply and generalized energy storage can be carried out. Based on the operation characteristics of generalized energy storage, the regulation ability of flexible load can be fully explored, and combined with demand-side response, a comprehensive model of power grid operation and energy storage capacity determination and location selection can be built.

However, the existing energy storage configuration methods cannot effectively balance technical and economic indicators, especially for comprehensive optimization considering the power source, grid, load and storage links, and the demand constraints for energy storage configuration under multiple operation scenarios have not been established yet. In addition, existing research on energy storage configuration optimization focuses on a single objective, which cannot effectively take into account technical and economic requirements; thus, the multi-objective optimization and the overall improvement of an energy storage system cannot be achieved. Therefore, it is of great theoretical and engineering significance to construct a multi-objective optimization method of energy storage configuration that comprehensively considers technology and economy for efficient utilization and performance improvement of energy storage in new power systems.

In a comprehensive optimization configuration, multiple objectives often restrict each other, so some scholars choose to distinguish the primary goal and secondary goal and try to optimize the overall objective function under this premise. In order to simplify the calculation process of multi-objective problems, the existing research mostly adopts the linear weighting method or selects one of the multiple objective functions for optimization, and the rest of the objectives are converted into constraints by adding limits. Finally, after simplification, it is still similar to the single-objective optimization to some extent [92]. Thus, this kind of method has some shortcomings, such as the boundary between single objective weight and objective function being difficult to determine, the dimensional disunity between each objective may lead to poor robustness and so on. Therefore, further research on optimization objectives can mainly consider putting forward new technical and economic indicators for the operation mechanism and operation mode of a new power system, as well as improving the multi-objective algorithm in the aspects of a multi-objective number, high dimension and dynamic optimization.

3.1.2. Configuration Method

With the application of energy storage devices becoming more and more extensive, a variety of planning theories and methods have been applied to energy storage configuration in various application scenarios. Currently, the mainstream energy storage configuration methods can be divided into the sequential operation simulation-based configuration method, certainty configuration method and uncertainty configuration method.

The configuration method based on sequential operation simulation is mainly used for single-objective configuration in pursuit of technical objectives. In this method, the historical operation data of the application target should be obtained at first. In addition, according to the different optimization objectives of the energy storage, for example, the prediction data of the corresponding time period should be required to compensate the prediction error as the objective, so as to clarify the technical indicators of the combined output of the optimization target and the energy storage, and formulate the charge and discharge control strategy of the energy storage system. Under the constraint conditions such as charging and discharging efficiency, SOC operating range and power balance, the temporal power demand data of the energy storage system are calculated by simulation. After considering confidence intervals or weighing energy storage investment and application effect, the rated power and capacity of the energy storage system are calculated based on the temporal power demand data samples [84–86].

The application of certainty allocation method is based on the certainty assumption of data samples. Based on the historical operation data and scheduling data of typical periods, etc., and the rated power, rated capacity and access location of energy storage, devices are taken as decision variables to establish a technical or joint technological and economic optimization model. Then, the appropriate intelligent solution algorithm to calculate the energy storage optimal configuration scheme is selected [69,70].

The uncertain allocation method is mainly based on uncertain programming theory, including stochastic programming, fuzzy programming, robust optimization, etc. Guided by these theories, a number of specific analytical methods have been developed for energy storage configurations. The scenario analysis method is to transform the probability distribution model of continuous random variables into a set of discrete scenarios, approximate the distribution of original random variables with as few scenarios as possible and solve the original problem under each scenario, so as to transform the stochastic optimization problem into a deterministic optimization problem [31,52,79]. Based on the robust optimization theory, uncertainty can be depicted through the deterministic variation of problem parameters or solutions, and the uncertain scenario set of a model input can be constructed, so as to seek the solution immune to uncertainty, that is, the optimal solution in the system fluctuation [32,39,64]. On the basis of obtaining a large number of data samples, the clustering algorithm is used to extract the typical scene set, which is a common method to improve the computing speed and ensure that the energy storage configuration covers sufficient uncertainty features [93]. In addition, some scholars have proposed the application of chance-constrained programming in this field, that is, transforming the traditional optimization into an optimization method where the probability of meeting the constraints is higher than a certain confidence level [94]. As it is neither economical nor practical to control the optimization objective with complete precision through energy storage configuration, this method reflects the minimum probability of meeting the chance constraints and the level of risk taking of the manager, which illustrates the nature of the uncertainty configuration method from another perspective.

The above-mentioned configuration methods can not only be used alone, but also can be combined to establish a more complete model to describe the energy storage configuration problem [62,77,81,87]. In conclusion, no matter what configuration method is used, the key is to combine the application scenario of energy storage and its optimization objectives for a comprehensive analysis of the problem.

3.2. Solving Algorithm

According to the mathematical model established for optimal configuration of energy storage, the solving algorithms can be divided into traditional optimization algorithm and intelligent optimization algorithm. Traditional optimization algorithms are generally designed for structural problems, with specific descriptions of problems and conditions, such as linear programming, quadratic programming, integer programming, mixed programming, with and without constraints, etc. [42,44,53]. According to the above method, because of its clear structural information and relatively fixed parameters, the computational complexity and convergence can be analyzed theoretically. Many traditional optimization algorithms belong to the category of convex optimization and have the unique global optimal advantage, which is very simple and reliable when dealing with small-scale single-objective problems.

However, the decision variables of optimal allocation of energy storage are often continuous variables, pursuing single or multiple objectives, and the constraints generally include linear constraints, nonlinear constraints, equality constraints, inequality constraints, etc., so the configuration models are often multi-objective and nonlinear mathematical models. In this case, the calculation of the traditional optimization algorithm is extremely complex, and the calculation speed and convergence are often not up to the requirements.

Therefore, intelligent algorithms such as GA [8], PSO [34], SA [40] and their improved algorithms have been rapidly applied and developed in the field of energy storage configuration. Generally, the intelligent optimization algorithm aims at the universal description of the problem and usually pays little attention to the structure information. For the multi-extremum problem, the intelligent optimization algorithm can achieve a good balance between jumping out of the local optimal and converging to a point through the effective design of its parameters, so as to find the global optimal. In addition, in order to obtain the global optimal solution and ensure the results within an acceptable time, after the energy storage configuration model is built, it is necessary to first test whether the model is a convex function. If not, it can be converted into a convex function by various approximation and relaxation means and then further call the commercial solver for solving [59].

However, most intelligent optimization algorithms are heuristic algorithms, which can be qualitatively analyzed but are difficult to prove quantitatively. Moreover, most algorithms are based on random characteristics, and their convergence is generally probabilistic, so the actual performance is not controllable. At the same time, there may be shortcomings such as single individual, precocious or local optimum, and if the data sample is too large, the solution may be too time-consuming or difficult to solve. Therefore, it is still the focus of current research to improve this kind of algorithm and make it have better convergence and efficiency in energy storage optimization allocation. In view of the existing problems, linearization of objective function and constraint conditions and transformation of multi-objective problems into single-objective problems are effective solutions.

There must be differences in the complexity and application fields of various algorithms. Corresponding algorithms should be designed for specific problems, and various algorithms should be improved or combined to better balance the local and global search ability when solving the corresponding problems [31,47,76]. Therefore, how to improve the computational efficiency of the algorithm, achieve large-scale, multi-objective and high-dimension optimization and how to seek and measure the global optimal solution are still the aspects of algorithm optimization that need further research.

4. Conclusions

In this paper, the state-of-the-art research progress in energy storage application scenarios, modeling method and optimal configuration strategies on power-generation side, grid side and user side are summarized according to the latest published literature. The mathematical models and optimization algorithm on the energy storage configuration for various application scenarios are comparatively analyzed and summarized. On this basis, the shortcomings that still exist in energy storage configuration research are summarized, and the future research directions and innovation points for energy storage configuration are prospected. This review can provide a reference value for the state-of the-art development and future research and innovation direction for energy storage configuration, expanding the application scenarios of distributed energy storage and optimizing the application effect of distributed energy storage in the power system.

Author Contributions: All authors contributed improving the quality of the manuscript. Specifically, Y.W. conceptualized the idea of this research, carried out the theoretical analysis and performed the experiments. Z.L. contributed on the designed the methodology and experiments, writing and revising the paper. T.S. provided important comments on the structure, language and format of the paper. Z.Q. designed the methodology and experiment set up. Q.W. and Y.W. contributed on the writing and revising the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China under grant No. 62273107 and No. 62273104, and The APC was funded by and the Science and Technology Planning Project of Guangdong Province under grant No. 2021A1515012398.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

DG	Distributed generation	LVRT	Low voltage ride-through
PV	Photovoltaic	AGC	Automatic generation control
SCES	Supercapacitor energy storage	SOC	State of Charge
SMES	Superconducting magnetic energy storage	GA	Genetic algorithm
AC	Alternating Current	PSO	Particle swarm optimization algorithm
DC	Direct Current	SA	simulated annealing algorithm

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