

The Research on Planning Methods for Energy Storage in Distributed Renewable Energy Distribution Networks

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Abstract. In order to accelerate the green transformation of the power grid, improve the absorption capacity of renewable energy, reduce distribution network operation costs, and balance the voltage stability issues caused by supply and demand fluctuations during different operating periods, this paper proposes an energy storage planning method for distribution networks with integrated distributed renewable energy. First, the load and renewable energy (wind and solar) data for the year are clustered to generate four temporal scenarios. Then, considering various economic costs associated with the operation of the distribution network as well as the investment and operational costs required for energy storage planning. Building upon this, an optimization model for the distribution network, both prior to and following the integration of energy storage planning, is developed, along with the associated constraints. Next, an optimization solution is sought using a weight-adaptive particle swarm optimization (PSO) algorithm. Finally, the effectiveness and feasibility of the energy storage planning are validated through simulation on the IEEE 33-bus test system. The simulation results show that after the introduction of energy storage planning, the overall operational cost of the distribution network with integrated distributed renewable energy is significantly reduced, while the voltage stability at each node during different periods is effectively improved.

Keywords: Distribution network; Distributed renewable energy; Energy storage planning; Renewable energy integration.

1. Introduction

With the continuous advancement of China's green sustainable development and the "dual carbon" goals, the clean transformation and self-innovation of the power system are flourishing, characterized mainly by wind and photovoltaic renewable energy. However, the intermittency and volatility of renewable energy generation pose significant challenges to the safety and stability of the distribution network[1-4]. In order to address these challenges and enhance the stable operation capability of the new power system as well as its capacity for renewable energy absorption, energy storage technologies have been widely applied in the planning and construction of modern power grids. Energy storage systems not only play a critical role in "peak shaving and valley filling," reducing the impact of load fluctuations on grid voltage, but also effectively reduce curtailment of renewable energy, lower the operating costs of the grid, and optimize its operational state, thereby improving the reliability and economic efficiency of power supply.

With the advancement of the Third Industrial Revolution, the essence of modern power grids has continuously evolved towards greener power generation and more efficient energy utilization[5]. Distributed renewable energy has gradually been integrated into the distribution network. Unlike traditional centralized power systems, distribution networks with integrated distributed renewable energy connect dispersed renewable energy units directly to low-voltage distribution systems. This configuration offers advantages such as high flexibility, ease of integration, and relatively low costs. However, due to the volatility of wind and photovoltaic power generation, which is heavily influenced by temporal factors, it is challenging to effectively address the mismatch between renewable energy absorption and the grid's regulation capability. Therefore, the rational planning of the energy storage system has become the key to ensure the efficient and stable operation of the distributed new energy distribution network.

Energy storage technology has been more maturely applied in Europe and the United States[6]. For example, the UK has installed thousands of energy storage devices in urban renewable energy stations to store excess electricity and release it during peak demand periods, effectively alleviating the pressure on the power system during peak hours. The European Union has set an ambitious goal to increase the total installed capacity of energy storage devices to 30% of the renewable energy generation capacity by 2030, thus helping to reduce the burden of urban electricity consumption during peak periods. China also places a high priority on the development of energy storage technology and has explicitly stated that the integration of energy storage systems will be considered in the planning of the new power system. Reference in[7] proposes a collaborative planning approach that integrates energy storage systems with demand-side response in wind power stations, thereby enhancing the utilization of renewable energy. Additionally, in[8], an optimization evaluation model for energy storage devices in integrated energy systems is analyzed, and an energy storage optimization strategy suitable for integrated energy grids is proposed. References[7] and[8] mainly focus on the application of energy storage in the renewable energy generation side of the system, with less emphasis on the application technologies within the distribution network.

Reference[9] uses a deep reinforcement learning algorithm, considering the characteristics of source-load power forecasting and the operational characteristics of distributed generation (DG) devices, and proposes an energy storage planning scheme for active distribution networks across multiple time scales. Reference[10] addresses the issue of reducing voltage violations in distribution networks by constructing a decision-making model for the coordinated planning of source-load storage in active distribution networks, considering different DG and load types, with the objective of minimizing operational costs as the optimization goal. Reference[11] proposes a stochastic optimal battery energy storage planning method for dynamic distribution networks, with the objective of minimizing total investment and operational costs. The method optimizes to determine the optimal energy storage capacity and location. References[9-11] all focus on energy storage planning and design in distribution networks with distributed generation, but do not consider energy storage planning in distribution networks that incorporate renewable energy sources.

Reference[12] considers the peak-shaving function of energy storage systems and determines the optimal energy storage planning scheme under the constraint of reliability indices. The algorithm is used to obtain the installation capacity of energy storage devices. However, in the cost calculation, only the operational costs of the distribution network are considered, without accounting for the corresponding conversion of the energy storage system's commissioning costs. Reference[13] considers the temporal variability of photovoltaic (PV) output and its correlation with load in distribution networks with distributed photovoltaic generation. The optimal energy storage capacity for the system is determined using a simulated annealing algorithm. Reference[14] aims to minimize both the distribution network's loss costs and the lifecycle costs of energy storage devices. It develops an optimization model for energy storage systems that is applicable to renewable energy-based distribution networks. References[12-14] in energy storage planning only consider the issue of effectively ensuring voltage stability in the distribution network during each period, without performing a comprehensive analysis of the total operational cost of the distribution network with distributed renewable energy after the integration of energy storage. This limitation may result in the operation cost of the energy storage system being significantly higher than the cost of renewable energy curtailment, thus failing to achieve economic optimization.

In summary, significant progress has been made in energy storage planning research in China, especially in using energy storage devices to ensure the stable operation of the power system and improve the integration of renewable energy. However, there is still a lack of research on energy storage planning methods for distributed renewable energy distribution networks [15, 16], and the operation costs of energy storage systems have not been incorporated into the total cost of the distribution network for consideration. This paper based on a distributed renewable energy distribution network, aims to minimize the total operational cost and studies the planning method of energy storage systems to improve the economic performance and voltage stability of the power

system. Firstly, the annual load, wind, and solar data are clustered into four typical scenarios. Then, optimization models for the distribution network before and after the integration of energy storage are constructed, and the weighted adaptive particle swarm optimization (PSO) algorithm is applied for optimization. Finally, the proposed energy storage planning method is validated through simulation models in MATLAB, effectively balancing the relationships between load response, economic benefits, and environmental protection.

2. Distributed Renewable Energy Operation Time Series Model

In the distribution network, two types of distributed renewable energy, wind power and photovoltaic power, are introduced. Due to the temporal characteristics of the output from these two energy sources, there are significant variations in wind speed and solar irradiance at different time intervals, resulting in noticeable differences in the output of renewable energy units. Therefore, this paper applies the K-means clustering method to cluster the load and wind-solar data of the distribution network with distributed renewable energy over the course of one year[17]. Four typical temporal scenarios are generated, and the probabilities of each scenario's occurrence are determined. The data for these typical scenarios are then normalized and plotted, as shown in Figure 1.

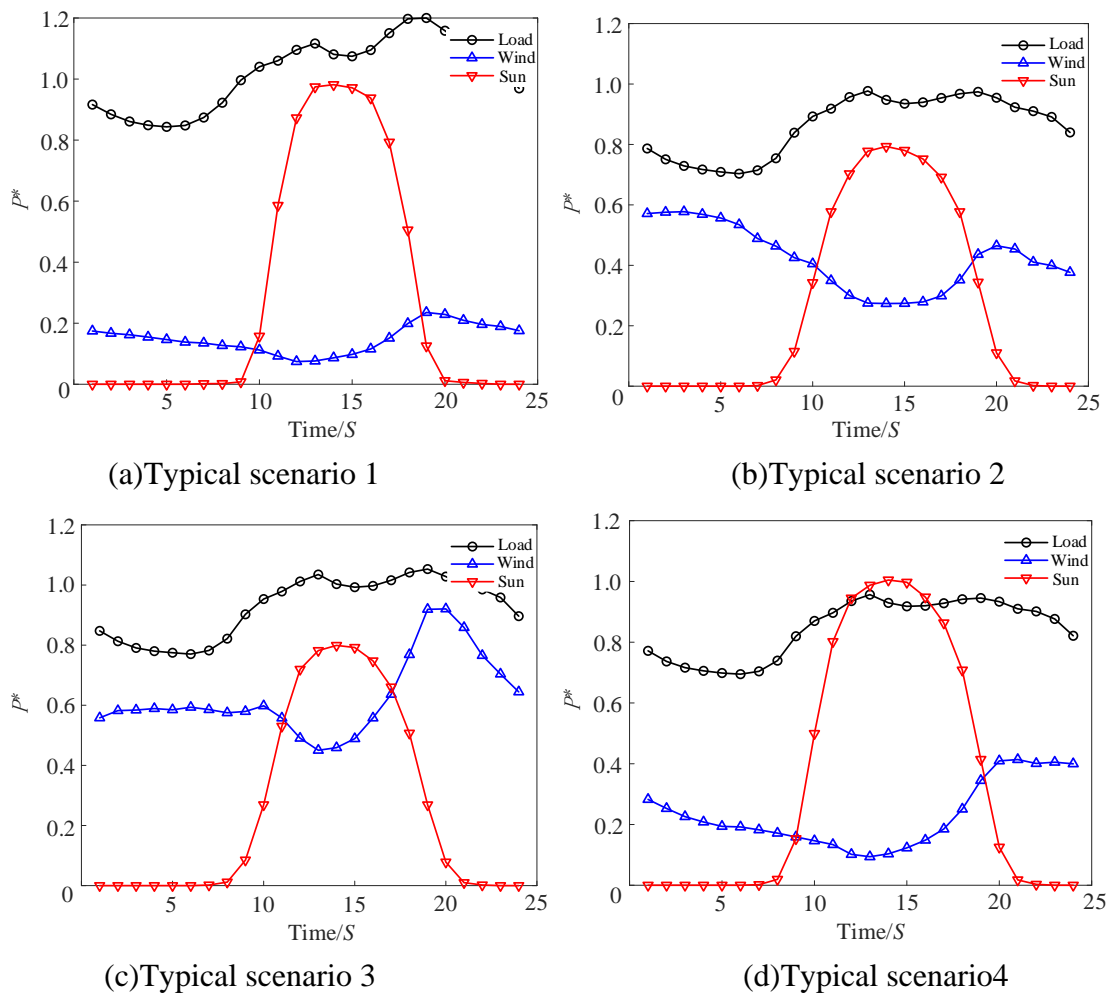


Figure 1. The power distribution chart of typical scenarios.

The data for each scenario display the power variation of load demand, wind power, and photovoltaic power over a 24-hour period. During certain operational periods, the total output of renewable energy units exceeds the required power demand from the load side, resulting in the curtailment of renewable energy. This not only leads to a waste of clean energy resources but also

increases the operational costs of the distribution network. Therefore, energy storage planning in such distribution networks, on one hand, store surplus energy to reduce the operating costs of the grid, and on the other hand, promote the large-scale application of renewable energy, accelerating the green transformation of the grid.

3. Construction of the Distribution Network Optimization Model

The purpose of energy storage system planning is to store the surplus electricity generated during renewable energy production, reducing the costs associated with wind and solar curtailment, and improving the economic operation of the power system, thereby lowering the overall cost of the distribution network. In addition, the energy storage system can achieve peak shaving and valley filling, significantly reducing voltage fluctuations in the distribution network during periods of high electricity demand, ensuring that the voltage at each node stays within the preset range, thus enhancing the stability of the power system. To more clearly and intuitively compare the improvements in the economic performance and operational stability of the distribution network after the introduction of energy storage planning[18], this paper constructs an optimization model for the distribution network before and after the incorporation of energy storage planning.

3.1 Optimization Model of the Distribution Network Before the Introduction of Energy Storage Planning

In the absence of energy storage system planning, the objective of distribution network optimization is to minimize the operational cost of the distribution network, which incorporates distributed renewable energy sources. This cost includes the electricity purchase cost from the upper grid, network loss costs, interruptible load compensation costs, wind and solar curtailment penalty costs, and the operation and maintenance costs of distributed renewable energy sources. The objective function is formulated as follows:

$$\min C^1 = 365 \sum_i^4 p_i (f_{sub} + f_{loss} + f_{DSR} + f_{RDG} + f_{DG}) \quad (1)$$

In the formula, C^1 represents the operational cost of the distribution network, p_i represents the probability of occurrence of the i th typical scenario, f_{sub} represents the cost of purchasing electricity from the higher-level grid, f_{loss} represents the cost of electricity network losses, f_{DSR} represents the compensation cost for interruptible load, f_{RDG} represents the penalty cost for wind and solar curtailment, f_{DG} represents the operation and maintenance cost of distributed renewable energy. The calculation methods for each cost are as follows:

(1) the cost of purchasing electricity from the higher-level grid f_{sub}

$$f_{sub} = C_{sub} P_{gen} \quad (2)$$

In the formula, C_{sub} represents the cost of purchasing electricity per unit of energy from the higher-level grid by the distribution network, P_{gen} represents the active power input from the higher-level grid.

(2) the cost of electricity network losses f_{loss}

$$f_{loss} = C_{loss} \left(\sum_{i=1}^n \sum_{j=1}^n (I_{ij}^2 \cdot Z_{ij}) \right) \quad (3)$$

In the formula, C_{loss} represents the network loss cost per unit of energy, I_{ij} represents the current flowing between node i and node j , Z_{ij} represents the impedance flowing between node i and node j .

(3) the compensation cost for interruptible load f_{DSR}

$$f_{DSR} = C_{DSR} \sum_{i=1}^n P_{DSR_i} \quad (4)$$

In the formula, C_{DSR} represents the compensation electricity price for interruptible load, P_{DSR_i} represents the magnitude of the i -th interruptible load participating in demand response.

(4) curtailed wind and solar penalty cost f_{RDG}

$$f_{RDG} = C_{RDG} \left(\sum_{i=1}^n (P_{RDG_{max}}^i - P_{RDG}^i) \right) \quad (5)$$

In the formula, C_{RDG} represents the unit penalty cost for curtailed wind and solar power, $P_{RDG_{max}}^i$ represents the total active power generated by the i -th renewable energy unit connected to the distribution grid, P_{RDG}^i represents the active power consumed by the distribution grid generated by the i -th renewable energy unit.

(5) operation and maintenance costs of distributed renewable energy f_{DG}

$$f_{DG} = C_{DG} \sum_{i=1}^n P_{RDG_{max}}^i \quad (6)$$

In the formula, C_{DG} represents the operation and maintenance cost required for the generation of one unit of electricity by distributed renewable energy.

Constraint 1: The distribution grid must satisfy the steady-state power flow balance constraint

$$\begin{cases} P_i = V_i \sum_{j=1}^n V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \\ Q_i = V_i \sum_{j=1}^n V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \end{cases} \quad i = 1, 2, \dots, n \quad (7)$$

In the formula, V_i and V_j represent the voltages at nodes i and j , G_{ij} represents the real part of the element at position (i, j) in the node admittance matrix, B_{ij} represents the imaginary part of the element at position (i, j) in the node admittance matrix, θ_{ij} represents the phase difference between the nodes, n represents the total number of nodes in the power grid, P_i and Q_i represent the active power and reactive power injected at the node

Constraint 2: The distribution network must satisfy output power constraints. This includes the upper and lower limits of active and reactive power injected by the upstream grid into the distribution network, the upper and lower limits of active power supplied by distributed renewable energy to the grid, and the upper and lower limits of the interruptible load power on the demand side.

$$\begin{cases} 0 \leq P_{gen} \leq P_{gen_{max}} \\ -Q_{gen_{max}} \leq Q_{gen} \leq Q_{gen_{max}} \\ P_{RDG_{min}} \leq P_{RDG} \leq P_{RDG_{max}} \\ P_{DSR_{min}} \leq P_{DSR} \leq P_{DSR_{max}} \end{cases} \quad (8)$$

In the formula, P_{gen} and Q_{gen} represent the active power and reactive power, injected by the upstream grid into the distribution network, P_{RDG} represents the active power supplied by distributed renewable energy to the grid, P_{DSR} represents the interruptible load power on the demand side.

Constraint 3: Each node in the distribution network must satisfy power flow constraints.

$$\begin{cases} U_{\min} \leq U_i \leq U_{\max} \\ I_{\min} \leq I_i \leq I_{\max} \\ U_i^2 + I_i^2 \geq P_i^2 + Q_i^2 \end{cases} \quad (9)$$

In the formula, U_i and I_i represent the voltage and current at node i , P_i and Q_i represent the total active power and total reactive power injected at node i .

3.2 Optimization Model of Distribution Network with Energy Storage Planning

After introducing energy storage planning, the distribution network needs to be optimized in a coordinated manner to minimize the overall total cost. Otherwise, the operational cost of the energy storage system may exceed the cost of curtailing renewable energy, which would fail to improve the economic efficiency of the power system and may even be counterproductive. Therefore, the total cost of the distribution network at this stage includes both the operational cost of the distribution network and the operational cost of the energy storage planning system. The objective function is constructed as follows:

$$\min F = C^1 + f_{ESS} + f_{op} \quad (10)$$

In the formula, F represents the total cost of the distribution network, C^1 represents the operational cost of the distribution network, f_{ESS} represents the annual fixed investment cost of the energy storage system, f_{op} represents the annual operating cost of the energy storage system. The calculation methods for each cost are as follows (the calculation methods are the same as in 2.1):

(1) annual fixed investment cost of the energy storage system f_{ESS}

$$f_{ESS} = b \left(\frac{(1+b)^{y_{ESS}}}{(1+b)^{y_{ESS}} - 1} \right) x_{ESS} c_{ESS} \quad (11)$$

In the formula, b represents the annual discount rate of the energy storage system, y_{ESS} represents the service life cycle of the energy storage device, x_{ESS} represents the number of energy storage devices installed, c_{ESS} represents the installation cost of a single energy storage device.

(2) annual operating cost of the energy storage system f_{op}

$$f_{op} = 365 * \sum_{i=1}^4 f_i p_i \quad (12)$$

In the formula, f_i represents the operating cost of the energy storage system in the i -th scenario.

Constraint 4: In addition to the condition constraints specified in Section 2.1, the energy storage system must also satisfy its own operational constraints. Specifically, the charging and discharging power of each energy storage device is limited by its maximum power and capacity, and the energy storage level must remain within a reasonable range at all time points.

$$\left\{ \begin{array}{l} 0 \leq P_{ESS-d} \leq P_{ESSmax} \\ 0 \leq P_{ESS-c} \leq P_{ESSmax} \\ W_{ESS} = P_{ESS-c}t_{ESS-c} - P_{ESS-d}t_{ESS-d} \\ 0.2 * S_{ESS} \leq W_{ESS} \leq 0.9 * S_{ESS} \end{array} \right. \quad (13)$$

In the formula, P_{ESSmax} represents the maximum power capacity of the energy storage device, P_{ESS-d} represents the discharge power, P_{ESS-c} represents the charging power, t_{ESS-d} represents the discharge duration, t_{ESS-c} represents the charging duration, W_{ESS} represents the remaining energy in the energy storage device, S_{ESS} represents the rated capacity of the energy storage device.

4. Example Description

4.1 Description of the distribution network example before the introduction of energy storage planning

With reference to the IEEE 33-node distribution network topology, wind and photovoltaic units are added at nodes 5, 12, 18, and 30 to construct a distribution network example model that incorporates distributed renewable energy. With reference to the current data from the Chinese electricity market[19], select the unit cost of electricity purchased from the upper grid $C_{sub} = 0.48$ CNY/kWh, unit loss cost per electricity quantity $C_{loss} = 0.5$ CNY/kWh, unit interruptible load compensation price $C_{DSR} = 0.4$ CNY/kWh, unit cost of curtailment for wind and solar power $C_{RDG} = 0.5$ CNY/kWh, operating and maintenance cost per unit of electricity generated by distributed renewable energy $C_{DG} = 0.45$ CNY/kWh. The optimization of the objective function in equation (1) is solved using YALMIP and the CPLEX solver, resulting in the minimum operational cost of the distribution network.

4.2 The description of the distribution network example after introducing energy storage planning.

Energy storage planning is carried out at the wind and solar unit nodes based on the distribution network topology constructed in Section 3.1. Firstly, with reference to the current data from the Chinese electricity market[19], the annual discount rate of the energy storage system is selected as $b = 6\%$, with a service life cycle of 20 years. The capacity of each energy storage unit is 2.4 MW, and the installation cost is 12,000 yuan. The operational costs of the energy storage system under four typical time-sequencing scenarios are as follows: 0.5CNY/kWh, 0.65CNY/kWh, 0.5CNY/kWh, 0.85CNY/kWh. Then, the objective function in equation (10) is optimized using the Inertia Weight Adaptive Particle Swarm Optimization (IWAPSO) algorithm, along with the YALMIP and CPLEX solvers. The optimal plan for installing energy storage devices at each renewable energy bus and the corresponding minimum operational cost of the distribution network are obtained. The optimal energy storage planning scheme is shown in Table 1.

Table 1. Energy Storage Device Planning Details

Installation Node	Number of Installations	Total Energy Storage Capacity (MW)
5	6	14.4MW
12	1	2.4MW
18	6	14.4MW
30	2	4.8MW

5. Simulation Analysis

5.1 Economical Analysis of Distribution Network Before and After Energy Storage Planning

Based on the optimization results of the objective function in the previous section, the economic costs of different parts of the distribution network before and after energy storage planning are shown in Table 2. By comparing the costs under both scenarios, the analysis evaluates the improvement in the economic efficiency of the distributed renewable energy distribution network after the introduction of energy storage planning.

Table 2. Comparison of Economic Costs of Distribution Network Before and After Energy Storage Planning

Cost before energy storage planning	Cost/1000 0yuan	Cost after energy storage planning	Cost/1000 0yuan
Cost of purchasing electricity from the higher-level power grid	482.93	Cost of purchasing electricity from the higher-level power grid	422.05
Network loss cost	65.79	Network loss cost	48.33
Interruptible load compensation cost	36.05	Interruptible load compensation cost	36.05
Wind and solar curtailment penalty cost	6.09	Wind and solar curtailment penalty cost	0.89
Renewable energy operation and maintenance costs	5.79	Renewable energy operation and maintenance costs	5.79
/	/	Annual investment cost of the energy storage system	19.96
/	/	The annual operating cost of the energy storage system	5.44
Total operational cost of the distribution network	596.65	Total operational cost of the distribution network	528.51

As shown in Table 2, after the introduction of energy storage planning, the distributed renewable energy distribution network demonstrates significant advantages in terms of economics, renewable energy consumption capacity, and grid operation efficiency. Notably, the total cost of the distribution network decreased by 681,400 yuan, approximately an 11.4% reduction, thereby enhancing overall economic benefits and reflecting the economic return capability of the energy storage system.

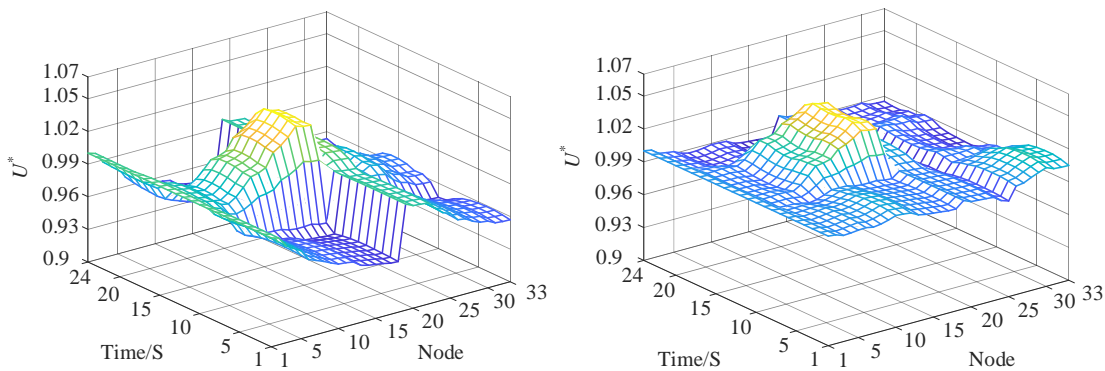
The energy storage system effectively reduces the purchasing cost from the upper-level grid by storing excess electricity during periods of surplus renewable generation and discharging stored energy during peak load times, resulting in a reduction of 608,800 yuan, approximately 12.6%. Additionally, the energy storage system can effectively absorb the fluctuating power from wind and photovoltaic generation, minimizing the waste of renewable energy and significantly reducing the economic losses caused by curtailment of wind and solar power. Specifically, after the implementation of energy storage planning, the penalty cost for wind and solar curtailment decreased significantly by 85.4%, indicating that the energy storage system effectively improved the utilization of renewable energy generation and reduced resource waste. Meanwhile, the introduction of the energy storage system optimized the power flow distribution within the grid, reducing energy losses during transmission, which lowered the network loss costs in the distribution network to 26.5% of the original amount, thereby further enhancing the operational efficiency of the grid.

Therefore, the implementation of energy storage planning in distributed renewable energy distribution networks is a crucial means of achieving a balance between technology and economics, as well as unifying environmental and social benefits. In the short term, the introduction of energy storage systems leads to significant reductions in purchasing costs, network losses, and renewable energy curtailment costs, thus enhancing economic benefits. At the same time, it substantially improves the integration of renewable energy and the operational efficiency of the grid. In the long term, energy storage planning not only enhances the grid's ability to absorb renewable energy but also

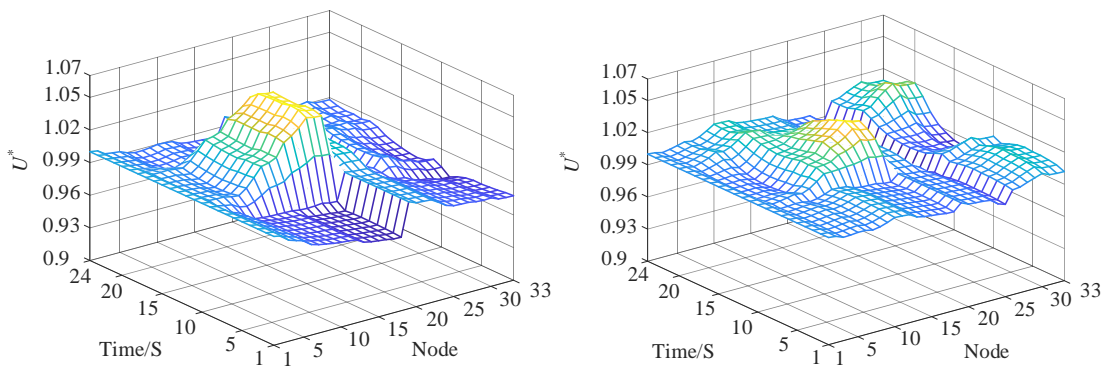
reduces reliance on traditional fossil fuels, providing important support for the development of a safe, economic, green, and reliable new power system. It also plays a critical role in ensuring the achievement of national energy transition goals.

5.2 Analysis of Distribution Network Stability Before and After Energy Storage Planning

Select typical Scenario 1 and Scenario 4, and analyze the improvement in voltage stability of the distributed renewable energy distribution network after the introduction of energy storage planning, using the node voltage data for each time period before and after the energy storage planning. The voltage curves of the distribution network before and after energy storage planning for typical Scenario 1 and Scenario 4 are shown in Figures 2 and 3, respectively.



(a) Voltage Curve Before Energy Storage Planning (b) Voltage Curve After Energy Storage Planning
Figure 2. Voltage Curve Comparison for Typical Scenario 1



(a) Voltage Curve Before Energy Storage Planning (b) Voltage Curve After Energy Storage Planning
Figure 3. Voltage Curve Comparison for Typical Scenario 4

In the three-dimensional voltage curve graph, darker colors indicate a greater deviation from the reference voltage. Prior to the implementation of energy storage planning, the voltage curves fluctuated significantly across different nodes and time periods, especially during midday and evening when load demand was higher. During these periods, some nodes experienced notable voltage drops or increases. Additionally, during off-peak hours, voltage drops were particularly significant, with some nodes' voltages approaching the lower limit of 0.95, leading to increased voltage fluctuations in the power grid and posing challenges to the stable operation of the distribution network.

After the introduction of energy storage planning, the voltage curves became overall smoother, with the voltage differences between nodes significantly reduced and the voltage fluctuations at each node greatly diminished. Energy storage devices effectively balanced the system's power by discharging energy during peak load periods and absorbing energy during off-peak periods, thereby mitigating voltage imbalances caused by load fluctuations. Meanwhile, the amplitude of voltage fluctuations over time was notably reduced, with the voltage values at each node becoming closer to

the nominal voltage (1.0), and no significant voltage dips observed. As a result, the system's voltage stability was improved, which in turn optimized the economic performance and operational efficiency of the distribution network.

6. Conclusion

This paper is based on a distribution network integrated with distributed renewable energy and focuses on the planning of energy storage systems. It proposes a method for the coordinated planning of both. First, an optimization model for the distribution network before and after energy storage planning is developed based on energy statistical data. Then, the configuration capacity of the energy storage devices is solved using a weight-adaptive particle swarm algorithm. On this basis, the minimum operational cost of the distribution network before and after energy storage planning is determined using YALMIP and the CPLEX solver. Finally, the IEEE 33-node case study simulation verifies that the introduction of energy storage planning in a distribution network with distributed renewable energy significantly reduces operational costs and improves the voltage stability at each node during different time periods. The simulation results demonstrate the role and value of the energy storage system in a distributed renewable energy distribution network, providing a reliable theoretical basis for the efficient use of renewable energy and the stability of the power grid.

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