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A comprehensive optimization mathematical model for wind solar energy storage complementary distribution network based on multi-regulatory devices under the background of renewable energy integration

Ke Zhou[1*], Biyun Zhang[1], Qingren Jin[1], Hao Bai[2], Weichen Yang[2] and Tong Liu[2]

*Correspondence:
13557019675@163.com

[1] Electric Power Research Institute of Guangxi Power Grid Co., Ltd., Nanning 530023, China
[2] Electric Power Research Institute, CSG, Guangzhou 510663, China

Abstract

In the context of global energy transformation and sustainable development, integrating and utilizing renewable energy effectively have become the key to the power system advancement. However, the integration of wind and photovoltaic power generation equipment also leads to power fluctuations in the distribution network. The research focuses on the multifaceted challenges of optimizing the operation of distribution networks. It explores the operation and control methods of active distribution networks based on energy storage and reactive power compensation equipment. The stable operation of the distribution network is analyzed under the conditions of wind and photovoltaic integration, with a particular focus on precise regulation to address the limitations of existing methods. Afterwards, the study proposes an improvement plan that combines on load tap changer transformers and reactive power compensation equipment to solve complex power balance problems through second-order cone programming relaxation method. The results of numerical analysis show that the constructed mathematical model maintains a stable voltage of 1 to 1.1 pu at distribution network nodes within 24 h. Especially during peak hours from 15:00 to 24:00, it remains normal without any abnormal fluctuations when the control equipment is not added. These results confirm that precise regulation of multiple devices ensures voltage stability and avoids low or high voltage issues.

Keywords: Wind power generation, Photovoltaic power generation, Optimization model, SVC, Distribution network

Introduction

In the context of global energy transformation and sustainable development, integrating and utilizing renewable energy effectively have become the key to the development of the power system. How to achieve efficient integration with traditional power grids is a major challenge facing the current power industry, especially in the context of the increasing number of renewable energy sources such as wind energy and Solar Energy (SE) (Hazra and Kumar 2023). In this process, the comprehensive optimization of Wind Solar Energy Storage Complex Distribution Network (WSESCDN) is particularly important. It not only relates to the effective utilization of energy, but also directly affects the power grid's stability and economy (Ari 2023). At present, although the complementary technology of wind and solar energy storage has been studied and applied to a certain extent in the power system, most research focuses on the optimization scheduling of a single energy source or simple combination of multiple energy sources. These methods have limitations in dealing with complex power grid environments and the comprehensive optimization of various control equipment (Morales 2023). In addition, as the electricity market develops and grid technology advances, the requirements for the Distribution Network (DN) optimization model are constantly increasing, requiring more comprehensive and systematic methods to address the complexity of the grid environment (Pearre and Swan 2023). Therefore, the research aims to construct a comprehensive optimization mathematical model for WSESCDN based on multiple regulatory devices. It will comprehensively consider the roles of wind energy, SE, energy storage equipment, and other regulatory equipment in DN, aiming to achieve efficient energy allocation and optimal grid operation. This not only includes the optimization of energy generation and consumption, but also involves a comprehensive consideration of the stability, economy, and environmental impact of the power grid. The research will focus on the construction of models and the analysis of practical application scenarios, exploring different types of DN configurations, and evaluating their applicability and performance in wind solar energy storage complementary systems. In addition, the study will also consider the complexity of actual power grid operation, including factors such as different types of loads, market price fluctuations, and environmental policies. The research aims to provide a comprehensive optimization plan for the efficient integration of renewable energy and the reliable operation of the power grid. In the case of new energy generation equipment integrated into the distribution network, the traditional distribution network uses distributed generation and energy storage devices in a comprehensive way, coordinating and cooperating for load power supply, with the main direction lying in the consumption of new energy power, not in the operation of the distribution network. The proposed system improves the limitations of the traditional method in practical application, focuses on the smooth operation of the distribution network, and captures and analyses the fluctuations in the grid more comprehensively through the optimized mathematical model, in order to improve the efficiency of the grid operation and ensure the safety of the grid in the complex and changing grid operation environment.

The research mainly includes four parts. Firstly, the development of DN under the background of renewable energy integration and the application of wind and photovoltaic power generation were introduced. Secondly, based on the analysis of wind power generation, photovoltaic power generation, and DN node systems, a comprehensive optimization mathematical model for WSESCDN based on multiple control devices is proposed. The third part tests and analyzes the performance of the model and algorithm. Finally, a summary and discussion are made on the above content.

Related works

The operating safety and stability of the power system are the fundamental guarantee for society and people's lives, and many scholars have conducted research on power grid safety issues. Lv et al. proposed a power system load forecasting model based on electricity distribution mode decomposition from the perspective of static security of the power grid. It combined electricity data to predict the trend of short-term electricity consumption in the power grid, providing data support for power grid planning and supply–demand regulation (Lv et al. 2021). Huang et al. proposed a distributed energy resource traded retail market mechanism to attract active participation of profit-oriented DER retailers in a deregulated manner, constructing a two-tier DSO dominated framework to simulate a virtual game merged between distribution system operators (DSOs) and DER retailers (Huang et al. 2021). Manamperi et al. developed a solution technique using sequential second-order cone programming for solving the optimal power flow problem in a low-voltage distribution network with distributed generation. The accuracy of the generated solution was verified after comparing it with the load flow. The proposed algorithm performs better in terms of optimality, execution time and accuracy compared to other methods (Manamperi et al. 2021). The integration of intermittent renewable energy in active DN may bring voltage control issues. Therefore, Sun and Qiu proposed a voltage and reactive power control model based on deep reinforcement learning to solve the DN voltage violation (Sun and Qiu 2021).

The operation of the power system under the background of renewable energy integration has attracted a large number of scholars to study. The paper paid close attention to the regulatory effects of various regulatory devices on the stable operation of the power grid. He proposed a low-voltage ride through control strategy for photovoltaic grid connected inverters to solve the grid instability caused by photovoltaic energy. Zhao et al. investigated a photovoltaic/thermochemical (PVTC) hybrid system via endothermic methanol steam reforming (MSR) reaction by introducing an innovative bifurcated tree structure into the flow channel configuration of the MSR reactor to improve heat transfer performance and methanol conversion. The methanol conversion of the new reactor was experimentally evaluated and showed an increase of 12.1 percentage points (26.5% relative improvement) compared to the conventional reactor with serpentine flow channel design (Zhao et al. 2023). Elhefny et al. proposed a joint simulation platform for residential communities with abundant photovoltaic power generation. This platform realized the joint simulation of residential high fidelity EnergyPlus, SE photovoltaic, and DN power flow models to adapt to the overall evaluation of different voltage control methods. These test results confirmed that adopting a flexible building load voltage regulation strategy could reduce the number of step voltage regulators operating, from 15 voltage adjustments per day to 4 (Elhefny et al. 2022). Hu et al. proposed a new active and reactive power optimization method for DN of photovoltaic systems with high penetration. The upper layer established a mixed model. The lower level adopted a master–slave consistency algorithm. These simulation results confirmed that this method could control all feeders' bus voltage changes within a predetermined range (Hu et al. 2022). Alburidy and Fan introduced a customized version of alternating direction multiplication to achieve centralized voltage and VAR optimization in distribution systems. The model used was a mixed integer nonlinear optimization problem, originating from the general optimal power flow problem. In addition, to determine the optimality of the proposed method, they also developed a direct search scheme to obtain a guaranteed global optimal result. This proposed method had significant advantages in convergence rate and optimal solution allocation (Alburidy and Fan 2021).

In summary, many scholars have studied the optimization of DN performance and stable operation by designing and optimizing different DN access devices. However, there is still limited research on WSESCDN, which has high application value in improving the operation of existing DN networks.

A comprehensive optimization mathematical model for wind solar energy storage complementary distribution network based on multiple regulatory devices

The study focuses on the multifaceted challenges of optimizing DN operation and explores the active DN operation control method based on energy storage and SVC. The stable operation of DN is analyzed under the conditions of wind and photovoltaic integration, with special attention paid to precise regulation to solve the limitations in existing methods. Afterwards, the study proposes an improvement plan that combines On-load Voltage Regulator Transformers (OLTC) and Static Var Compensator (SVC) to solve complex power balance problems through SOCP and CPLEX solvers. It aims to achieve more efficient and accurate DN operation regulation.

Mathematical model for scheduling optimization of wind solar energy storage complementary distribution network

The study takes the energy storage equipment in the distribution network as the active regulation unit and the group-switching capacitor bank as the reactive power regulation unit, respectively. The operation amount of the regulation equipment is converted into economic cost, the active power is used to express the operating state of the distribution network uniformly, and the minimum operating cost is taken as the objective function, so that the optimisation model of the distribution network operation under the wind and photovoltaic access is established, and the particle swarm algorithm is used to find the optimum. The example scenario is set up using IEEE33 node system data, wind and solar output data, and time-sequence load data. Wind power generation, as a renewable energy technology, utilizes the wind energy of the Earth's climate system to generate electricity. Wind power is a widely existing resource that is not only endless and clean, but also meets society's demand for sustainable energy (Catalán et al. 2023; Tang et al. 2023). Figure 1 shows the model of wind turbine power generation equipment selected in the study.

In Fig. 1, wind power generates electricity by converting wind power into electrical energy. The blades of a wind turbine rotate under the action of wind, and mechanical energy is transmitted to the generator through the shaft. The relative motion between the rotor and stator generates electromagnetic induction, which in turn generates current. The obtained electricity is regulated by transformers and connected to the power grid to provide electricity to users. The power generated by the wind turbine is represented by Eq. (1).

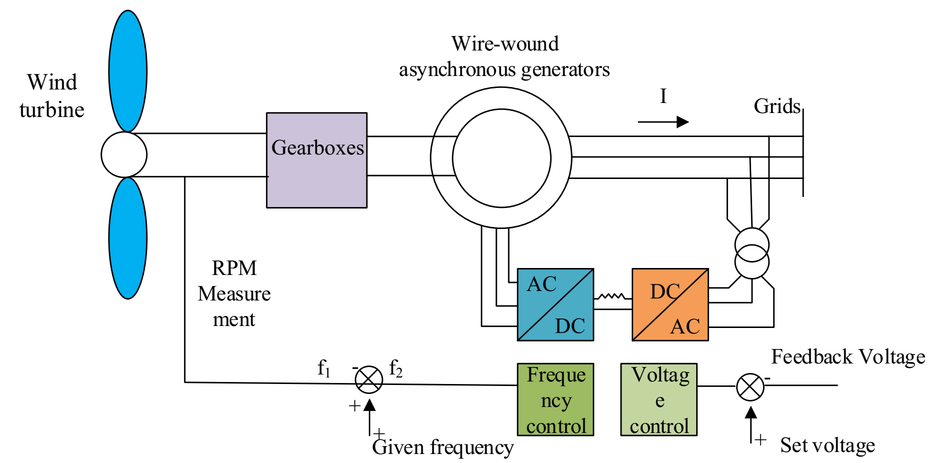


Fig. 1 Model of wind turbine power generation equipment

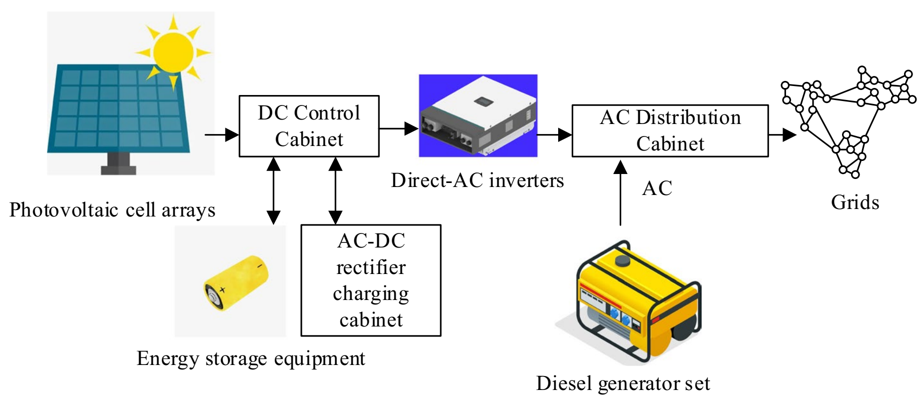


Fig. 2 Model of solar power generation equipment

$$P_{i,t}^{w} = 0.5\rho_{\alpha}A_i \cdot v_{i,t}^{3} \quad (1)$$

In Eq. (1), $P_{i,t}^{w}$ represents the maximum value of device power. $P_{i,t}^{w}$ represents air density. A_i is the coverage area of the fan blades. $v_{i,t}^{3}$ represents wind speed. The formula for the active power supplied by a wind turbine can be obtained from the air density, the wind speed, the area swept by the fan blades. Figure 2 shows the SE power generation equipment model selected in the study.

In Fig. 2, the photovoltaic cell array is a collection of multiple photovoltaic panels, whose main function is to capture sunlight and convert it into Direct Current (DC). These battery panels are wired together to the DC combiner box, which is responsible for integrating the current from each panel and conducting preliminary current and voltage management (Senapati et al. 2023; Niaz et al. 2023; Paul et al. 2023). Subsequently, the DC in the combiner box is fed into a DC-AC inverter, where the DC is converted into an Alternating Current (AC) that can be used by households or the power grid. The entire process reflects the conversion from SE to electrical energy, and the existence of inverters ensures that the conversion of electrical energy meets the standards of modern power grids. Through this approach, photovoltaic power generation systems effectively convert renewable SE sources into clean electricity resources. This photovoltaic power generating system's output power is represented by Eq. (2).

$$P_{i,t}^{PV} = \eta^{PV} A_i S_{i,t} \tag{2}$$

In Eq. (2), $P_{i,t}^{PV}$ is the effective power of device i during the time period t. η^{PV} represents conversion efficiency. A_i is the area of sunlight exposure on the device. $S_{i,t}$ represents the radiation intensity received during the time period t. According to the length and intensity of sunlight, solar photovoltaic panels are subjected to the area of radiation can be deduced from the photovoltaic power generation system into the power grid, photovoltaic power generation system of solar photovoltaic panels are mainly composed of photovoltaic batteries, each photovoltaic cell produces a very small amount of power so it is necessary to series–parallel connection of them to form a photovoltaic array that can meet the conditions. In the study, case analysis, mathematical model construction, and performance testing are conducted on the proposed model based on the IEEE-33 bus distribution node system. Figure 3 is its wiring diagram.

In Fig. 3, this system is a standard testing model provided by the Institute of Electrical and Electronics Engineers (IEEE), widely used in research and teaching in the power systems. The system consists of 33 nodes designed with a radial network structure to simulate the DN network layout in the real world (Erenoğlu and Erdinç 2023). Each node represents a power distribution point, connected to the power supply through a single path, reflecting the typical characteristics of the DN network. This testing system provides a detailed dataset, including key information such as line impedance, load, and node voltage, making it an ideal tool for DN analysis, optimization, and control strategy evaluation. WSESCDN operation optimization is a dynamic optimization problem on the timeline. Unlike traditional static scheduling optimization problems that only consider a single line loss objective, the integration of wind and photovoltaic power generation equipment leads to power fluctuations in DN. To meet the scheduling requirements of DN, the study first establishes an objective function to maintain stable operation of DN and reduce losses. Equation (3) is the objective function.

$$P_{\text{loss}} = \sum_{i \in N} \sum_{j \in N} G_{ij} \left(V_i^2 + V_j^2 - 2 V_i V_j \cos \theta_{ij} \right) \tag{3}$$

In Eq. (3), P_{loss} is the power loss of the power grid. G_{ij} represents the conductivity value of the connection between nodes i and j. θ_{ij} represents the difference in voltage phase angle between two points. V_i and V_j are the voltages corresponding to i and j,

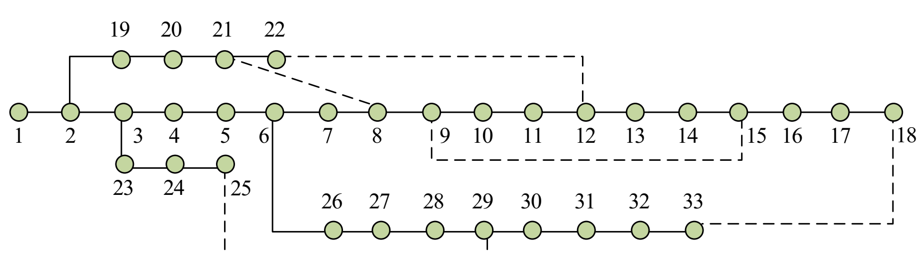


Fig. 3 IEEE-33 bus distribution node system

respectively. N represents the number of nodes. After establishing the objective function, it is necessary to consider the power balance conditions in the network. That is, the power inflow from the load node needs to be equal to the power outflow from the load node. The DN power balance constraint is represented by Eq. (4).

$$\begin{cases} P_i = P_{Gi} - P_{Li} = V_i \sum_{j \in i} V_j (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}) \\ Q_i = Q_{Gi} - Q_{Li} - Q_{Ci} = V_i \sum_{j \in i} V_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}) \end{cases} \tag{4}$$

In Eq. (4), δ_{ij} represents the phase angle value between nodes. B_{ij} is the two point admittance value. P_{Gi} and Q_{Gi} are the active and reactive power of the generator node, respectively. P_{Li} and Q_{Li} refer to the active and reactive power of the load node. Q_{Ci} represents the reactive power compensation capacity of the node. Q_i is the reactive power flowing in from node i. Q_i represents active power. Coupling constraints are considered between each optimization time section, which include compensating device control variables. The limitation on the times this control equipment is reduced to an economic cost issue to achieve overall decoupling. When optimizing DN scheduling, it is not only necessary to consider the direct cost of operating equipment, but also to evaluate the economic burden caused by factors such as maintenance, manual operation, and reduced equipment lifespan. To simplify the objective function, the unit adjustment cost of OLTC, capacitor bank, and energy storage device is studied, and power loss is combined with economic cost. OLTC is capable of adjusting the voltage without stopping the power supply, improving the flexibility of the grid and the reliability of the supply. However, its disadvantages include relatively complex structure, higher cost and more stringent maintenance requirements. It is widely used in applications where precise voltage control is required, especially in places with large load fluctuations and high requirements for voltage stability. Economic considerations include equipment investment costs, adjustment and maintenance expenses for reactive power optimization equipment, cost differences in open loop control systems, and the impact of equipment adjustment frequency on its life. In addition, the failure of DN network equipment may also bring economic losses, so it is necessary to ensure that the protection system can respond quickly and minimize equipment damage in the event of a failure. The optimization objective in the established mathematical model is represented by Eq. (5).

$$\min f_{D1} = \Delta P + C_T \sum_{i=1}^{n_T} \Delta u_{Ti} + C_S \sum_{i=1}^{n_Q} \Delta u_{Ci} + C_B \sum_{i=1}^{n_B} \Delta u_{Bi} \tag{5}$$

In Eq. (5), f_{D1} is the minimum operating cost function. ΔP represents the difference in active power loss. Δu_{Ti}, Δu_{Ci}, Δu_{Bi} are column vectors for OLTC action, capacitor switching, and energy storage device changes, respectively. C_T, C_S, and C_B represent the unit adjustment costs of OLTC, synchronous phase-shifting camera, and energy storage device, respectively. n_T. n_Q and n_B refer to the adjustments made to OLTC, generator, and energy storage device, respectively. DN needs to determine state variables and control variable constraints as inequality constraints during operation. Distribution network in operation also need to determine the state variable and control variable constraints as inequality constraints, the study takes the node voltage magnitude as the state variable in the network, while the operation of various types of regulation equipment is taken as the control variable, as the variable to be preferred. The inequality equilibrium condition and complete mathematical model are represented by Eq. (6).

$$\begin{cases} \min & \sum_{t=0}^{23} f_{D1} = \Delta P + C_S \sum_{i=1}^{n_Q} \Delta u_{C_i} + C_B \sum_{i=1}^{n_B} \Delta u_{B_i} \\ \text{s.t.} & h(C_{Ct}, V_{Gt}, B_t) = 0 \\ & \underline{C}_{Ct} \le C_{Ct} \le \overline{C}_{Ct} \quad t = 0, 1, 2, \ldots, 23 \\ & \underline{Q}_{gt} \le Q_{gt} \le \overline{Q}_{gt} \quad t = 0, 1, 2, \ldots, 23 \\ & \underline{B}_t \le B_t \le \overline{B}_t \quad t = 0, 1, 2, \ldots, 23 \end{cases} \tag{6}$$

In Eq. (6), C_{Ct}, Q_{gt}, and B_t represent the number of capacitor banks, reactive power output of generator nodes, and energy storage device output during the period t, respectively. The upper and lower lines represent the upper and lower limits, respectively. V_{Gt} is the reactive power of the generator during the time t. h is a constraint function. If the economic loss caused by the failure is not taken into account, for 110 kV on-load regulator transformer, the cost of tapping unit adjustment is about 1.0–2.0 yuan/time; 220 kV transformer ratio adjustment is about 1.5–2.5 yuan hin once. In the above voltage level does not take into account the equipment recovery years. Extrapolate this to the rule applied to the reactive power compensation device 10 kV of reactive power compensation capacitor bank unit adjustment economic cost is about 0.5–1.2 yuan times. In the energy storage device equipment using battery energy storage, the cost of its equipment regulation according to its use of time for economic conversion, and the optimisation of the time period for 1 h, the unit regulation of the economic cost of 0.5–1.0 yuan/time.

Mathematical model for scheduling optimization of wind solar energy storage complementary distribution network under multiple device connections

On the basis of the WSESCDN scheduling optimization mathematical model, OLTC and SVC type SVC are added for power regulation to achieve precise control of DN in Fig. 4.

In Fig. 4, a suitable load time series prediction model is constructed based on the characteristics of wind and photovoltaic power generation equipment. It can solve the randomness

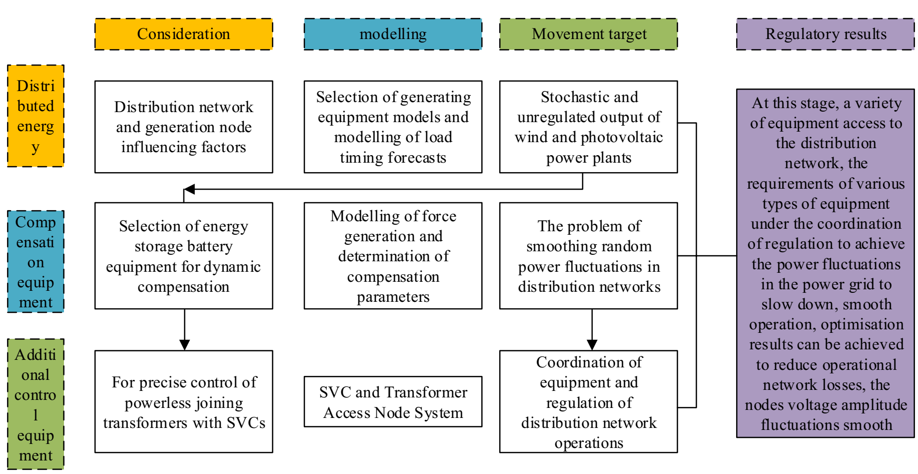


Fig. 4 Mathematical model solution for distribution network scheduling optimization

and un-regulation of wind and photovoltaic equipment output. Then, a WSESCDN scheduling optimization mathematical model is constructed to solve the random power fluctuations in the power grid. To further regulate reactive power, transformers and SVC are added to the IEEE-33 node system based on the WSESCDN scheduling optimization mathematical model. Multiple devices are comprehensively considered to coordinate their actions and regulate the DN network. The study aims to minimize the operating cost of DN, and Eq. (7) is used to construct the objective function.

$$\min \sum_{t=0}^{23} f_{D1} = \Delta P + C_T \sum_{i=1}^{n_T} \Delta u_{Ti} + C_S \sum_{i=1}^{n_g} \Delta u_{Ci} + C_B \sum_{i=1}^{n_b} \Delta u_{Bi} + C_{SVC} \sum_{i=1}^{n_{SVC}} \Delta u_{i,SVC} \tag{7}$$

In Eq. (7), C_{SVC} represents the adjustment cost of SVC. $\Delta u_{i,SVC}$ is the column vector of its action. n_{SVC} represents the number of SVC device adjustments. The optimization of complementary operation of wind and solar energy storage in DN is essentially a complex nonlinear programming problem involving multiple constraints such as power flow, generation, and voltage. Conventional intelligent algorithms are sensitive to parameter selection and slow in searching for optimal values. Applying SOCP to transform it into more manageable problems can effectively overcome these challenges. Optimization involves adjusting control variables such as transformers, capacitors, and reactive power compensation devices to achieve a power flow distribution that meets all operational constraints. Firstly, Second Order Cone Programming Relaxation (SOCP) is used to transform nonlinear programming problems in power systems into more easily solvable second-order cone programming problems. Subsequently, the problem is solved using the CPLEX solver. SOCP by transforming a nonlinear planning problem in a power system into a second-order cone planning problem where the system can be effectively approximated by linearisation. The second-order cone planning relaxation method used is able to simplify the complexity of the original problem without significant loss of accuracy. Although SOCP is able to simplify the complexity of the problem, a loss of accuracy may be introduced during the relaxation process. The hyperparameters (e.g., relaxation coefficients) in the SOCP solution process need to be carefully chosen to avoid inaccuracy of the solution. The problem after SOCP relaxation is solvable for the CPLEX solver, i.e., there exists a solution space where CPLEX can efficiently find the optimal or approximate solution. With the SOCP relaxation, the CPLEX solver can complete the solution in an acceptable amount of time. CPLEX may require a significant amount of computational resources when solving complex problems, especially when faced with large-scale power system optimisation. For particularly complex models, although CPLEX is very efficient, the solution time may still be a bottleneck. When optimizing the complementary wind and solar energy storage, cone optimization method is needed. The second-order cone programming model used is essentially a norm cone problem, represented by Eq. (8).

$$\{(x,t) | \parallel x \parallel_{x \le t}\} = \left\{ \begin{bmatrix} x \\ t \end{bmatrix}^{\top} \begin{bmatrix} I & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} x \\ t \end{bmatrix} \le 0, t \ge 0 \right\} x \in \mathbb{R}^n, t \in \mathbb{R}\} \tag{8}$$

In Eq. (8), the last digit of the sequence is t. I represents the identity matrix. The digital model of power system optimization problem under second-order cone programming is represented by Eq. (9).

$$\min P_{loss} = \sum_{0}^{23} I_{ij}^2 r_{ij} \tag{9}$$

In Eq. (9), I_{ij} represents the current value of the connection between i and j. r_{ij} represents the line resistance. The constraint conditions are represented by Eq. (10).

$$\begin{cases} V_i \leq \left|\overline{V}_i\right| \leq \overline{V}_i, \quad \forall i \in N \\ \underline{S}_i^g \leq S_i^g \leq \overline{S}_i^g, \quad \forall i \in N \\ \underline{I}_{ij} \leq I_{ij} \leq \overline{I}_{ij}, \quad \forall (i,j) \in \varepsilon \end{cases} \tag{10}$$

In Eq. (10), V_i represents the node voltage. S_i^g is the generator power. N represents the number of system nodes. ε means the existence of a very small positive number greater than 0. The above constraints can ensure stable power supply at grid nodes. By applying SOCP, the solution space of power system optimization problems can be expanded. In the minimized scenario, the optimal value of the relaxed problem becomes a lower bound estimate of the optimal value of the original problem. This method ensures that the optimal solution of the wind and solar energy storage DN optimization model is consistent with the optimal solution of the original problem after being transformed into a second-order cone programming problem. Figure 5 is a schematic diagram of SOCP conversion.

In Fig. 5, the solution domain of the original non convex problem is $F_{original}$, which is transformed into a convex second-order conical domain F_{SOCP} through SOCP technique. This transformation reshapes the original problem into a convex optimization problem. The optimal solution Z obtained in the domain F_{SOCP} after SOCP conversion is the lower bound of the optimal solution of the original problem. If Z also belongs to $F_{original}$, it indicates that relaxation is effective. In this case, the Z in the new domain matches the Z of the original problem. Government policy support is a key factor in promoting renewable energy access and its integrated optimisation with the distribution grid. These include financial subsidies, tax incentives, green certificates and renewable energy quota systems, which aim to reduce the investment costs of renewable energy projects and increase their economic attractiveness. Increased subsidies and tax

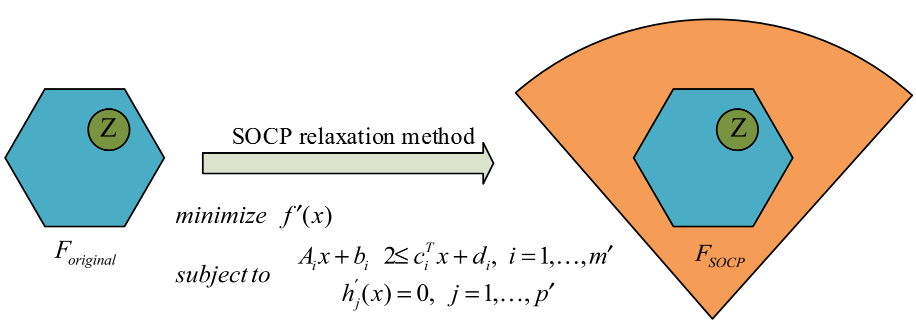


Fig. 5 Schematic diagram of SOCP conversion

adjustments affect the economic parameters in the model, such as cost and benefit calculations, and need to increase the weighting of environmental benefits and reduce the economic benefit targets. Requirements for voltage levels and frequency stability may determine the size and type of reactive power compensation devices. The proposed carbon neutral objective will lead to the adjustment of the model optimisation objective from pure cost–benefit optimisation to multi-objective optimisation that includes environmental impact assessment.

The study proposes a mathematical model for integrated optimisation of wind, energy, storage and complementary distribution networks, which not only emphasises the smooth operation and efficiency improvement of the distribution network through refined control and optimisation strategies, but also gives due consideration to economic factors. The implementation of the research model helps to reduce dependence on fossil fuels and lower carbon emissions compared to traditional energy integration models, thereby reducing environmental compliance costs and potential carbon tax charges in the long term. In a market environment where new energy prices are becoming increasingly competitive, the model further enhances the economic attractiveness of the grid by increasing access and utilisation efficiency of renewable energy sources.

Mathematical model analysis of comprehensive optimization of wind solar energy storage complementary distribution network based on multiple control devices

The proposed wind solar energy storage DN model and algorithm were validated using an IEEE-33 node system. The system integrated wind power, photovoltaic, and energy storage devices to form a complex nonlinear problem, which was solved using Particle Swarm Optimization (PSO) algorithm. The kernel of the test environment is a laptop computer with intel Core i7-4600 M and a frequency of 2.90 GHz. Considering the existence of time requirements for the distribution network regulation and compensation device, the upper limit of the number of particle swarm iterations is set to 100 times to meet the optimisation and time requirements. Table 1 shows DN devices and parameters.

The total load of DN used in the study was 3715 kilowatts and 2300 kilovolts, with voltage levels maintained between 0.95 and 1.05 pu. The reactive power compensation facilities were located at nodes 7, 24, and 30. The photovoltaic and energy storage system was connected to nodes 25 and 32. The wind power and energy storage equipment were connected to node 8. In the analysis of the optimisation problem, the wind photovoltaic power generation equipment is considered as an uncontrollable active power source, in order to demonstrate the characteristics of the active output of the two equipment,

Table 1 Equipment and parameters of distribution network

Device name	Adjustment range	Access location
Capacitors	200 kMVar, 5 sets per node	Nodes 7, 24, 32
Wind power generation equipment	200 kW	Node 8
Photovoltaic power generation equipment	200 kW	Nodes 25 and 32
Energy storage equipment	480 kW-h	Nodes 8, 25, 32

i.e., the active power provided by the wind photovoltaic power generation equipment remains unaffected by the load demand with the peak load, and to create a prerequisite for the optimal regulation of the distribution network operation by using the storage equipment and the capacitor bank. Figure 6 shows the DN24 hour load curve and active power output curve under load timing factors.

Figure 6a shows the trend of load changes throughout the day, with peak periods occurring from 10 a.m. to 2 p.m. and 5 p.m. to 11 p.m., while low periods occur from 0 to 9 a.m. and 3 p.m. to 4 p.m. Figure 6b shows the power generation of wind and photovoltaic power generation equipment. The maximum daily active output of wind and photovoltaic power generation within 24 h was 200 kW, but the output of wind power generation was unstable, especially during peak load periods. The main power supply period for photovoltaic power generation was from 6 a.m. to 6 p.m., with a reactive power output range of −0.15 to 0.45 MVar. In the optimization analysis, wind and photovoltaic power were considered as uncontrollable active power sources, demonstrating their output characteristics that were independent of peak load demand. These findings provide a basis for optimizing DN regulation using energy storage devices and capacitor banks. The voltage deviation of the distribution system before grid connected new energy was 0.1376, and reactive power compensation through node selection could improve the voltage level. If only using capacitors for reactive power compensation, it will not be able to meet the reactive power needed by the distribution network. In the scheduling ideology, firstly applying grouped switching capacitor banks for a large amount of reactive power compensation, and then applying continuous reactive power compensator SVC for compensation when it is smaller than the reactive power compensation capacity of each group of capacitors, which should be considered as such in terms of both economy and equipment maintenance. The reactive power compensation device starts to call from 5 a.m., and the capacitor banks are in full load working condition from 5 a.m. to 8 p.m. The dynamic adjustment of reactive power by SVC reduces the irrational flow of reactive power in the network, reduces the network loss, and supports the voltage of each node. Based on PSO optimization calculation, the optimal action variables of DN devices were obtained, and the optimal adjustment schemes for each device were sorted out considering the optimal effect of DN. Figure 7 shows the comparison of DN loss values before and after the implementation of the plan.

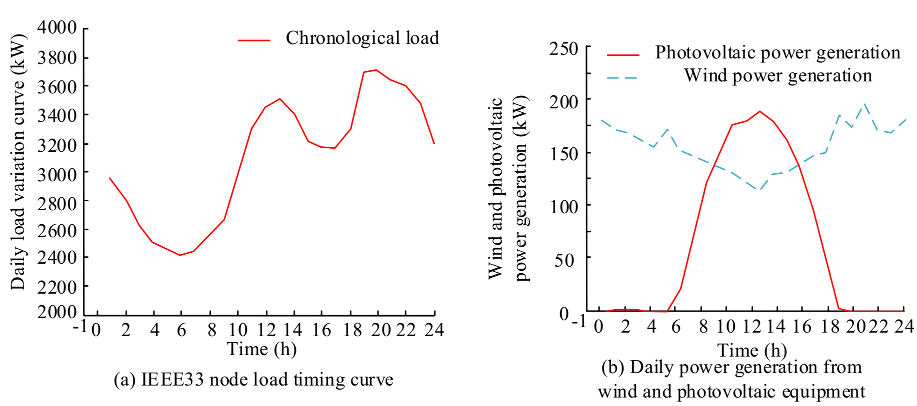


Fig. 6 24-h load curve and active output curve

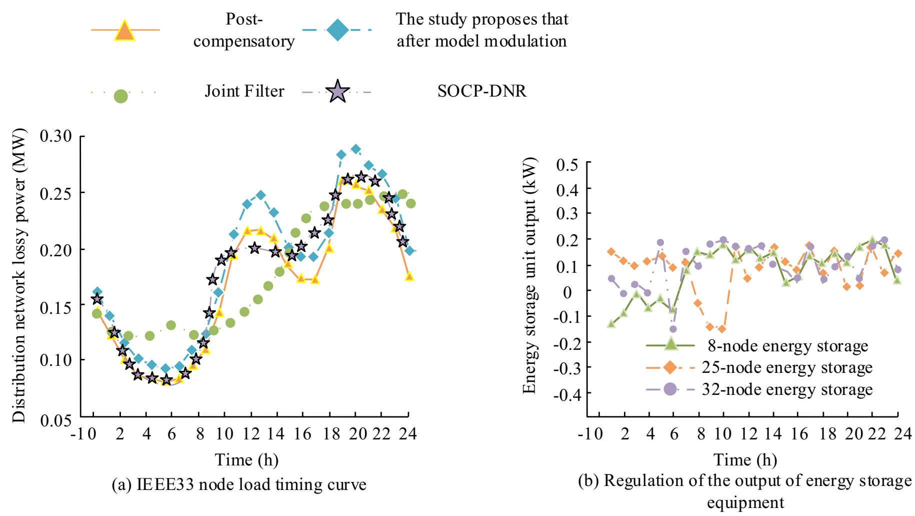


Fig. 7 Comparison results of distribution network loss values

Figure 7a shows the dynamic variation of active power loss within DN24 hours. The performance of the proposed model for regulation of compensation devices is more stable than Joint filter model (Yu et al. 2018) and Second-order cone planning model for distribution network reconfiguration (SOCP-DNR) model (Ma et al. 2019), which reduces the impact of sudden fluctuations in the grid. In the optimization results after introducing optimized compensation equipment, an average of 0.05 MW of active power loss could be reduced per hour, and approximately 1.03 MW of active power could be saved in a cumulative day. Figure 7b depicts the output of energy storage devices at nodes 8, 25, and 32. Energy storage devices absorbed excess active power from DN during off peak hours. During the peak period from 11 to 23, active power was released to DN to meet the increased electricity demand and ensure stable operation of DN. In a variety of equipment regulation, distribution network active power and reactive power can achieve a stable dynamic balance, especially continuous reactive power compensation equipment SVC and on-load voltage regulator transformer to join, control reactive power compensation is more accurate adjustment is more reasonable, so that the load node voltage fluctuations slowed down. Figure 8 shows the voltage at each node of the 24-h DN.

Figure 8 shows the voltage amplitude of each node within DN24 hours. Remote node 18 remained within the normal voltage range. This is thanks to reactive power compensation and energy storage devices, which ensure voltage stability even under fluctuations in wind and solar power generation. Overall, the DN voltage fluctuated steadily between 0.95 pu and 1.05 pu, indicating the overall stability of the system and that user electricity consumption was not affected by fluctuations in wind and solar power generation. In the optimized IEEE-33 node system simulation, OLTC and SVC type reactive power compensation devices were integrated into DN. OLTC was usually located at the outlet of the generator node, while wind and photovoltaic equipment were connected to the end node to cope with low voltage. The capacitor

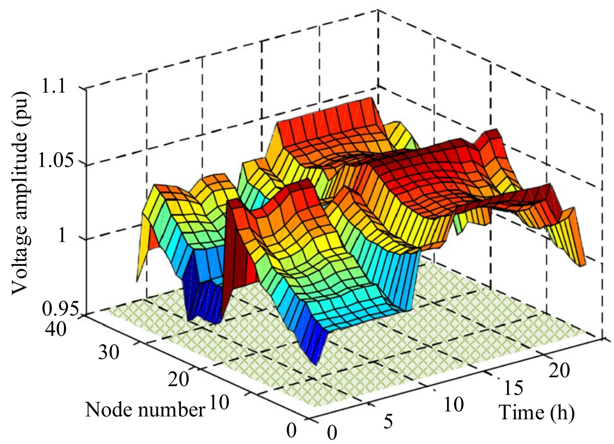


Fig. 8 24-h distribution network voltage at each node

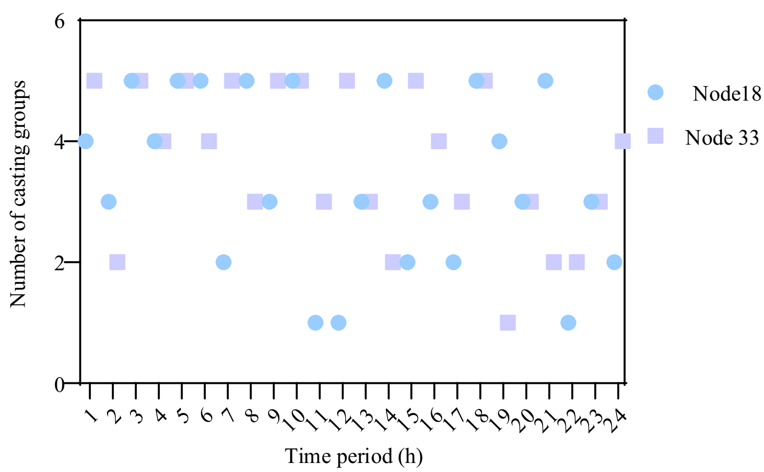
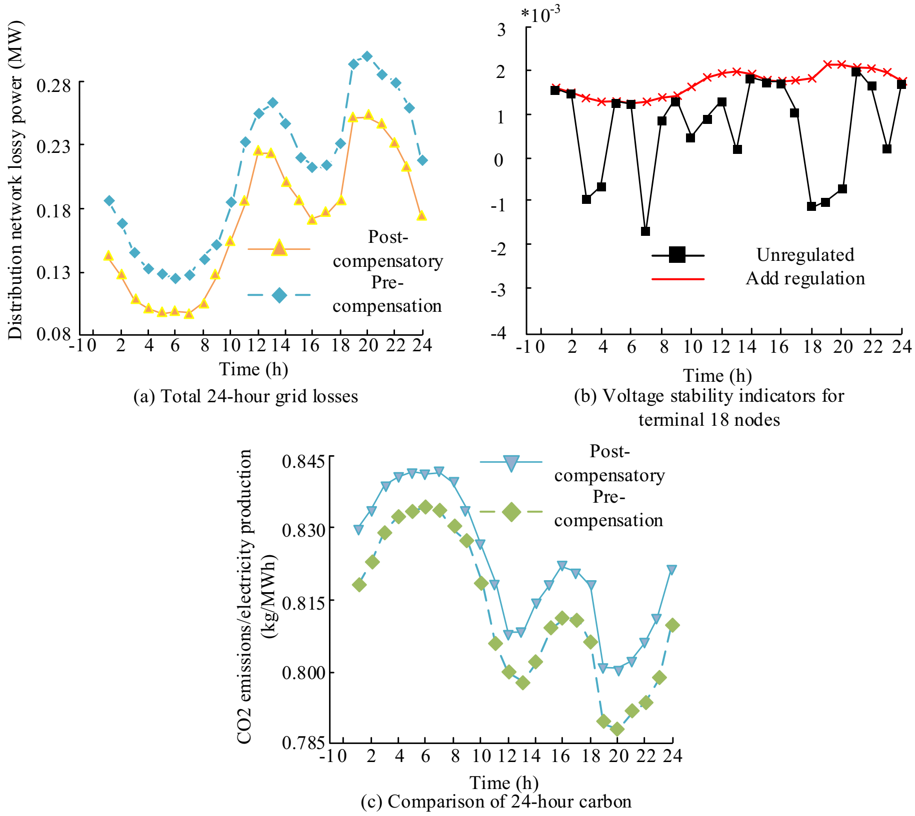


Fig. 9 Number of node casting groups

bank and SVC were installed at these two nodes, considering the multiple branches of nodes 6 and 16 as the DN end. Figure 9 shows the DN24 hour node switching groups.

Figure 9 shows the switching situation of nodes 18 and 33 in DN within 24 h. During period 1, nodes 18 and 33 cast 4 and 5 sets of capacitors, respectively. In period 2, node 18 cast 3 groups and node 33 cast 2 groups. In the following hours, the capacitor banks switched between the two nodes changed respectively. In period 3, both nodes had 5 groups, while in period 4, there were 4 groups. During periods 6 to 8, the number of casting for node 18 gradually decreased from 5 to 3 groups, while node 33 first decreased to 4 groups and then increased to 5 groups. During periods 9 to 11, the value of node 18 varied between groups 3 to 1, while node 33 was between groups 5 to 3. In the afternoon, the casting numbers of the two nodes continued to change, for example, during period 14, node 18 had 5 groups, and node 33 had 2 groups. During the evening to evening period from 17 to 19, the values of the two nodes decreased slightly. Finally, at the end of the 24 h period, node 18 had 2 groups and node 33 had 4 groups. Overall, the casting numbers of the capacitor banks of the two nodes show different trends within a day. Figure 10 shows the changes before and after DN regulation.



(a) Total 24-hour grid losses
(b) Voltage stability indicators for terminal 18 nodes
(c) Comparison of 24-hour carbon emissions

Fig. 10 Changes before and after distribution network regulation

Figure 10a shows a comparison of the total loss of DN within 24 h. After applying multi-device regulation, the average 24-h active power loss of WSESCDN decreased by 0.07 MW, especially during the peak period from 17 to 23 h. Figure 10b shows the voltage stability changes at terminal 18 nodes. The voltage stability of optimized terminal node 18 was stable between 0.0015 and 0.0017, but fluctuated significantly when not regulated. After introducing SVC and OLTC, the active and reactive power were effectively balanced, reducing voltage fluctuations. Figure 10c shows the comparison of carbon emission intensity, and the overall decrease of carbon emission intensity after regulation is about 0.015 kg/MWh compared with that before regulation. Figure 11 shows the amplitude of DN network nodes within 24 h.

In Fig. 11, the voltage of the DN node stabilized at 1 to 1.1 pu within 24 h. Especially during peak hours from 15 to 24 h, it remained normal without any abnormal fluctuations when the control equipment was not added. Multi-device precise regulation ensures voltage stability and avoids low or high voltage issues. The application of second-order cone programming relaxation algorithm effectively shortens optimization time and ensures the fast and accurate operation of DN. The CPU usage of the model while in use was tested by performing solving and scenario simulation and the results are shown in Fig. 12.

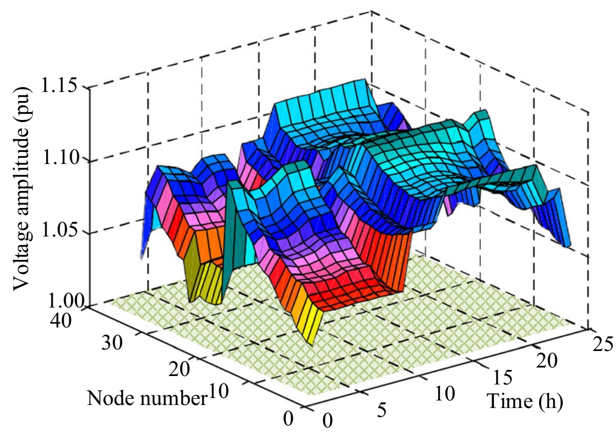


Fig. 11 Changes in amplitude of distribution network nodes

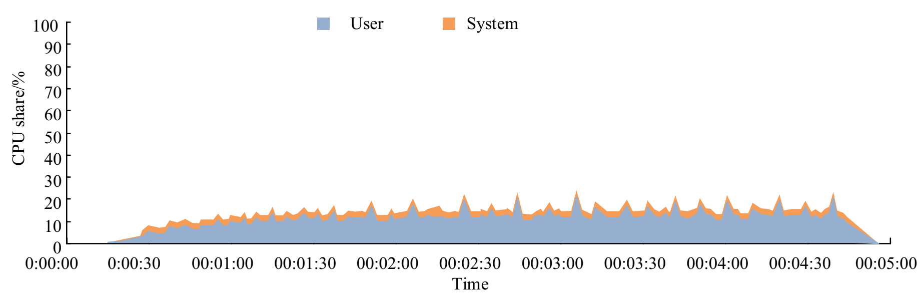


Fig. 12 Performance evaluation results

As shown in Fig. 12, it is the result of the system CPU occupancy test during the running time of the model, with the continuous running of the solution, the CPU occupancy of the server increases, and the overall trend is upward, but the fluctuation is large, and the highest CPU occupancy is 21.7%, and the lowest CPU occupancy is at the beginning of the process, and the CPU occupancy basically stays below 20% throughout the simulation running period, and the server resource occupancy is within the controllable The ratio of server resources is within the controllable range. The trend of the system CPU ratio over time is similar to the server resource ratio, and slightly higher than the server resource ratio. During the entire running time of the solving process, the highest CPU occupation is 27.6%, the lowest CPU occupation is at the beginning of the process, and the CPU occupation basically stays below 30% during the entire running time of the script, and the final computation time is 4 min and 56 s.

Conclusion

In the context of global energy transformation and sustainable development, integrating and utilizing renewable energy effectively have become the key to the development of the power system. The study focuses on the multifaceted challenges of optimizing DN operation and explores the active DN operation control method based on energy storage and SVC. A WSESCDN comprehensive optimization mathematical model based on multiple regulatory devices is analyzed. These results indicate that the peak load period of DN occurs from 10 a.m. to 2 p.m. and from 5 to 11 p.m., while the low load period is from 0 to 9 a.m. and from 3 to 4 p.m. The optimization results after introducing optimized compensation equipment show that an average of 0.05 MW of active power loss can be reduced per hour, and approximately 1.03 MW of active power can be saved in a cumulative day. Energy storage equipment absorbs excess active power from DN during off peak hours and releases active power to DN during peak periods from 11 to 23 o'clock to meet increased electricity demand, ensuring stable operation of DN. Overall, the DN voltage fluctuates steadily between 0.95 pu and 1.05 pu, indicating the overall stability of the system and that user electricity consumption is not affected by fluctuations in wind and solar power generation. After applying multi-device regulation, the average 24-h active power loss of WSESCDN has decreased by 0.07 MW, especially during the peak period from 17:00 to 23:00. The voltage stability of optimized terminal node 18 is stable between 0.0015 and 0.0017, but fluctuates significantly when not regulated. After introducing SVC and OLTC, the active and reactive power are effectively balanced, reducing voltage fluctuations. The voltage of the DN node remains stable at 1 to 1.1 pu within 24 h, especially during peak hours from 15 to 24 o'clock, without any abnormal fluctuations when the control equipment is not added. These results indicate that precise control of multiple devices ensures voltage stability and avoids issues of low or high voltage. The application of second-order cone programming relaxation algorithm effectively shortens optimization time and ensures the fast and accurate operation of DN. However, the study does not delve into the solutions to maintain DN stability under fault conditions. For this reason, in the subsequent research, the method of using network reconfiguration to restore power to the loads in the wind, solar, and storage complementary distribution network can be considered in the line failure scenario. In the case of fewer affected load nodes after line failure, load restoration can be carried out by contact switch action only, without having to consider power constraints such as energy storage equipment, reducing economic losses. At the same time, the wind, light and storage complementary active distribution network operation, the emergence of a variety of factors interacting with each other, should be the first to restore the power supply to the important loads. The study also lacks a comparative model under real-world data, which makes the study insufficiently robust, and subsequent studies can investigate the co-optimisation model of regulation parameters using multiple deep learning algorithms and apply the model to the wind power transmission grid in Northwest China to improve the study robustness. At the same time, in order to promote the practicality of the model, it can be considered that feedback from potential users and distribution network operators can be included in the construction of the subsequent intelligent system to build an interactive intelligent deployment system.

Author contributions

Ke Zhou: Conceptualization, Methodology, Writing – original draft Biyun Zhang: Writing – original draft, Software, Formal analysis Qingren Jin: Writing – review & editing, Supervision Hao Bai: Data curation, Investigation Weichen Yang: Writing – review & editing, Investigation Tong Liu: Data curation,

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Availability of data and materials

The data will be made available on request.

Declarations

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Not applicable.

Consent for publication
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The authors declare that there is no conflict interests.

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