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A Multi-Time-Scale Source-Load-Storage Collaborative Optimization Scheduling Model with Source-Load Matching Degree

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Abstract:

In the context of a high proportion of new energy sources accessing distribution networks, the uncertainty surrounding new energy sources and loads puts pressure on distribution networks to reduce peak demand. For medium and low voltage distribution networks with a high proportion of new energy sources, this paper proposes a multi-time-scale active distribution network scheduling model that considers flexible load scheduling. Firstly, based on information entropy theory, a source-load matching index is proposed to measure the degree to which the load matches the new energy output. A regulation plan is then formulated for the day-ahead energy storage system and flexible load to optimise the day-ahead load of the distribution network. Secondly, during the intraday phase, the output of gas turbine units, flexible loads and energy storage is optimised to minimise dispatching costs and achieve an optimal operating scenario for fully absorbing new energy. Finally, the economic cost optimisation of the multi-time scale source-load-storage collaborative optimal scheduling model is verified using the IEEE-33 node, and the model is solved using the CPLEX and particle swarm optimisation algorithms. The effectiveness of the proposed model was verified.

Keywords: Active distribution network, flexible load, source-load-storage coordination, multiple time scales.

INTRODUCTION

In recent years, distributed power generation, mainly from new energy sources, has become an important development direction for the future of electricity [1]. However, in the context of the large-scale integration of new energy sources, the proportion of thermal power has decreased and the self-regulation capacity of distribution networks has declined. This has resulted in increasingly prominent problems [2], such as the insufficient absorption of new energy and imbalances in power and electricity within distribution networks. At the same time, the significant increase in new energy access has led to greater uncertainty in the power generation sector of distribution networks. It is necessary to consider not only the peak shaving demand brought about by changes in the time period of new energy and load demand, but also the impact of seasonal changes and long-term uncertainty in new energy output on load supply [3-5].

In response to these issues, some experts have divided the operation of distribution networks into multi-stage optimisation decision-making problems based on the high randomness and volatility of distributed generation (DG), as represented by photovoltaic power [6]. This ensures the stable operation of the distribution network system by optimising the power supply, demand-side resources [7], or energy storage resources in each time period [8]. A model of power source expansion with a high proportion of renewable energy has been established in the literature [9] to predict the future development of China's power source structure. Another study prioritises a rough scheduling plan for long-duration energy storage based on historical data, tracking it during real-time scheduling to achieve dynamic planning. Other literature [10] takes into account changes in distribution network planning structures, building multi-stage models of urban distribution networks to achieve precise long-term predictions. This model contains a large number of decision variables and includes non-linear parameters. Due to limitations [11] in hardware capabilities, simplified operations are required and the model is only suitable for evolution analysis of small-scale systems [12-13]. Conversely, in the context of the rapid development of distribution networks, there are many uncertainties to consider, which makes building and solving the model overly cumbersome.

As research into resources such as energy storage and transferable loads deepens, the operating mode of distribution networks is gradually shifting from 'source following load' to a dynamic power and energy balance [14] coordinated by 'source, load and storage'. Some scholars have studied collaborative dispatch strategies for various flexible dispatch resources of 'source-load-storage'. The literature [15] presents a source-storage peak-load scheduling strategy that includes wind, solar, and storage systems, [16] and establishes a deep source-load-storage peak-load scheduling model based on price demand response and phased electricity prices. A flexible planning model for energy storage unit types and capacity, considering flexible load, is proposed [17]. Although the aforementioned study examined various resources within the distribution network, it failed to propose indicators that could clearly quantify the balancing capacity of the network. Consequently, it was unable to ensure the effective utilisation of source, load and storage resources, nor the safe operation [18] of the network following the integration of new energy sources such as wind and solar.

In response to these issues, this paper uses the theory of information entropy to construct a balance index that measures the absorption capacity of the distribution network system. This achieves effective quantification of system balance capacity and full utilisation of various flexible resources that current research on medium and low voltage distribution networks has not effectively quantified. The main research contents and innovation points are as follows:

1) A multi-time-scale scheduling model is established that considers source-load-storage collaborative optimisation in order to ensure the safe and stable operation of the distribution network.

2) A multi-time-scale intelligent optimisation and regulation model for active distribution networks has been established.

3) Considering the uncertainty of the active distribution network in multiple time periods, an index for quantifying the source-load-power balance is constructed based on information entropy theory. The forms in which source-load side resources affect distribution network operation were analysed, as were the results of optimised scheduling.

CONSTRUCTION OF SOURCE-LOAD BALANCE INDEX BASED ON INFORMATION ENTROPY THEORY

Access to new energy sources, such as wind and solar power, has introduced issues such as source-load imbalance to the distribution network. This increases the pressure to reduce peak demand on the upper-level grid and affects the stable operation of the distribution network. Therefore, it is necessary to optimise the distribution of flexible resources, such as flexible loads and energy storage systems, in the grid by coordinating the dispatch of power sources, loads, and energy storage, in order to enhance the capacity of the distribution network to accommodate new energy.

1.1 Active distribution network multi-time scale optimisation and regulation

The uncertainty of new energy sources, such as wind and solar power, and their loads, affects the operation of distribution networks in two main ways:1) New energy sources are affected by environmental factors, which impact the stability and safety of distribution networks [19]. 2) When energy storage equipment is used to maintain source-load balance, there is an error between the planned and actual states, affecting the system's future regulation capacity [20]. Therefore, based on the concept of rolling optimisation for multi-time-scale scheduling, the output of energy storage charging and discharging, as well as gas turbine units, is optimised according to the real-time output fluctuations of wind and solar power, as well as load, within the day in the day-ahead scheduling plan. This ensures the day-ahead plan while reducing the daily operating cost of the distribution network. The multi-time scheduling model framework is shown in Figure 1.

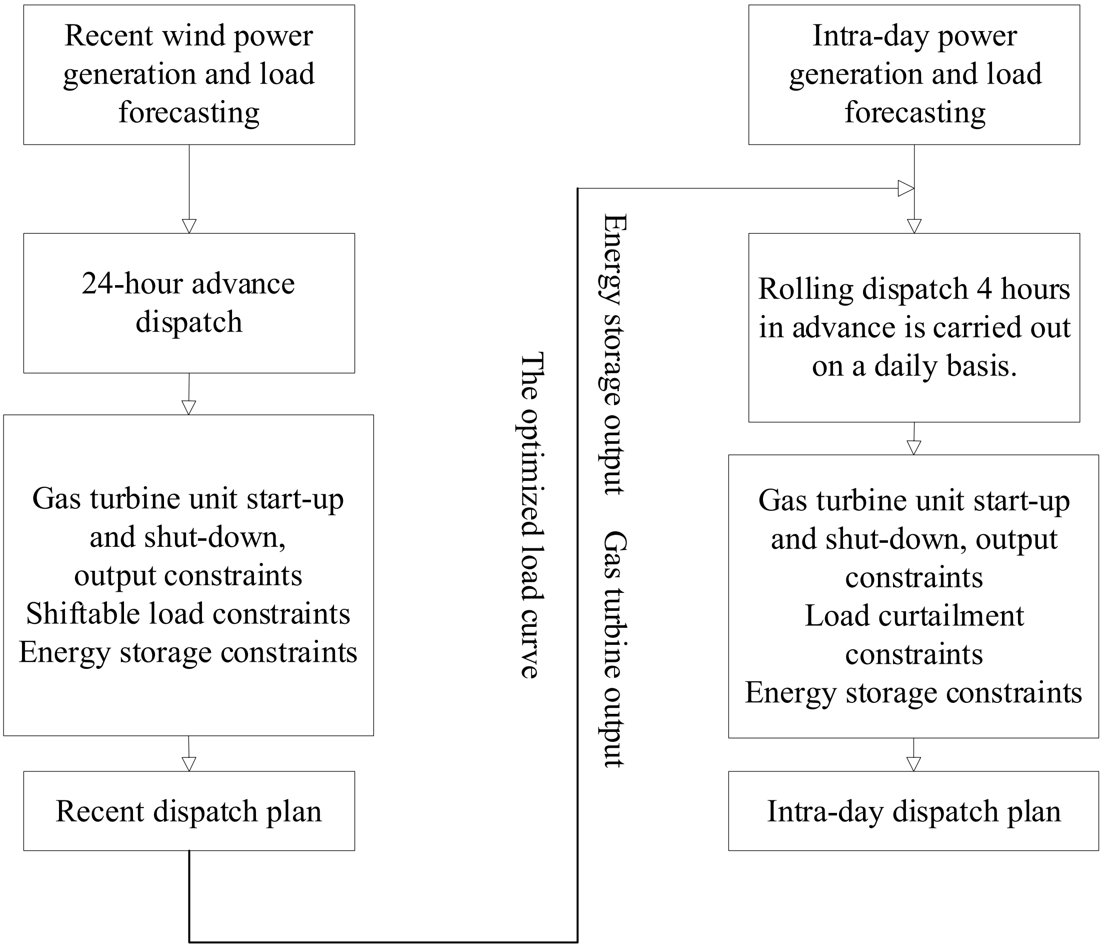


Fig.1 Multi-time scheduling model framework

1.2 Numerical measurement methods for source-charge time series

In mathematics, the Euclidean distance is generally used to represent the numerical and morphological similarity between two data sequences. The smaller the distance, the more similar they are; otherwise, the less similar they are. However, in this scenario, the traditional Euclidean distance mainly reflects the proportion of new energy rather than the similarity of curves. Therefore, this paper proposes a new method of measuring source-load time series that can bridge the significant disparity between new energy output and load output.

The traditional Euclidean distance calculation expression is as follows:

$$D(X,Y)=\sqrt{\sum_{t=1}^{T}(x_t-y_t)} \tag{1}$$

The improved Euclidean distance formula reduces the difference between the two by translating the new energy curves, and then calculates the gap between them to minimise the impact of differences in the data on curve similarity. The formula for the improved Euclidean distance is:

$$D'(X,Y)=\sqrt{\sum_{t=1}^{T}(x_t-y_t)-\Delta XY} \tag{2}$$

$$\Delta XY=\max(\min(X-Y),\min(X-Y)) \tag{3}$$

In the formula: $\delta=D'(X,Y)$ let be numerical similarity; $D(X,Y)$ is the traditional Euclidean distance between time series X and Y; T is the length of the time series.

1.3 New energy - load balance

Taking into account the uncertainty on both sides of the source and load, the pre-day source and load prediction results are optimised. In other words, the obtained daily load curve and the new energy output curve are discretised to produce the corresponding time series. The scene generation method is then used to transform the stochastic optimisation problem into a deterministic optimisation problem, reducing prediction error and simplifying computational complexity.

Discretisation of the conventional daily load curve and the DG daily output curve is performed as follows:

The regular load time series is:

$$\{L_{TR,t}\} = \{l_{TR,1}, l_{TR,2}, ..., l_{TR,n}\} \tag{4}$$

In the formula: $L_{TR,n}$, where n is the load data corresponding to the distribution network at time n.

The time series of new energy output is:

$$\{P_{DG,t}\} = \{p_{DG,1}, p_{DG,2}, ..., p_{DG,n}\} \tag{5}$$

In the formula: $P_{DG,t}$, where t represents the output data of the new energy at the nth moment.

From Equations (6) and (7), the load time series is as follows:

$$\{L_{NL,t}\} = \{L_{TR,t}\} - \{P_{DG,t}\} \tag{6}$$

$$\{L_{NL,t}\} = \{L_{TR,1}, L_{TR,2}, ..., L_{TR,n}\} \tag{7}$$

In the formula: $L_{NL,n}$, where n represents the net load data at the nth moment. Taking the absolute value of the net load data gives the net load data:

$$\{L_{NL,t}\} = \{L_{NL,t1}, L_{NL,t2}, ..., L_{NL,ti}\} \tag{8}$$

After normalising the net load data, we get:

$$b_{t,i} = \frac{|l_{NL,ti}|}{\max |l_{NL,ti}|} \tag{9}$$

In the formula: b_t represents the normalized value of the net load at the i-th moment; $l_{NL,t}$ represents the net load value at the i-th moment..

$$H(B_{t,i}) = -\sum_{k=1}^{T} b_{t,i} \ln b_{t,i} \tag{10}$$

According to the theory of information entropy, the more similar the source-load operation curves are, the smaller the net load and the greater the potential for absorbing new energy. Conversely, the opposite is true. Therefore, this paper proposes constructing the source-charge balance index through information entropy as a quantitative measure of source-charge balance.

Let the information entropy of the net load at time t be $H(B_{t,i})$, then:

$$H(B_{t,i}) = -\sum_{k=1}^{T} b_{t,i} \ln b_{t,i} \tag{11}$$

At this time, the smaller $H(B_{t,i})$, the smaller the net load, the higher the load's absorption of new energy, and the higher the source-load balance of the distribution network. Therefore, the degree of matching between the output of new energy and the power of the load in time series is defined as follows:

$$K_{bi} = (1 - \frac{H(X_{t,i})}{H_{s\tan d}}) \times 100\% \tag{12}$$

In the formula: K_{bi} is the source-load balance at the i-th moment, and H_{stand} represents the baseline value of the net load processing information entropy. The source-load balance K_{bi} can effectively describe the degree to which source-load data matches in a time series. The greater the Kbi value, the greater the balance between the output of new energy and conventional load. Consequently, the consumption level of new energy will improve significantly, effectively reducing the operating cost of the distribution network.

CONSTRUCTION OF SOURCE-LOAD BALANCE INDEX BASED ON INFORMATION ENTROPY THEORY

In the day-ahead stage, the CPLEX solver is used to solve the scheduling model. The load forecast power, flexible load response capacity, and source-load balance indicators are introduced into the day-ahead distribution network scheduling model to obtain the day-ahead source-load-storage scheduling plan for the distribution network. The intra-day particle swarm algorithm is then used to schedule the actual state of charge of energy storage and flexible load, taking into account the difference between the short-term predicted power and the day-ahead power prediction. This ensures the economic operation of energy storage and achieves the optimal source-load balance in each period of the distribution network.

2.1 Optimising the scheduling in advance

The objective of the day-ahead scheduling in this paper is to maximise the source-load balance and adjust the dispatchable resources for the day ahead. The day-ahead scheduling model has a time window length of 24 hours and an interval of 1 hour. This pre-determines the flexible load scheduling for each period, the charging and discharging periods for energy storage and the flexible load adjustment range.

2.1.1 Day-ahead objective function

The day-ahead source-load-storage collaborative optimisation scheduling model takes the maximum balance degree during the entire operation period as the objective function, denoted as F.:

$$\max F = \sum_{i=1}^{T} K_{bi} \tag{13}$$

In the formula: K_{bi} is the source charge equilibrium at the i-th moment, which can be calculated by formula (12).

2.1.2 Constraints

In addition to traditional constraints such as the power flow equation, line power and node voltage constraints, the operation of the distribution network during the regulation period also needs to meet the relevant energy storage system and flexible load constraints.

1) Flexible load constraints

There are various forms of flexible loads on the user side. Among them, the transferable loads are mainly industrial loads. Constrained by the production process, the electricity load needs to be planned in advance and arranged for day-ahead regulation. The constraints are that the total load remains unchanged within the regulation cycle and there are upper and lower limits for power transfer.

$$\sum_{t=0}^{T} P_{shift}(t) = \sum_{t=0}^{T} P_{shift}^{ori}(t) \tag{14}$$

$$P_{shift}^{\min}(t) \le P_{shift}(t) \le P_{shift}^{\max}(t) \tag{15}$$

In the formula: P_{shift}(t) and $P_{shift}^{ori}(t)$ represent the transferable loads before and after the transfer, respectively; $P_{shift}^{max}(t)$ and $P_{shift}^{min}(t)$ represent the lower and upper limits of the power of the transferable load at time t, respectively.

2) Operational constraints of the energy storage system

To ensure the safe operation of energy storage, the charging and discharging power of the energy storage must not exceed the charging and discharging power of the battery.

$$-P_{bess} \le P_{bat}(t) \le P_{bess} \tag{16}$$

In the formula: $P_{bat}(t)$ is the charge and discharge power of the energy storage to the system at different time periods. P_{bess} represents the maximum allowable charging and discharging power of the energy storage system. Positive values represent discharge and negative values represent charge.

3) State of charge constraint of the energy storage system

To avoid impacting the battery's lifespan through overcharging or overdischarging, the state of charge is limited to a certain range.

$$\begin{cases} 0.1 \le S(t) \le 0.9 \\ S(0) = S(24) \end{cases} \tag{17}$$

In the formula: S(0) and S(24) are the state of charge of the energy storage system at times 0 and 24, respectively.
4) Charge and discharge energy conservation constraints within the daily cycle:

The transformer area must maintain a balance between the real-time power it interacts with users and the real-time power it interacts with the distribution network and new energy sources.

$$P_{PV}(t) + P_{grid}(t) + P_{bat}(t) = P_L(t) \tag{18}$$

In the formula: $P_{PV}(t)$ is the output of new energy in the transformer area, $P_{grid}(t)$ is the power flowing from one node to another on the distribution network; $P_{bat}(t)$ is the charge and discharge power of energy storage in time t, and $P_L(t)$ is the transformer area load power.

5) Gas turbine unit constraints

To ensure the solution can be applied in practice and avoid situations where the continuous discharge period exceeds the remaining storage capacity or the continuous charge exceeds the storage capacity, certain charge and discharge constraints are imposed.

$$\begin{cases} u_{k,t}^{G} P_{k,\min}^{G} \le P_k^G(t) \le u_{k,t}^{G} P_{k,\max}^{G} \\ D_k^{G+} \le \Delta P_k^G(t) \le D_k^{G-} \\ T_K \le \Delta T \end{cases} \tag{19}$$

In the formula: $u_{k,t}^{G}$ is the operating state variable of the k-th gas unit at time t, with the operating state being 1 and the off state being 0; $P_k^G(t)$ is the output of the k-th gas unit at time t, $P_{k,min}^G$, $P_{k,max}^G$ are the maximum output and minimum output of the thermal power unit, respectively; $\Delta P_k^G(t)$ is the rate of change of output power of k gas units at time t, and D_k^{G+}, D_k^{G+} are the maximum upward and downward power changes of conventional units under unit operating time; ΔT is the output interval of the gas unit, T_K is the k minimum start-up time of the coal-fired unit.

2.2 Intraday optimal dispatch

According to the day-ahead scheduling scheme, the day-ahead flexible load scheduling and the day-ahead output of gas units are optimised in a rolling manner at 15-minute intervals within a 4-hour time window, based on the normal distribution error of the day-ahead forecast curve, to minimise the day-ahead operating cost.

2.2.1 Intraday objective function

The objective function of intraday scheduling is to minimise the operating cost of the distribution network, as shown in equation (20).

$$f = \sum_{t=1}^{T} (C_{grid}(t) + C_{loss}(t) + C_{ES}(t) + C_{FL}(t)) \tag{20}$$

In the formula: T is the number of regulatory periods within the regulatory period; $C_{grid}(t)$ is the purchase and sale cost of the distribution network at time t, $C_{loss}(t)$ is the active power loss cost of the distribution network at time t, $C_{ES}(t)$ is the regulation cost of the energy storage equipment at time t, and $C_{FL}(t)$ is the flexible load invocation cost. The specific calculation formulas for each cost variable in the formula are as follows:

1) Interaction cost of the upper-level grid

$$C_{grid}(t)=\lambda_{grid}\left|P_{grid}(t)\right| \tag{21}$$

2) Network loss cost

$$C_{loss}(t)=\lambda_{loss}(P_{loss\cdot grid}(t)+P_{loss\cdot ES}(t)) \tag{22}$$

3) Energy storage loss cost

$$P_{loss\cdot ES}(t)=(1-\eta_{cha})P_{ES}^{cha}(t)+(\frac{1}{\eta_{dis}}-1)P_{ES}^{dis}(t)+\eta_{dis}^{self}S_{ES}\cdot SOC(t) \tag{23}$$

$$C_{ES}(t)=\lambda_{ES}(\eta_{cha}P_{ES}^{cha}(t)+\frac{P_{ES}^{dis}(t)}{\eta_{dis}}) \tag{24}$$

4) Compensation costs for flexible loads

$$C_{ES}(t)=\lambda_s P_s(t)+\lambda_t P_t(t)+\lambda_c P_c(t) \tag{25}$$

In the formula: λ_{grid}, λ_{loss}, λ_{ES} are unit electricity price, loss cost coefficient, energy storage regulation, and cost coefficient, respectively; $P_{grid}(t)$, $P_{grid}^{loss\cdot}(t)$, $P_{\cdot ES}^{loss}(t)$, $P_{ES}^{cha}(t)$ and $P_{ES}^{dis}(t)$ are respectively the interaction power of 33 nodes with the upper-level grid, the active power loss of 33 nodes in the distribution network, the active power loss of energy storage, the charging power of energy storage and the discharging power of energy storage at time t; η_{cha}, η_{dis} and η_{self} dis represent the charging efficiency, discharging efficiency and self-discharging rate of the energy storage system, respectively; SES is the total capacity of the energy storage system; λ_s, λ_t, and λ_c are compensation prices for translable loads, transferable loads, and reducible loads in units, and $P_s(t)$, $P_t(t)$, and $P_c(t)$ are loads involved in optimization among translable loads, transferable loads, and reducible loads.

2.2.2 Constraints

Except for flexible loads, the other constraints are consistent with day-ahead scheduling. Intra-day dispatchable flexible loads mainly include transferable and translable loads. These loads are flexible in terms of their power consumption characteristics and time, and are used by commercial and entertainment industries. They are scheduled within the day.

1) Transferable load constraints:

$$P_t^{\min}(t)\le P_t(t)\le P_t^{\max}(t) \tag{26}$$

$$\sum_{t=1}^{T}P_t(t)=0 \tag{27}$$

In the formula: $P_{\max t}$ (t) and $P_{\min t}$ (t) are the upper and lower limits of the transferable load for the t-th operating period.

2) Reducible load constraints:

$$P_c^{\min}(t)\le P_c(t)\le P_c^{\max}(t) \tag{28}$$

In the formula: $P_{\max_c}(t)$ and $P_c^{min}(t)$ is the upper and lower limits of transferable load for the t-th operating period.

METHODS

The multi-time-scale distribution network scheduling model considering source-load-storage co-optimisation is solved using the CPLEX and PSO optimisation algorithms. PSO has good global search performance and convergence speed and can quickly determine the energy storage capacity and power configuration when the new energy consumption rate is at its highest. This process is illustrated in Figure 2.

The specific operation process of target optimisation scheduling is as follows:

(1) Input the parameters of the distribution network, such as the network topology, branch impedance, node load, the various parameters of wind and solar DG, energy storage and flexible load controllable components, as well as the relevant parameters of the PSO algorithm.

(2) The CPLEX algorithm is used to determine the maximum source-load matching degree, generating the current planning scheme for the energy storage and grid connection of the distribution network, which is then sent to the day ahead.

(3) The parameters of the day-ahead planning scheme are brought into the day-ahead PSO particle swarm algorithm, the particle population is initialised and the fitness of the corresponding particle swarm is calculated.

(4) Considering the flexible load response capacity within the day, the PSO calculates each resource scheduling problem based on the day-ahead planning scheme with the goal of minimising the overall operating cost, generating the day-ahead scheduling plan.

(5) Repeat step 4 until the fitness of all particles is equal to the optimal group value or the maximum number of iterations has been reached, then output the final optimised scheduling result.

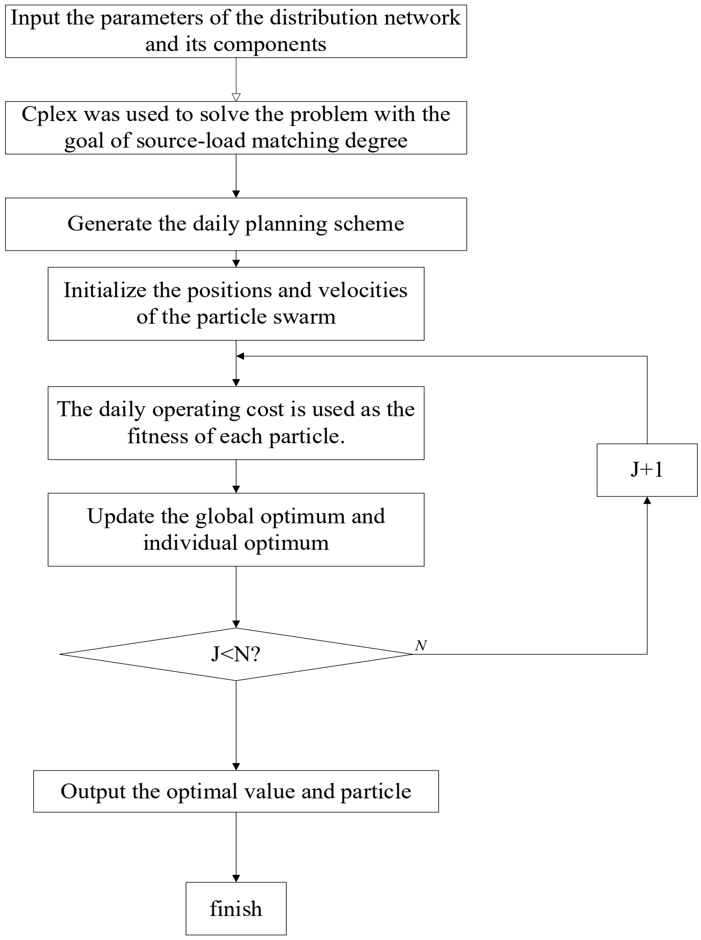


Fig.2 Flowchart of the algorithm

RESULTS

4.1 Scene Setup

Based on the 33 standard node, the gas turbine, wind, solar access nodes, and parameters were modified to construct a source-load-storage collaborative optimisation scheduling model including wind, solar, flexible loads, and energy storage devices. A case study was conducted for this purpose. The specific model structure diagram is shown in Figure 3.

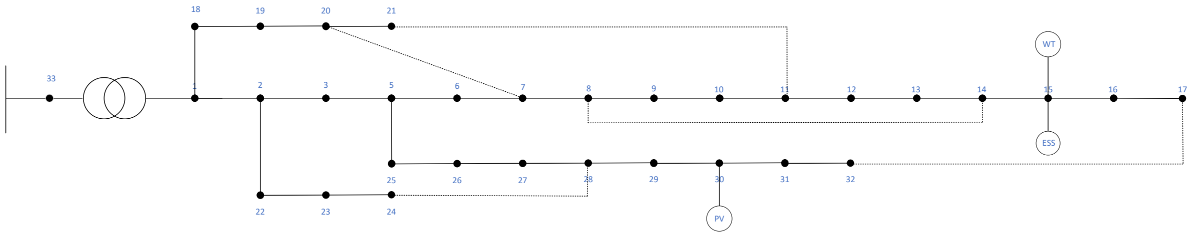


Fig.3 shows the diagram of the 33-node active distribution network.

The following modifications are made to the 33 nodes: 1. Connect the photovoltaic 30 nodes and the wind power to the 15 nodes, and connect the energy storage at the 15 nodes. 2 Connect 135kVA gas-fired units at 3, 6 and 9, with an operating cost of 1000 yuan /MW. 3. Translable load access 21 nodes, interruptible load access 20 nodes, reduced-load access 15 nodes.

A multi-time scale dispatching model for distribution networks is built based on source-load balance degree. Recently, indicators of the source-load balance degree were generated based on new energy output and load data. The following three scenarios have been set up for comparative analysis:

Scenario 1: The day-ahead stage is analysed without considering flexible loads, and the day-ahead dispatching results of the distribution network's source-load-storage are examined.

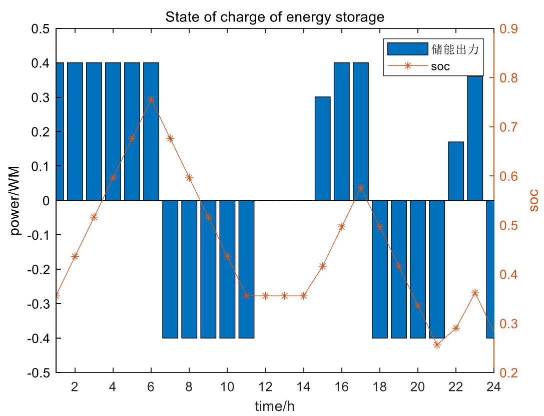
Scenario 2: The operation mode is to analyse the multi-period dispatch results of the distribution network's source-load-storage without considering the margin of the energy storage system or the optimisation of reducible and interruptible flexible loads in the intraday stage, while maintaining the constraints of day-ahead flexible loads and the balance degree.

Scenario 3: The operation mode comprehensively considers the scheduling situation of flexible loads and the margin of the energy storage system in the day-ahead stage. It also analyses the impact of the model proposed in this paper on the operation of the distribution network.

4.2 Result analysis

1) Day-ahead operational benefit analysis

Evaluate the results of flexible load optimisation based on Scenarios 1 and 3, as shown in Figures 4 and 5.



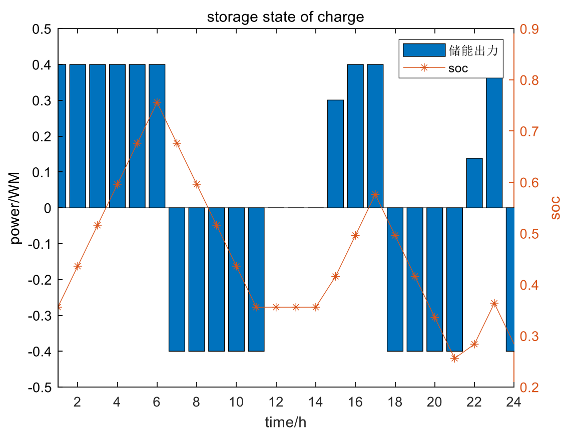


Fig.4 Scene One – Energy storage output diagram

Fig.5 Scene Three – Energy storage output diagram

According to the charge and discharge situation of the energy storage system, the overall charge and discharge situation shows that the energy storage system charges during late-night or off-peak electricity consumption between 07:00 and 12:00 and 18:00 and 21:00. Peak discharge and overall charging and discharging achieve the effect of peak shaving and valley filling, reducing deep charging and discharging situations. According to the battery capacity loss formula, the daily charge and discharge cost and daily capacity loss of the energy storage system are reduced compared with scenario 1, as shown in Table 1.

Table.1 The cost table of energy storage loss within the current day

Comparison metrics	Consider flexible loads recently	Flexible load was not considered a few days ago	Comparison metrics
Charge and discharge cycles	6	6	Charge and discharge cycles
Capacity loss (kw/h)	5260	5740	Capacity loss (kw/h)

2) Intraday operation benefit analysis

Considering the uncertainty of new energy output, an error value of 6% is added to the wind power and load forecast output every two hours, with an additional error of 0.5%, to ensure the impact of the time span on the forecast results is accounted for.

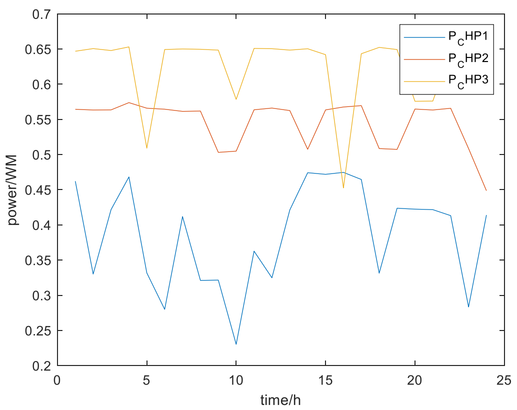


Fig.6 The gas turbine unit has recently been operating

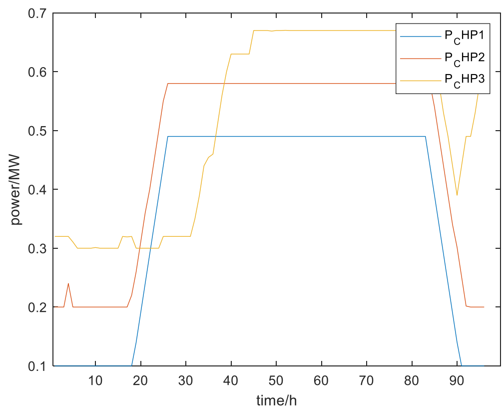
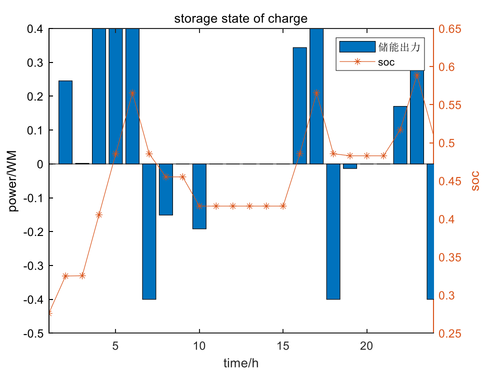


Fig.7 The output of the gas turbine unit within the day

Figures 6 and 7 show the output of the gas turbine unit before and during the day. It can be seen that the output fluctuates more before 10 a.m., and there are also two to three peaks in the middle and afternoon due to the influence of photovoltaic output. After rolling optimisation with a period of four hours and a time step of 15 minutes, the output of gas units 1 and 2 becomes stable and the number of output ramps of gas unit 3 decreases. By calculating the dispatch cost of the gas units, considering only the translable load, the power generation cost is found to be 23,853.5787 yuan through multi-time rolling optimisation within the day, compared to 26,593.4543 yuan before the day. This is a decrease of 10.31% compared to the day before, which confirms the optimisation of the gas unit cost in scenario 3 compared to scenario 1.



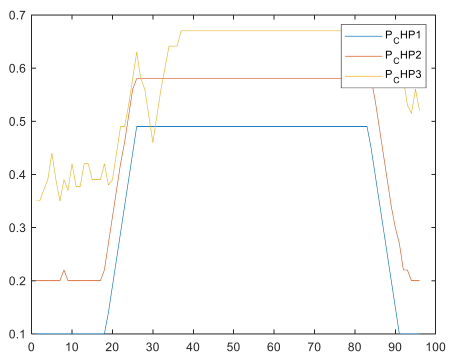
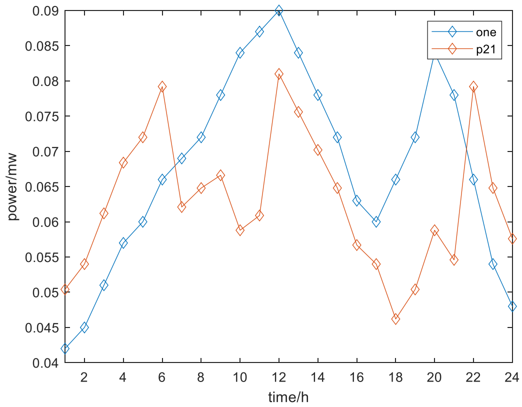


Fig.8 shows the energy storage output map for Scene 2. Fig.9 shows the gas unit output for two days in Scene 2.

As Figures 9 and 10 show, energy storage is heavily involved in distribution network dispatch to optimise operating costs without flexible load participation in dispatch. The daily energy storage loss cost can be calculated to be 540.247 yuan, which is 25.78% higher than in Scenario 3. Furthermore, the number of gas turbine unit output climbs and the overall operating cost rises accordingly.

As can be seen from the comparison in Figure 10 between Scenes 1 and 2, flexible load scheduling optimises the day-ahead load curve, reduces the peak-to-valley load difference, shifts load during periods of peak electricity consumption, lowers electricity costs and shares electricity pressure with the distribution network. This plays a role in stabilising the distribution network output and ensuring balance between supply and demand. For reducible and interruptible loads, it provides a basis for adjusting the flexible load that requires adjustment time.



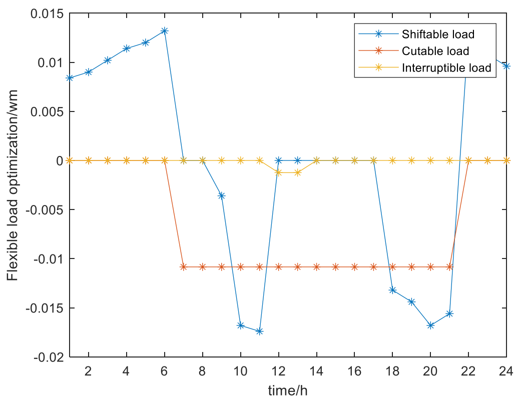
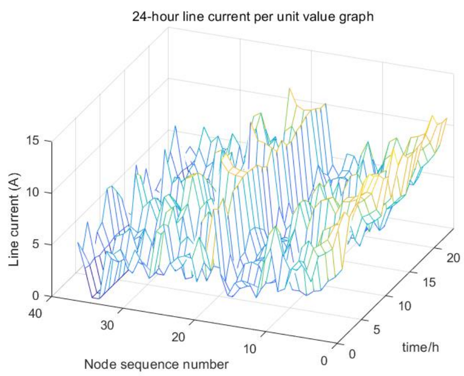


Fig.10 shows the day-ahead optimisation result graph Fig.11 shows the flexible load scheduling result diagram.

Figure 11 shows the daily load reduction and charge/discharge adjustment of the energy storage device. The transferable load from 9:00 to 12:00 and from 18:00 to 22:00 is allocated to the early morning and evening power consumption periods, respectively, to relieve pressure on the distribution network's power supply. During the intra-day stage, from 07:00 to 22:00, the curtailable and interruptible loads play a role. Comparing the line current diagrams of the day-ahead and intra-day stages in Figures 12 and 13 shows that the line current becomes more stable after intra-day rolling optimisation. Network line loss current was reduced from 96.2700 MW to 7.5638 MW, significantly lowering operating costs.



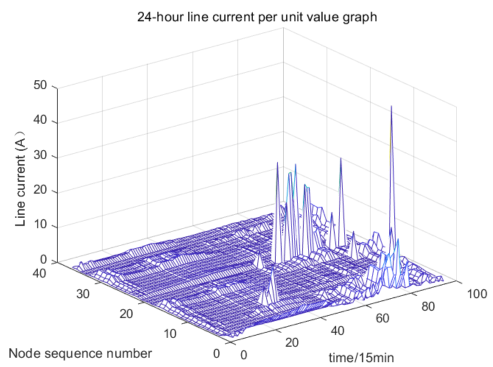


Fig.12 Line current diagram recently. Fig.13 Intra-day line current diagram.

The day-ahead optimisation cost of the distribution network can be calculated to be 128,357.4203 yuan. Of this, the costs of energy storage devices and flexible load dispatching are 138.3124 yuan and 943.0799 yuan respectively, while the interaction cost with the upper-level grid is 98,255.206 yuan. Following intra-day dispatching, the costs of the energy storage devices and flexible loads were 127,711.62 yuan and 1,051,764.305 yuan, respectively. The intra-day interaction cost with the upper-level grid was 66,731.28 yuan and the overall optimisation operation cost was 201,121.02 yuan. Compared with day-ahead non-rolling optimisation, the overall daily operating cost decreased by 36.17%, reducing the load peak-valley difference by 137.52 kW. This confirms the effectiveness of the proposed model in reducing daily operating costs while ensuring wind and solar power consumption.

DISCUSSION

This paper presents a multi-time scale source-load-storage collaborative optimisation scheduling model with a source-load matching degree, which is solved using the CPLEX and particle swarm optimisation algorithms. The following conclusions are drawn:

1) Considering the different characteristics of flexible loads, a day-ahead hierarchical scheduling strategy based on load characteristic differences was constructed. This effectively improved the feasibility and response accuracy of flexible loads participating in system scheduling.

2) A source-load balance index was proposed to measure a load's ability to accommodate wind and solar consumption. Through the collaborative optimisation of various dispatching resources, the operating cost of the distribution network was reduced, as was the network's power quality.

3) A source-load-storage collaborative optimisation model based on rolling optimisation was designed. With source-load balance and economic operating costs as the multi-time scale optimisation objectives for each day, a multi-time scale scheduling scenario was formed to enable the full utilisation of flexible loads and energy storage devices.

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