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A quantitative assessment method for regulating capacity sufficiency under medium- and long-term supply and demand risk scenarios of provincial power grids with high proportion of new energy sources driven by multilevel temporal and spatial combinatorial optimization algorithms

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ABSTRACT

The regulatory capacity sufficiency of the grid is not only a technical indicator for dispatchers to measure the safe and stable operation of the grid, but also an important indicator for assessing the reliability of the grid, and an important basis for the planning and transformation of the grid. This paper combines the objective function and constraints of time and space scale optimal scheduling of provincial power grids with a high proportion of new energy, and establishes a model for optimal scheduling of power grids. Improved DE-ICA stochastic optimization search algorithm is used to seek the optimal value of the model, to obtain the optimal regulation method of the power grid driven by the multilevel spatio-temporal combinatorial optimization algorithm, and to put forward the quantitative assessment method of the adequacy of the power grid regulation capacity. Simulations and empirical case studies show that the regulation cost of the provincial grid is reduced after the application of the optimization algorithm, and the power balance effect and the regulation capacity adequacy are improved compared with the traditional scheme. The quantitative evaluation method of grid regulation capacity adequacy proposed in this study can comprehensively and accurately describe the transmission capacity of the grid under long-term supply and demand, which can provide more accurate reference information for power system security and planning.

Keywords: objective function, constraints, DE-ICA model, grid scheduling, regulation capacity adequacy

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1. Introduction

At present, under the background of China's construction of a unified market, the flourishing new energy is accelerating its integration into China's power market [1-2]. With the gradual realization of the “dual-carbon” goal, new energy will usher in a larger scale and high quality development, and it is crucial to accelerate the establishment of institutional mechanisms for green energy production and consumption, and to give full play to the decisive role of the market in the process of resource allocation [3-6].

In the high proportion of new energy scenarios, to ensure the balance of the power system is facing a huge challenge, mainly reflected in the gradual reduction of the size of the traditional thermal power installed capacity, to ensure the adequacy of power supply and flexibility of the ability to become more and more scarce, to maintain the power balance of the power grid is increasingly challenging [7-10]. In the face of the national strategic development goal of “double carbon”, power companies need to assume a more difficult social responsibility. Based on the analysis of the characteristics of China's traditional power grid system, the use of new energy in the current power generation system is the core way to improve the comprehensive utilization of resources in all aspects [11-14]. With the increasing electrification level of the whole society, more and more carbon emissions are transformed from the terminal industry to the power industry, and the pressure of energy saving and emission reduction in the power industry is also increasing [15-17]. Therefore, to accelerate the construction speed of new energy power system in the process of continuous exploration and research is a necessary way for the power industry to assist the society to achieve the goal of “dual-carbon”, to promote its own energy saving and emission reduction, and is also the core way to ensure the high-quality development of the entire power industry [18-21].

Literature [22] points out that the proportion of new energy in China's energy structure is increasing, and reveals the challenges faced by the power system, based on which the power system to meet the diversified energy supply and demand demand at the same time to achieve rapid and accurate control, to achieve the balance of supply and demand. Literature [23] discusses the series of measures taken by the State Grid Corporation of China to promote the regulation of new energy sources, including guiding new energy sources to connect to the grid in a scientific manner and enhancing the energy regulation capability, etc. It also looks into the trend and characteristics of new energy development and outlines the suggestions for the future high-quality development of new energy sources from the aspects of flexible operation. Literature [24] analyzed the key factors affecting new energy water abandonment in China, and based on the new energy consumption problem, it examined the measures to alleviate the renewable energy consumption problem in terms of optimizing demand-side management and strengthening inter-provincial trading. Literature [25] emphasized the importance of the decarbonization strategy of renewable energy in the power system, and argued that even without a high penetration of new energy, energy storage systems can achieve low-cost operation and low emissions, and that new energy reduces the economic and environmental performance of coal power units, which is counteracted by energy storage systems. Literature [26] describes the current energy and power situation of China's power system, discusses the challenges it faces, outlines the characteristics of the future Chinese power grid, and highlights representative projects. Literature [27] describes the shortcomings of new energy, such as low controllability and high security risk, and briefly introduces the new energy power system, puts forward methods such as the strong development of energy storage technology and the construction of a “low-carbon power technology development mechanism”, and makes suggestions for corresponding policies. Literature [28] through the construction of provincial power grid power purchase cost model, from the perspective of new energy generation uncertainty and other perspectives on the power purchase situation, to achieve in the premise of meeting the constraints to minimize the average purchase price, for the grid enterprise to formulate the power purchase strategy to provide a reference. Literature [29] proposes a multi-province joint hierarchical optimal dispatch model with strong adaptability, which can effectively inhibit the impact of uncertain fluctuations in new energy output, thus improving the absorption performance of new energy, and reveals the effectiveness of the model. Literature [30] builds a provincial power consumption efficiency evaluation index system based on the influence of power supply, power market and other aspects on power consumption, and selects the indicators of power supply and demand, new energy development and other indicators, emphasizing that the power market is the most important in the whole system. Literature [31] established a comprehensive planning model consisting of multiple regression model and linear planning model, revealing that through the inter-provincial distribution of new energy power, it helps to promote the optimal allocation of new energy resources.

In this paper, we design the objective function and constraints of high proportion new energy provincial grid scheduling optimization from both time scale and space scale, and construct the coordinated grid scheduling optimization model with multilevel time and space combination. Combining the differential evolution operator to improve the stochastic optimization search ability of the empire competition algorithm in solving the model, the DE-ICA model is obtained, and the optimal value of the multilevel temporal and spatial combination model of the grid is searched for through the operations of the algorithm's mutation, crossover, and selection to achieve the optimal scheduling of the provincial power grids of the high-percentage new energy sources. Then, a quantitative assessment method of grid regulation capacity adequacy is proposed, and finally, a simulation example and an empirical case of grid optimal dispatch are designed to analyze the driving effect of the multilevel spatio-temporal combination optimization algorithm on the grid's regulation capacity adequacy under the medium- and long-term supply and demand risk scenarios.

2. Design of optimization algorithm for multilevel space-time combined grid scheduling

2.1. Multi-timescale coordinated scheduling model

2.1.1. Coordination of weekly and annual plans. In order to meet the constraints of the annual planned power generation of each unit in the new energy provincial grid, the annual planned power generation needs to be decomposed into each week to be accomplished specifically. The upper and lower limits of the planned power generation of week t of unit i obtained from the annual plan can be calculated according to the following formula:

$$\begin{cases} E_{Gi\max}^{w} = \dfrac{E_{Gi\max}^{y}}{\sum\limits_{i=1}^{T_{Gi\max}} E_{Git}^{w}} E_{Git}^{w} \\ E_{Gi\min}^{w} = \dfrac{E_{Gi\min}^{y}}{\sum\limits_{i=1}^{T_{j\omega\omega r}} E_{Git}^{w}} E_{Git}^{w} \end{cases} \tag{1}$$

As the time approaches, the accuracy of the wind power and load forecasts gradually improves and the original power generation plan needs to be revised. The rolling plan for the year is calculated once a week, and the unit maintenance plan and power plan for the remaining weeks of the year are rescheduled based on the latest medium- and long-term rolling forecasts of wind and load power and the actual completion of unit power in the previous week. Every other week, the upper and lower limits of the planned power of each unit for the remaining weeks of the year are updated according to the following formula:

$$\begin{cases} E_{Gi\max}^{y} = E_{Gi\max}^{y} - E_{Gi\_week}^{r} \\ E_{Gi\min}^{y} = \max(E_{Gi\min}^{y} - E_{Gi\_week}^{r}, 0) \end{cases} \tag{2}$$

Where $E_{Gi\_week}^{r}$ is the actual generation of unit i in the previous week.

2.1.2. Coordination of daily and weekly plans. Similar to the breakdown of the unit's annual planned power into weeks for specific completion, the unit's weekly planned power needs to be broken down into days for specific completion. The specific calculation method for determining the upper and lower limits of each unit's daily planned power from the weekly plan is similar to the determination of the upper and lower limits of the weekly planned power. The formula is:

$$\begin{cases} E_{Gi\max}^{d} = \dfrac{E_{Gi\max}^{w}}{\sum_{\tau=1}^{T_{wosk}} u_{i\tau} P_{Gi\tau} \Delta T_{w}} \sum_{\zeta=1}^{T_{doy}} u_{i\zeta} P_{Gi\zeta} \Delta T_{d} \\ E_{Gi\min}^{d} = \dfrac{E_{Gi\min}^{w}}{\sum_{\tau=1}^{T_{wosk}} u_{i\tau} P_{Gi\tau} \Delta T_{w}} \sum_{\zeta=1}^{T_{doy}} u_{i\zeta} P_{Gi\zeta} \Delta T_{d} \end{cases} \tag{3}$$

The intra-week rolling plan is calculated once a day, and based on the latest forecasts of wind power and load power and the actual completion of the unit power on the previous day, the unit start/stop plan and power plan for the remaining period of the week are rescheduled. Every other day, the upper and lower limits of the planned power consumption of the units for the remaining period of the week are updated according to equation (4):

$$\begin{cases} E_{Gi\max}^{w} = E_{Gi\max}^{w} - E_{Gi\_day}^{r} \\ E_{Gi\min}^{w} = \max(E_{Gi\min}^{w} - E_{Gi\_day}^{r}, 0) \end{cases} \tag{4}$$

Where $E_{Gi\_d\sigma v}^{r}$ is the actual generation of unit i on the previous day.

2.1.3. Coordination of real-time and daily planning. The intra-day rolling plan is calculated every 30 min, and based on the latest forecasts of wind power and load power in the provincial grid and the actual power completion of the units in the previous 30 min, the unit output plan for the remaining period of the day is rescheduled. The upper and lower limits of the planned power output of each unit for the remaining period of the day are updated according to the following formula:

$$\begin{cases} E_{Gi\max}^{d} = E_{Gi\max}^{d} - E_{Gi\_30\min}^{r} \\ E_{Gi\min}^{d} = \max(E_{Gi\min}^{d} - E_{Gi\_30\min}^{r}, 0) \end{cases} \tag{5}$$

where $E_{Gi\_30\min}^{r}$ is the actual power generation of unit i in the first 30 min.

2.1.4. Continuous constrained optimization problems. For the optimization problem:

$$\begin{aligned} &\min f(x) \\ &s.t.\, g_i(x) = 0 \quad i = 1, 2 \cdots, n \\ &h_j(x) < 0 \qquad j = 1, 2 \cdots, m \end{aligned} \tag{6}$$

The penalty function method [32] is to write the constraints as penalty phases into the objective function as shown in the following equation:

$$F(x)=f(x)+\sum_{i=1}^{n}\alpha_i G_i(x)+\sum_{j=1}^{m}\beta_j H_j(x)$$
$$G_i(x)=|g_i(x)| \tag{7}$$
$$H_j(x)=\max(0,h_j(x))$$

where $G_i(x)$ and $H_j(x)$ are functions of the corresponding violated quantities for the equality and inequality constraints, respectively, and $\alpha_i \cdot \beta_j$ is the corresponding penalty factor. If there is an inequality constraint greater than 0 in the constraint, it is simply transformed into the form of $h(x)<0$. The adjustment of the penalty factor has a large impact on the optimization of the particles. If the penalty factor is too small, the infeasible solution is not punished enough, and it is not easy to get a feasible solution. If the penalty factor is too large, it is difficult to obtain an excellent solution. The constrained optimization problem is transformed into an unconstrained optimization problem, which can be solved using the optimization algorithm.

2.2. Spatial zoning regulation model of the power grid

2.2.1. Objective function. Aiming at the deviation of "source-load" power prediction in the power grid, which easily causes voltage overrun and network loss change, the zonal self-regulation takes suppressing voltage fluctuation as the primary goal, and further reduces loss on this basis. The minimum voltage deviation objective function is expressed as:

$$\min f(x)=\sum_{i=1}^{I_n}|(U_{i,t}-\Delta U_{i,t})-U_{ref}| \tag{8}$$

where i, I_{n-1} is the node number and the number of nodes in the partition n, respectively, U_i is the feeder node i ultra-short-term predicted voltage value, which is calculated from the ultra-short-term injected active/reactive power deviation of each node based on the day-ahead steady-state node voltage and voltage/power sensitivity matrix. U_{ref} represents the feeder node voltage reference value, and $\Delta U_{i,l}$ is the node voltage regulation amount, which is the zonal state variable and is calculated from the dynamic reactive power compensation amount ΔQ_i^{rddo} within the zones, i.e., ΔQ_i^{rddo} is the control variable.

The zonal self-regulating rolling regulation minimum network loss objective function is:

$$\min f(x)=\sum_{i=1}^{I_n}(S_i^{R_{loss}P}\cdot\Delta P_j+S_i^{R_{loss}Q}\cdot\Delta Q_i) \tag{9}$$

where S_i^{nap}, S_i^{nal} is the power/net loss sensitivity of section P_i, Q_i, respectively.

2.2.2. Spatial regional optimization models. The global feedback correction adjusts the reactive equipment day-ahead operation scheme according to the updated and finer prediction information, and maintains the original action state of the discrete equipment as much as possible. Therefore, on the basis of the operating economy and load balancing objectives of the day-ahead optimization model, the optimization objective of minimizing the adjustment amount is added:

$$\min \Delta X^{adj}=\sum_{t=t'}^{T}\sum_{x\in X}|(x_t^{adj}-x_t^{da})/x_t^{da}| \tag{10}$$

Where x is the distribution network regulation resource control variable, $x=[x^{NR}x^{RDC}x^{TC}x^{SC}]$, t' are the starting feedback correction time points, x_i^{ds} is the vector of regulation resource states in the previous day's operation program, and x_i^{adj} is the vector of regulation resource states after feedback correction.

2.3. Multi-source Co-optimization Algorithm

2.3.1. Improving the Imperial Competition Algorithm. The empire competition algorithm [33] is a stochastic optimization search method inspired by imperialist colonial competition, which is used in this paper to realize the optimal solution of multi-level time and space regional models in high percentage new energy provincial power grids.

1) Generating the initial empire. Similar to chromosomes in genetic algorithms (GA) and particles in particle swarm algorithms (PSO), populations in ICA are represented by countries:

$$country = [p_1, p_2, p_3, ..., p_n] \tag{11}$$

Denote the power of a country by $f(country) = f(p_1, p_2, p_3, ..., p_n)$.

Of the N_{pop} randomly generated countries, the N_{imp} most powerful countries are chosen to become imperialist countries, and the remaining countries are colonized and randomly assigned to each imperialist country according to their power. A total of N_{imp} initial empires are formed.

2) Assimilation mechanism. In ICA, the assimilation mechanism is realized by the constant movement of colonies to the empires they belong to. After updating the positions of all colonies, if a colony's power size is larger than that of the empire to which it belongs, the two identities will be exchanged.

The distance a colony moves to its empire can be expressed as:

$$x \sim U(0, \beta \times d) \tag{12}$$

Where $\beta > 1$, d is the distance between the two.

3) Competition mechanism. In the process of competition among the empires, the weakest empire with the weakest power puts out the weakest colonies to compete. The total power of each empire is expressed as:

$$T.C._n = f(imp_n) + \xi \times \frac{\sum_{i=1}^{N.C._n} f(col_i)}{N.C._n} \tag{13}$$

where $T.C._n$ is the total power size of the nth empire, imp_n is the nth imperialist country, ξ represents the influence factor of the colony on the empire to which it belongs, and $0 < \xi < 1$.

4) Demise of empires. After repeating the assimilation and competition sessions over and over again, the power differentials of the empires will become more and more pronounced. The ICA provides for the annihilation of an empire if there is nothing in it but imperialist states. The final strong empire with imperialist countries will be the optimal value for the algorithm to find the best value.

2.3.2. Improved empire competition algorithm based on differential evolution operator. In this paper, the DE-ICA model is constructed by combining the differential evolution operator [34], which improves the accuracy of empire competitive optimization. According to the characteristics of the ICA algorithm, the mutation, crossover and selection operations in the differential evolution algorithm are redesigned.

1) Differential variation is performed for all colonies Col within the current empire with MR probability according to Eq:

$$C = Col_{r3} + F(Col_{r1} - Col_{r2}) + rand(imp_{best} - Col) \tag{14}$$

Where $Col_{r1}, Col_{r2}, Col_{r3}$ is the three randomly selected individual colonies, F is the scaling factor, which is used to control the magnification of the difference between the colonies, and its value range is usually [0.5, 1]. Rand is a random number between [0, 1], imp_{best} is the global optimum, and MR is the differential variation probability, the size of which will affect the time efficiency of the algorithm.

2) Differential crossover is performed on each dimension of the colony C generated from the first step as well as the currently existing colony Col before generating a new colony D. The differential crossover formula is defined as follows:

$$D_i = \begin{cases} C_i, & rand < CR \\ Col_i, & otherwise \end{cases} \tag{15}$$

where Rank is a random number in the interval [0, 1] and CR is the crossover probability.
3) If the value of the cost function of the new colony D is less than the current colony Col, the new colony D enters the next round of iteration, otherwise, the current colony Col is retained.

3. Quantitative assessment methods for grid regulation capacity adequacy

3.1. Indicators for ATC probability assessment

ATC is a dynamically changing quantity in time and space, which is suitable to be measured by probability statistical results, so the ATC assessment index calculation method is defined by Monte Carlo simulation method after taking into account the influence of system uncertainty, randomness and time-varying factors in order to accurately characterize the adequacy of transmission regulation capability of provincial power grids with a high proportion of new energy [35].
1) Expected value E_{ATC} of ATC at moment t:

$$E_{ATC}(t) = \frac{1}{N}\sum_{i=1}^{N} F_{ATC}[x_i(t)] \tag{16}$$

where $F_{ATC}[x_i(t)]$ is the ATC value in the i rd simulation state at moment t, $x_i(t)$ is the i th simulation state at moment t, and N is the number of simulations at moment t.
2) The variance V_{ATC} of the ATC at moment t:

$$V_{ATC}(t) = \frac{1}{N}\sum_{i=1}^{N} \left\{F_{ATC}[x_i(t)] - E_{ATC}(t)\right\}^2 \tag{17}$$

3) Coefficient of variation β of ATC at moment t:

$$\beta(t) = \frac{\sqrt{V_{ATC}(t)}}{E_{ATC}(t)} \tag{18}$$

4) The maximum value $F_{ATC}^{\max}$ of ATC at the moment t:

$$F_{ATC}^{\max}(t) = \max\{F_{ATC}[x_i(t)], \quad i \in N\} \tag{19}$$

5) The minimum value of ATC at moment t, $F_{ATC}^{\min}(\mathrm{t})$:

$$F_{ATC}^{\min}(t) = \min\left\{F_{ATC}[x_i(t)], \quad i \in N\right\} \tag{20}$$

6) The probability that ATC is equal to zero P_{PAEZ}, indicating that the current power supply network is unable to meet the load demand, and measures must be taken to ensure normal power supply, such as generation redispatch or load shedding. The formula is:

$$P_{PAEZ} = \frac{M_{ATC=0}}{N_{sum}} \tag{21}$$

Where $M_{ATC=0}$ is the number of simulations where the ATC value is equal to zero and N_{sum} is the total number of simulations.
7) Duration of ATC equal to zero T_{DAEZ}:

$$T_{DAEZ} = \Delta h \cdot M_{ATC=0} \tag{22}$$

Where Δh is the simulation step, here 1 hour is taken.

8) ATC deficiency probability P_{PANS} refers to the probability that the ATC value is less than a specific value, and let C be a specific value:

$$P_{PANS} = \frac{M_{ATC<C}}{N_{sum}} \tag{23}$$

Where $M_{ATC<C}$ is the number of simulations in which the ATC value is less than a specific value C.

9) ATC insufficient duration T_{DANS}:

$$T_{DANS} = \Delta h \cdot M_{ATC<C} \tag{24}$$

10) ATC deprivation E_{EANS}:

$$E_{EANS} = \sum_{x \in I} (C - F_{ATC}(x)) \tag{25}$$

where I is the set of system states with ATC values less than a specific value C.

3.2. Harmonized format for indicators of adequacy

The adequacy indicators for quantitative analysis of the regulation capability under long-term supply and demand risk scenarios for provincial grids with a high proportion of new energy sources selected from the ATC probability assessment indicators are as follows, probability of ATC equals to zero P_{PAEZ}, duration of ATC equals to zero T_{DAEZ}, probability of ATC insufficiency P_{PANS}, duration of ATC insufficiency T_{DANS}, and amount of ATC scarcity E_{EANS}. These indicators, although with different forms of expression, have a common feature, i.e. They are all equivalent to calculating the expected value of a given test function, so the ATC indicator calculation can be expressed by a unified formula as follows:

$$E(F) = \sum_{x \in X} F(x)P(x) \tag{26}$$

Where x denotes the system state vector, which consists of the states of all devices, assuming that the grid system consists of G devices, and letting S_k represent the state of the kth device, then $x = (S_1, S_2, \ldots, S_k, \cdots S_G)$, and since S_k is a random variable, x is also a random vector.

Assuming that each device in the provincial power grid has only 2 states, fault and operation, and that the faults of the devices are independent events from each other, and that u_k represents the probability of device k failing (i.e., the degree of ineffectiveness), and a_k represents the probability of device k functioning normally (i.e., the degree of effectiveness), then S_k is a discrete random variable, as shown in the following equation:

$$S_k = \begin{cases} 1 & \text{Device } k \text{ operation} \\ 0 & \text{Device } k \text{ failure} \end{cases} \tag{27}$$

For device k, assuming a failure rate of λ_k and a repair rate of μ_k, there is:

$$\begin{cases} u_k = P(S_k = 0) = \lambda_k / (\lambda_k + \mu_k) \\ a_k = P(S_k = 1) = 1 - \mu_k = \mu_k / (\lambda_k + \mu_k) \end{cases} \tag{28}$$

where X represents the system state space, which is the set of all possible cases of the system state vector x, $F(x)$ represents the test function of the sufficiency index with the system state vector as the independent variable, $P(x)$ represents the probability of occurrence of the system state x, i.e., the probability distribution function of x, and when it is assumed that all the equipment states are random variables independent of each other, $P(x) = P(S_1)P(S_2)\ldots P(S_k)\ldots P(S_G)$, $E(F)$ represents the probability expectation of the random function $F(x)$, and when $F(x)$ is taken as the interested different test functions, $E(F)$ then also represents different sufficiency metrics.

4. New energy provincial grid scheduling optimization effect

4.1. Simulation example analysis

4.1.1. Simulation grid construction. This section first investigates the feasibility and effectiveness of scheduling scenarios through multilevel spatio-temporal combinatorial optimization methods for provincial grid systems with a high percentage of new energy access through simulation experiments. The developed offline provincial grid environment PSE can provide scenarios with different penetration levels for the training and testing of multi-combinatorial optimization algorithms. An improved IEEE39 node system is built for testing, which contains 10 conventional thermal power units, 4 wind farms, 1 photovoltaic power plant and 4 energy storage devices in the simulated grid system. The maximum output power and climbing capacity of each generating unit are shown in Table 1, and the relevant parameters of the energy storage devices are shown in Table 2. The controlled generators controlled by the optimization algorithm scheduling are connected to buses 31, 35 and 37, and the energy storage devices are connected to buses 33, 36, 38 and 40, respectively. The dataset used in the environment consists of five years of monthly grid operation scenarios in a province. Extracted from the open source platform “grid2op”, the total renewable energy penetration of wind and PV in the scenario set fluctuates randomly in the range of 15% to 75%.

Table 1. Grid parameters

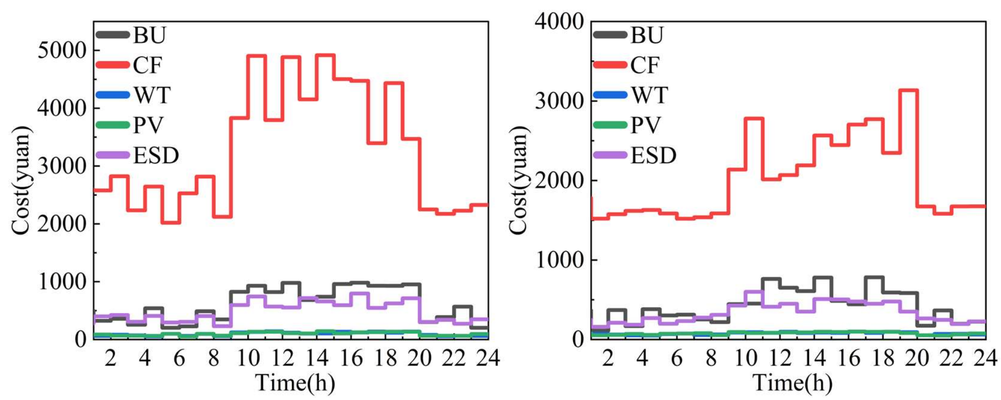
Dynamo	Access bus number	Capacity (MW)	Climbing capacity (MW/h)
Balancing unit	30	527	273
Conventional fire unit 1	29	850	375
Conventional fire unit 2	32	922	253
Conventional fire unit 3	33	792	440
Conventional fire unit 4	34	678	342
Conventional fire unit 5	35	999	323
Conventional fire unit 6	36	701	375
Conventional fire unit 7	37	795	224
Conventional fire unit 8	38	832	422
Conventional fire unit 9	39	815	266
Conventional fire unit 10	40	688	256
Wind farm	31	1881	——
Wind farm	36	1575	——
Wind farm	38	1759	——
Wind farm	40	1543	——
Photovoltaic power station	33	1200	——

Table 2. Storage equipment parameters

Energy storage equipment	Access bus number	Capacity (MW)	SoC climbing rate (h)	Initial SoC
Energy storage equipment 1	33	750	0.26	0.42
Energy storage equipment 2	36	650	0.18	0.46
Energy storage equipment 3	38	500	0.15	0.55

Energy storage equipment 4	40	450	0.13	0.62

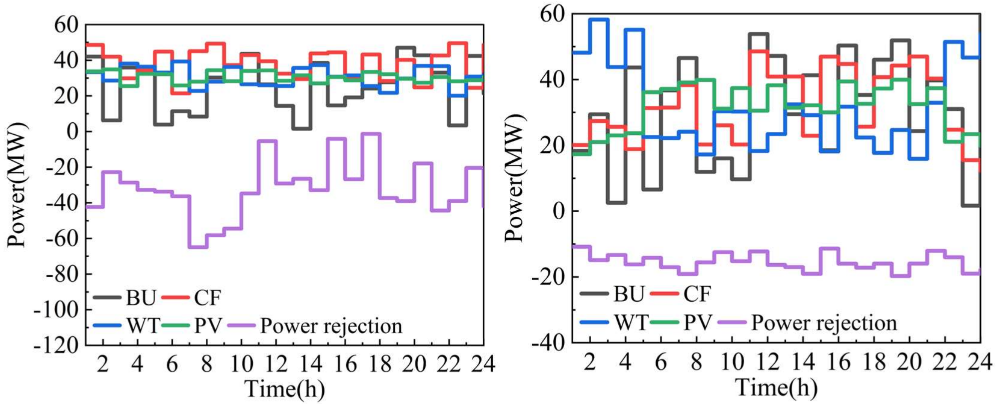
4.1.2. Coordinated Optimization Analysis for Grid Simulation. Two scenarios are set up to validate the method proposed in this paper, Scenario 1 is the traditional coordinated scheduling method for high percentage new energy grid, and Scenario 2 is the coordinated scheduling optimization method for high percentage new energy provincial grid based on multilevel spatio-temporal combinatorial optimization. The grid regulation costs of the two schemes are shown in Fig. 1, and (a) and (b) are the regulation cost analysis results of Scheme 1 and Scheme 2, respectively. In the figure, BU, CF, WT, PV and ESD represent the regulation costs of balancing units, thermal units, wind power units, photovoltaic units and energy storage devices in the simulated grid system, respectively. Taken together, the grid regulation cost of Scenario 1 is much higher than that of Scenario 2, with an average total cost of 4522.24 yuan per hour of regulation. Scenario 1 needs to rely on traditional thermal power and external grids to support the power within the high percentage of new energy provincial grids, based on traditional thermal power and external grid support will make the high percentage of new energy provincial grids with high power regulation costs. Scenario 2 is based on multi-scale time and space optimization scheduling model and method, which can effectively reduce the start-up of traditional thermal power in the hours when the grid power demand is low. It can also rely on new energy resources and multi-scale temporal and spatial energy coordination to provide demand power support for the grid during daytime, which can reduce the dependence on the external grid. The total cost of grid scheduling is only 2908.72 yuan/hour, and the regulation cost of thermal power units is 2004.29 yuan/hour.



(a) Solution 1 (b) Solution 2

Fig. 1. The analysis of the cost analysis of the grid

The power balance analysis results of the two scenarios after implementation in the simulated provincial grid environment are shown in Fig. 2, with (a) and (b) showing the analysis results of Scenario 1 and Scenario 2, respectively. Scenario 1 is operated by the traditional grid coordination and scheduling method, with a uniform grid scheduling cycle of 2h, while Scenario 2, after considering the multi-temporal and spatial scale optimization and coordination, has a power scheduling cycle of 20min, which is able to regulate the provincial grid in a more detailed way. Traditional regulation program 1 night wind power generation and heat load is high, by the heat to set power limitations, the power output is still maintained at a high level, which will lead to serious wind abandonment phenomenon, at the same time will lead to the power supply of the grid at night in the ultra-high inertia state, the cost of power supply is also higher. Daytime only thermal power and new energy can not meet the long-term demand support, need to rely on the external grid to the high proportion of new energy provincial power grids for power support. After considering the optimization and coordination of multi-temporal combinations, it can be seen that the total output of thermal power units at night is significantly reduced, while wind power units and photovoltaic units can be used to coordinate the power supply and demand together, thus reducing wind abandonment and improving the power supply level of the grid.



(a) Solution 1 (b) Solution 2

Fig. 2. The analysis of power balance analysis of the grid

4.1.3. Results of simulation assessment of ATC metrics for power grids. The base capacity of the simulated grid system is taken as 100 MW, and loads 30, 31 and 32 are selected as the load side of the section, then the transmission capacity at this point is the sum of loads 30, 31 and 32. The sampling number is set to be 1000, and the Monte Carlo simulation method is used to simulate the state of the sampling system, and the specific parameters are shown in Table 3. Then the first-order sensitivity analysis is used to find the ATC value in each state, and finally the expected value, variance and error of ATC, and the obtained partial results are shown in Table 4. Based on the average ATC calculated value of this simulated grid driven by the multilevel space-time combination optimization algorithm is 55.14 MW, it can be seen that the grid regulation capacity sufficiency is high after piggybacking on the optimization algorithm.

Table 3. Monte carlo simulation method sampling system parameters

Fault probability	Generator failure probability	Transformer failure probability	Regulating rule of transformer split		Load fluctuation pattern
0.020	0.015	0.010	110%	0.110	Normal distribution
			105%	0.150	
			100%	0.500	
			95%	0.150	
			90%	0.110	

Table 4. The monte carlo simulation method calculates the results of ATC

Sampling frequency	TTC(MW)	ATC(MW)	Sampling frequency	TTC(MW)	ATC(MW)
1	61.91	58.31	11	63.05	56.39
2	61.76	55.54	12	60.25	58.19
3	45.26	43.29	13	64.12	55.49
4	64.11	56.54	14	62.15	55.77
5	52.96	50.26	15	59.86	56.6
6	64.11	57.25	16	60.66	56.92

7	64.03	58.53	17	61.91	56.58
8	60.67	56.28	18	60.54	57.76
9	43.52	41.26	19	61.91	58.94
10	61.88	57.54	20	61.52	55.41

4.2. Analysis of empirical applications to provincial power grids

In this section, the optimization algorithm proposed in this paper is verified by using an actual example - the actual system of Hebei high proportion new energy south grid, which belongs to the main power supply grid of Hebei province and is in the long-term supply-demand risk scenario, and the baseline capacity of the grid system is taken as 100 MW. Due to the characteristics of the south grid in Hebei, which is used for the south-north transmission of electricity, and for the east-west transmission of electricity, therefore, the 2 2 main current sections, the east-west section and the north-south section, are chosen to calculate the transmission regulation capacity adequacy of the grid. The main loads involved in the east-west section are 1G Anping11, 1G Dongsi11, 1G Gaocheng11, 1G Hantong11, 1G Jiazhuang11, 1G Ningjin11, 1G Baixiang11, 1G Longyao11. The main power generation is 1G HengshuiG1, 1G HengshuiG2, 1G HengshuiG3, 1G HengshuiG4. The main loads in the north-south section and the main loads involved in the north-south section are 1G Anping11, 1G Gaobei11, 1G Gao Cheng 11, 1G Lai Yuan 11, 1G Lixian 11, 1G Rongcheng 11, 1G Shuolu 11, 1G Suncun 11, 1G Zhangxi 11, 1G Zhuozhou 11, 1G Zhaotong 11. major generation are 1G Handan G1, 1G Handan G2, 1G Hanfeng G1, 1G Hanfeng G2, 1G Matou G1, 1G Matou G2, 1G Matou G8, 1G Xingtai G4, 1G Xingtai G8. 1G Xingtai G9. The sampling number is set to be 1000, and the Monte Carlo simulation method is used to simulate the states of the sampling system, and then the ATC value under each state is obtained, and finally the expected value of ATC is obtained. The partial results of the east-west section are obtained as shown in Table 5, and the partial results of the north-south section of the grid are shown in Table 6. After applying the time-space combination optimization scheduling method, the average ATC values of the high proportion new energy grid system in Hebei are 925.74 MW and 7952.13 MW, which are found to improve the adequacy of the grid's regulating capacity in comparison with the traditional scheduling method.

Table 5. Part of the results of the ATC

Sampling frequency	TTC(MW)	ATC(MW)	Sampling frequency	TTC(MW)	ATC(MW)
1	1015.78	910.46	11	1012.02	926.49
2	1007.71	944.46	12	1017.45	901.79
3	1000.66	948.56	13	1002.57	905.06
4	1005.4	933.38	14	995.71	948.11
5	1014.27	949.93	15	994.9	929.97
6	1000.94	931.7	16	1000.16	908.16
7	993.72	911.91	17	1017.11	901.26
8	1009.03	931.79	18	998.92	938.7
9	995.27	934.12	19	1008.78	947.4
10	995.76	906.83	20	996.45	904.63

Table 6. Part of the results of the ATC

Sampling frequency	TTC(MW)	ATC(MW)	Sampling frequency	TTC(MW)	ATC(MW)
1	1931.6	1648.14	11	1960.16	1616.3
2	1931.27	1746.52	12	1967.02	1706.38
3	1968.29	1743.62	13	1974.04	1736.05
4	1991.08	1796.98	14	1947.2	1643.15
5	1925.71	1604.16	15	1994.64	1632.13
6	1925.61	1711.44	16	1926.88	1672.68
7	1971.18	1610.71	17	1953.34	1722.23
8	1950.19	1709.98	18	1966.8	1652.17
9	1913.35	1631.62	19	1975.08	1689.76
10	1963.99	1652.18	20	1905.12	1611.52

5. Conclusion

This paper establishes an optimal coordinated dispatch model for provincial power grids with high proportion of new energy based on time and space scales, and selects the ATC index as a quantitative assessment index of the adequacy of grid regulation capacity. It is verified by simulating grid arithmetic and a new energy provincial power grid in Hebei, and the results show that:

1) the multi-scale time and space optimization scheduling method based on the multi-scale time and space can effectively reduce the start-up of traditional thermal power during the time of low grid power demand, and reduce the total cost of grid dispatch from 4522.24 yuan/hour to 2908.72 yuan/hour, while ensuring the coordination and loss of power in the grid system.

2) After applying the time-space combination optimization scheduling method, the average ATC assessment values of a high percentage of new energy grid system in Hebei Province are 925.74 MW and 7952.13 MW, and the grid regulation capacity sufficiency is improved.

The quantitative assessment method of grid regulation capacity adequacy in this paper can provide more accurate transmission capacity information for market participants under the power market, which provides important reference information for grid investment decisions and equipment maintenance. In addition, the proposed multilevel spatio-temporal combination optimization method can improve the efficiency and economic benefits of provincial power grids with a high proportion of new energy.

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