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RESEARCH ARTICLE

A Joint Optimization Approach on Monthly Balancing Mechanism and Unit Maintenance Scheduling

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ABSTRACT In the Chinese electricity market, the deviation between monthly actual electricity demand and generation plans has become particularly prominent amidst deepening power system reform. This study focuses on the uncertainties of wind power and photovoltaic power generation in the medium to long term electricity market. It also examines the impact of maintenance scheduling for conventional generation units on the implementation of medium to long-term generation scheduling plans. The article proposes a model for optimizing the joint generation and maintenance scheduling on a monthly basis. The model is based on deviation handling and employs upward and downward price incentive mechanisms. The aim is to minimize the cost of adjusting the deviation of monthly transaction contract quantities. To deal with the challenges posed by source-load uncertainties, the model utilizes fuzzy chance-constrained programming. The research findings confirm that the proposed model can significantly reduce system operating costs, curtailment of wind power and photovoltaic power, and enhance the market integration of renewable energy. Additionally, it can achieve uniformity in the completion rate of monthly contract quantities for conventional thermal power units, ensuring a balanced power system in terms of economy and security. The study presents an optimization method for executing contract quantities in the electricity market, contributing to improved efficiency in power resource allocation and reduced energy losses. The research enriches the theoretical foundation of power system scheduling and provides practical operational guidelines for power dispatch, making it significant for promoting sustainable development in the power industry and ensuring energy security.

INDEX TERMS Fuzzy chance-constrained programming, balancing mechanism, long-term transactions, maintenance scheduling, contract power.

I. INTRODUCTION

China's medium and long-term power market is currently transitioning from contract-based trading to spot market trading [1], [2].The monthly dispatch plan for new energy generation is significantly impacted by uncertainties in demand, wind power, photovoltaic, and maintenance plans for conventional thermal power units [3], [4]. Given the uncertainties surrounding unit maintenance and supply-demand, it is crucial to conduct joint optimization dispatch of monthly generation and maintenance based on deviation power quantity treatment in the medium to long-term

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electricity market in China. The trading objects are the annual and monthly electricity consumption.

Renewable energy uncertainties involve randomness and fuzziness. Stochastic mathematical methods are typically used to address randomness, but accurately describing the probability distribution of random variables within the medium to long-term monthly dispatch cycle is challenging. Fuzziness is usually quantified using membership functions. To address the optimization dispatch problem caused by supply-demand uncertainty, various methods are commonly used for model establishment, including reserve capacity [5], robust optimization dispatch [6], [7], [8], [9], [10], and stochastic optimization dispatch [11], [12], [13], [14], [15] Reference [16] describes robust optimization as representing random variables in the form of sets, which requires the worst-case scenario to satisfy the requirements, making it overly conservative and potentially lacking an optimal solution. Common stochastic optimization methods include scenario-based stochastic optimization [17], [18], [19], [20] and chance-constrained programming-based stochastic optimization [21], [22]. Scenario-based stochastic optimization involves obtaining a scenario set that conforms to certain characteristics through sampling when the probability distribution of the random variables is known. Chance-constrained programming, on the other hand, ensures that the stochastic constraint conditions hold with a certain confidence level. Methods for converting chance constraints into deterministic constraints include stochastic simulation [23], [24] and analytical methods [25], [26]. Stochastic simulation technology utilizes random generation of variable values to solve problems. The results may have some degree of randomness, which can lead to non-uniqueness and potential errors. The output sizes of wind power and photovoltaic power in medium to long-term cycles are described using three fuzzy attributes: most conservative, most likely, and most optimistic. This article presents a fuzzy variable approach to describe source-load uncertainty and establishes a fuzzy chance-constrained planning model. The system power balance constraint and reserve capacity constraint are the only ones that involve fuzzy variables and chance constraint conditions. The decision variables and fuzzy variables can be separated and transformed into deterministic models with clear equivalence classes for solving.

The monthly planning of electricity market dispatch, which takes into account the uncertainty of source-load, generally aims to minimize system costs and reduce the curtailment rate of renewable energy [27], [28], [29].However, this approach may not fully reflect the fairness of dispatch under market conditions or the economic incentives of market pricing. Reference [30] proposes methods for settling the deviation quantity of long-term market base errors. These methods include expected revenue compensation, deviation quantity substitution matching, and average price difference compensation. However, there is a risk that these deviation processing methods may benefit some units at the expense of other market participants. Reference [31] proposes a rolling dispatch method for water, fire, and wind power deviation quantities under the mechanism of pre-listing monthly deviation balance. The monthly contractual electricity volume is initially broken down into daily amounts, followed by dispatching aimed at reducing the daily imbalance cost for power units. Thermal power units are the only ones engaging in pre-listing trades, while wind and hydroelectric power are excluded from monthly adjustment, limiting market participation. Inadequate planning of thermal unit maintenance in the monthly electricity market dispatch can compromise system safety and increase renewable energy curtailment. Deviations in actual electricity volumes from contracts among market entities can stem from inaccuracies in renewable energy and load forecasts, unexpected outages in conventional units, grid equipment failures, or temporary maintenance leading to lowered grid operation limits. These factors may lead to power generation and consumption discrepancies. To mitigate these issues, two strategies are employed: pre-deviation management and post-deviation settlement. This article advocates for pre-deviation management, which involves adjusting the contract volumes and managing deviations through a market dispatch plan that allows for upward or downward adjustments, thereby reducing overall electricity deviations within a month or over several days..

This paper conducts an in-depth study on the handling of deviations in medium to long-term electricity market contracts based on existing research and proposes an innovative joint optimization scheduling model. Reference [32] considers the influence of market transition and the decomposition of electricity quantity in medium to long-term contracts on short-term multi-objective generation dispatch. Reference [33] investigates the optimization decision of complex provincial-level electricity market transactions considering internal inter-regional cooperation. Compared to the studies in reference [32] and reference [33], this paper not only focuses on market trading rules and dispatch strategies but also emphasizes the handling of contract quantity deviations. reference [34] and reference [35] respectively research the joint optimization scheduling of monthly unit combination and maintenance plans in a wind power integrated power system, as well as the joint optimization scheduling method considering maintenance plans in medium to long-term hydro-thermal power systems. Based on this research, this paper introduces fuzzy chance-constrained programming to cope with source-load uncertainty and improve the adaptability and robustness of scheduling. Moreover, this paper learns from reference [36] that analyzes methods for handling base deviations in medium to long-term power market and proposes compensation methods for expected revenue, deviation quantity substitution matching, and average price difference compensation. Reference [31] studies the rolling scheduling method for unit deviation quantity under the pre-listed monthly deviation balance mechanism. It puts forward a new dynamic adjustment strategy based on price incentives to optimize the execution of contract quantities, which is less common in previous research and provides a new deviation handling strategy for electricity markets.

This article employs fuzzy chance constraints to handle the uncertainty on the supply and demand sides, considering the regular maintenance of thermal power units. The objective is to minimize the cost of adjusting the deviation electricity volume of monthly transaction contracts. To adjust the cost of deviation electricity volume for conventional thermal power, wind power, and photovoltaic power, a unified market clearing price for deviation electricity volume services is used as a 'bottom support' execution. A joint optimization dispatch model for monthly power generation plan and maintenance is established based on the deviation electricity volume handling mechanism. The monthly contracted electricity volume is strictly enforced to enhance the utilization of new energy in long-term power trading and meet the economic and safety requirements of system operation.

II. SUPPLY AND DEMAND UNCERTAINTY MODEL

The membership function is a useful tool for quantifying the degree of membership of fuzzy variables to fuzzy sets. The size of the membership degree indicates the degree to which each element belongs to the fuzzy set. The closer the membership degree is to 1, the higher the possibility that the element belongs to the fuzzy set. Conversely, when the membership degree is closer to 0, the possibility of the element belonging to the fuzzy set is lower. Membership functions are typically determined using the intuition method, assignment method, or fuzzy statistical method. These functions have a subjective nature, and commonly used ones include triangular [37], trapezoidal [38], and Gaussian membership functions [40]. The medium and long-term sizes of wind power and photovoltaic output are determined using conservative, likely, and optimistic fuzzy attributes that are appropriate for triangular membership functions.

This paper introduces fuzzy variables to describe the uncertainty of the source load. The fuzzy parameters for wind power at time t are denoted as $\tilde{P}_{W,t}$, for photovoltaic power as $\tilde{P}_{\mathrm{V},t}$, and for load as $\tilde{P}_{\mathrm{L},t}$. The expression for representing these fuzzy parameters is based on the triangular fuzzy parameter model.

$$\begin{aligned} \tilde{P}_{W,t} &= \left(P_{W1,t}, P_{W2,t}, P_{W3,t}\right) \\ \tilde{P}_{V,t} &= \left(P_{V1,t}, P_{V2,t}, P_{V3,t}\right) \\ \tilde{P}_{L,t} &= \left(P_{L1,t}, P_{L2,t}, P_{L3,t}\right) \end{aligned} \tag{1}$$

In the expression, $P_{W1,t}, P_{W2,t}, P_{W3,t}$ represents the membership degree parameter for wind power within the given time period, $P_{V1,t}, P_{V2,t}, P_{V3,t}$ represents the membership degree parameter for photovoltaic power within the given time period, and $P_{L1,t}, P_{L2,t}, P_{L3,t}$ represents the membership degree parameter for load within the given time period. These membership degree parameters represent the decision maker's most conservative, most likely, and most optimistic estimations, respectively.

The expression for the expected value of the triangular fuzzy parameter is as follows:

$$\begin{aligned} E\left(\tilde{P}_{W,t}\right) &= P_{\mathrm{Wc},t}\left(\frac{1-\alpha}{2}P_{W1,t} + \frac{1}{2}P_{W2,t} + \frac{\alpha}{2}P_{W3,t}\right) \\ E\left(\tilde{P}_{V,t}\right) &= P_{\mathrm{Vc},t}\left(\frac{1-\alpha}{2}P_{V1,t} + \frac{1}{2}P_{V2,t} + \frac{\alpha}{2}P_{V3,t}\right) \\ E\left(\tilde{P}_{L,t}\right) &= P_{\mathrm{Lc},t}\left(\frac{1-\alpha}{2}P_{L1,t} + \frac{1}{2}P_{L2,t} + \frac{\alpha}{2}P_{L3,t}\right) \end{aligned} \tag{2}$$

where α is the confidence level, which depends on the decision maker's risk attitude, and $P_{W\mathrm{c},t}, P_{Vc,t}, P_{Lc,t}$ are the predicted values for wind power, photovoltaic power, and load at time t respectively.

III. DEVIATION QUANTITY HANDLING MECHANISM

The trading volume of medium and long-term market contracts is determined through market transactions by market participants. Traders on both the supply and demand sides make judgments, which may vary depending on their trading strategies. The trading volume of the contract represents the predicted actual underlying asset, without considering the overall balance of generation and consumption. The trading volumes of generation and consumption contracts are decoupled, considering only the multi-year characteristics of generation and consumption and the average values of operation in the same region. To avoid irrational trading decisions made by traders who are extremely pessimistic or optimistic, the effectiveness of contract volumes is verified. The trading price of contract volumes is determined through market mechanisms, providing the settlement basis. The dispatching institution creates a generation plan in advance based on the contracted volumes, taking into account the overall balance of generation and consumption in the system. The contracted volumes are divided into daily and real-time power matching, and deviations in the execution of contracted volumes may occur among various market participants. Two methods can be used to solve this problem: pre-bias handling and post-bias settlement. Bias handling and bias settlement are closely related. Bias handling involves adjusting the contracted trading volume through intra-month (multi-day) trading to reduce the execution bias of the contract. It also involves market-based trading of bias power through the bias power handling mechanism in the intra-month (multi-day) pattern, where the adjustment cost caused by bias is borne by the benefiting party. The settlement serves to handle bias and resolve the issue of monetary imbalance after power balance. Power generation companies are responsible for excess or shortfall of power output, while users are responsible for excessive or insufficient power consumption. Settlement is done based on the bias settlement price.

A. BIAS POWER HANDLING MECHANISM IN THE INTRA-MONTH (MULTI-DAY) PATTERN

For entities involved in conventional thermal power generation, the primary power generation party has the ability to adjust the monthly contracted trading volume and declare the corresponding upward and downward adjustment power volumes and their respective prices before the 20th day of each month. The pricing structure incentivizes adjustable units with regulation capabilities to participate in the upward and downward declaration. There are no upper or lower limits for the declared prices, in principle. The declaration of upward adjustment power volume creates a call order list for adjustable units in ascending order of prices, while the declaration of downward adjustment power volume creates a call order list for adjustable units in descending order of prices. The dispatching organization adjusts the power generation plan for units with cleared trading volume based on the remaining trading period within the month. This adjustment takes into account load and renewable energy forecasts and allows for upward and downward adjustments to achieve real-time balance of power supply and demand while ensuring safety and stability.

For entities generating renewable energy, such as wind power and photovoltaics, only the monthly contracted trading volume is adjusted before the 20th day of the month. No bias power volume or price is declared. The cost of adjusting the bias power volume of conventional units with regulation capabilities is 'bottomed out' and settled by the benefiting wind power and photovoltaic companies based on the unified market bias power volume service price.

B. DEVIATION POWER SETTLEMENT MECHANISM

The monthly contract power is the total amount of electricity traded by the power generation entity through various types of medium and long-term electricity market agreements and contracts. This includes the annual contract decomposition power, monthly centralized trading power, and bilateral negotiated trading power. The mechanism for handling deviation power is the imbalance between trading power, actual grid power, and contracted electricity consumption between power generation and user entities. The power contracted on a monthly basis can be adjusted within the same month. At the end of the month, any deviations between the actual grid power and the contracted trading power, as well as any deviations between the actual electricity consumption and the contracted trading power, cannot be carried over to the following month or remaining months of the year. Settlement of deviation power is performed based on the principle of monthly settlement and clearance. Various provinces have issued different policy bases for deviation power settlement. For instance, in Xinjiang, the settlement rules are as follows:

The settlement price for electricity users is determined by dividing the deviation power between the actual measured electricity consumption and the contracted power into excess power and insufficient power. The price deviation for excess power is currently determined by the benchmark electricity price of thermal power units, while the deviation price for insufficient power is calculated based on the annual average trading price of power generation enterprises multiplied by a penalty coefficient of 0.8.

The settlement pricing for power generation companies varies based on whether they produce more or less electricity than required from traditional thermal and hydroelectric sources. For surplus generation, the settlement price is determined by applying a penalty factor of 0.8 to the annual average trading price of thermal and hydropower. On the other hand, for under-generation, the settlement price is calculated using a penalty factor of 1.2 times the same annual average trading price. It's crucial to understand that these calculations are strictly based on objective standards and are not influenced by subjective assessments.

IV. FUZZY CHANCE-CONSTRAINED PLANNING FOR SCHEDULING MODEL

When creating a model for a monthly generation schedule that takes into account the uncertainty of both the source and the load in the electricity market environment, there are fuzzy parameters to consider. As a result, the scheduling results may not fully satisfy the constraint conditions. The scheduling organization's decision-makers must specify a confidence level beforehand. They require that the possibility measure of the fuzzy parameter constraints should be no less than the confidence level when the scheduling results hold.

The general form of the fuzzy chance-constrained planning [14] is as follows:

$$\begin{cases} \min f(x,\xi) \\ s.t.\ Pr\{g(x,\xi) \leq 0\} \geq \alpha \end{cases} \tag{3}$$

where x is the decision variable, ξ is the fuzzy random variable, $f(x)$ is the objective function, $g(x,\xi)$ is the constraint function, and $Pr\{\bullet\}$ is the possibility measure for the event to hold, which represents the probability.

The fuzzy chance-constrained planning model involves fuzzy variables in both the objective function and the constraint conditions. Although the general form mentioned above has no specific mathematical meaning, there are indirect mathematical methods to solve it. To solve this model, it is necessary to transform the objective function with fuzzy variables into the expected value of the objective function. Two common methods for solving fuzzy chance-constrained planning models are the fuzzy simulation technique and the transformation method. The fuzzy simulation technique generates random values for fuzzy variables to obtain a solution, which has some randomness and is not unique. The transformation method is suitable for cases where the decision variable and the fuzzy variable can be separated or have a linear correlation.

A. OBJECTIVE FUNCTION

In this study, the objective is to minimize the cost of adjusting the deviation between the monthly contracted electricity quantity and the actual electricity quantity. The expression for the objective function is as follows:

$$\min f = \sum_{i=1}^{N} \max(C_i^{+}(Q_i^{w} - Q_i), C_i^{-}(Q_i - Q_i^{w})) \tag{4}$$

where f represents the cost of deviation, C_i^+, C_i^- represent the priceq3e for increasing and decreasing electricity quantity, respectively, for the power generation entity i, Q_i^w, Q_i represent the actual electricity quantity and the contracted electricity quantity for the power generation entity i in a month, and N is the total number of power generation entities. Considering that increasing or decreasing electricity quantity cannot occur simultaneously, the max function is used to determine whether the power generation entity is in an increasing or decreasing situation after the actual scheduling operation.

B. CONSTRAINT CONDITIONS

Due to the fuzzy parameters involved, strict equality or inequality constraints cannot be used to address the constraints of system power balance and reserve capacity. Therefore, the system power balance and reserve capacity constraints are relaxed to strictly hold under a certain confidence level. The constraints with fuzzy parameters are treated as events, and the probability of the fuzzy event occurring satisfies the predetermined confidence level.

1) SYSTEM POWER BALANCE CONSTRAINT

$$\Pr\left\{\sum_{i=1}^{N_G} u_{i,t}P_{i,t} + \tilde{P}_{W,t} + \tilde{P}_{V,t} = \tilde{P}_{L,t}\right\} \geq \alpha \tag{5}$$

2) RESERVE CAPACITY CONSTRAINT

$$\Pr\left\{\tilde{P}_{L,t} - \tilde{P}_{W,t} - \tilde{P}_{V,t} - \sum_{i=1}^{N_G} u_{i,t}P_{i,\max} \leq 0\right\} \geq \alpha \tag{6}$$

3) CONVENTIONAL UNIT CONSTRAINT

$$u_{i,t}P_{i,\min} \leq P_{i,t} \leq u_{i,t}P_{i,\max} \tag{7}$$

where $P_{i,\min}$ represents the minimum output limit for power generation unit.

$$-R_d \leq P_{i,t} - P_{i,t-1} \leq R_u \tag{8}$$

where R_d, R_u represents the upward and downward ramp rates for the unit.

$$-R_d \leq P_{i,t} - P_{i,t-1} \leq R_u \tag{9}$$

where $T_{j,on}$, $T_{j,off}$ represents the minimum on/off time limits for power generation unit i, and $T_{j,on,t-1}$, $T_{j,off,t-1}$ represents the continuous running or shutdown time of power generation unit i in the previous period $t-1$.

4) WIND POWER AND PHOTOVOLTAIC POWER OUTPUT CONSTRAINT

$$\begin{aligned} 0 \leq P_{W,t} \leq E\left(\tilde{P}_{W,t}\right) \\ 0 \leq P_{V,t} \leq E\left(\tilde{P}_{V,t}\right) \end{aligned} \tag{10}$$

5) NETWORK SECURITY CONSTRAINT

In this study, the nonlinear network security constraint is transformed into a linear constraint using DC power flow constraints and generator output power distribution factors.

$$P_{l,\min} \leq \sum_{m=1}^{M} G_{l,m}P_m^t \leq P_{l,\max} \tag{11}$$

where $P_{l,\max}$, $P_{l,\min}$ represents the flow constraint limit for line l, $G_{l,m}$ represents the power distribution factor from node m to line l, P_m^t represents the active power injected by node m at time t, and M represents the total number of system nodes.

6) MAINTENANCE PLAN-RELATED CONSTRAINTS

(a) Maintenance status constraint

$$y_{m,k} = \sum_{k_1=k-M_{Cm}+1}^{k} x_{m,k_1} \tag{12}$$

where $y_{m,k}$ represents the maintenance status variable for power generation unit m at time k, M_{Cm} represents the maintenance duration for power generation unit m, and x_{m,k_1} represents the status variable for starting maintenance.

(b) Earliest and latest start time constraints for maintenance

$$\sum_{k=k_{m,\min}}^{k_{m,\max}} x_{m,k} = 1 \tag{13}$$

where $k_{m,\min}$, $k_{m,\max}$ represents the earliest and latest start times for the maintenance plan of power generation unit m.

(c) Sequential maintenance constraint

$$\sum_{k_1=k-M_{Dm}+1}^{k} x_{m_1,k_1} + x_{m,k} \leq 1 \tag{14}$$

where M_{Dm} represents the time interval that maintenance project m_1 needs to be completed before maintenance project n, and k_1 represents the project number for maintenance.

$$\sum_{k_1=1}^{k-1} x_{m_1,k_1} - x_{m,k} = 0 \tag{15}$$

(d) Exclusive maintenance constraint

$$\sum_{k=1}^{K} (y_{m_1,k} + y_{m,k}) \leq 1 \tag{16}$$

where K represents the number of maintenance projects.

(d) Simultaneous maintenance constraint

$$\sum_{k=1}^{K} (x_{m_1,k} - x_{m,k}) \leq 0 \tag{17}$$

(e) Maintenance resource constraint

$$\sum_{k=1}^{K} y_{m,k} \leq E_m \tag{18}$$

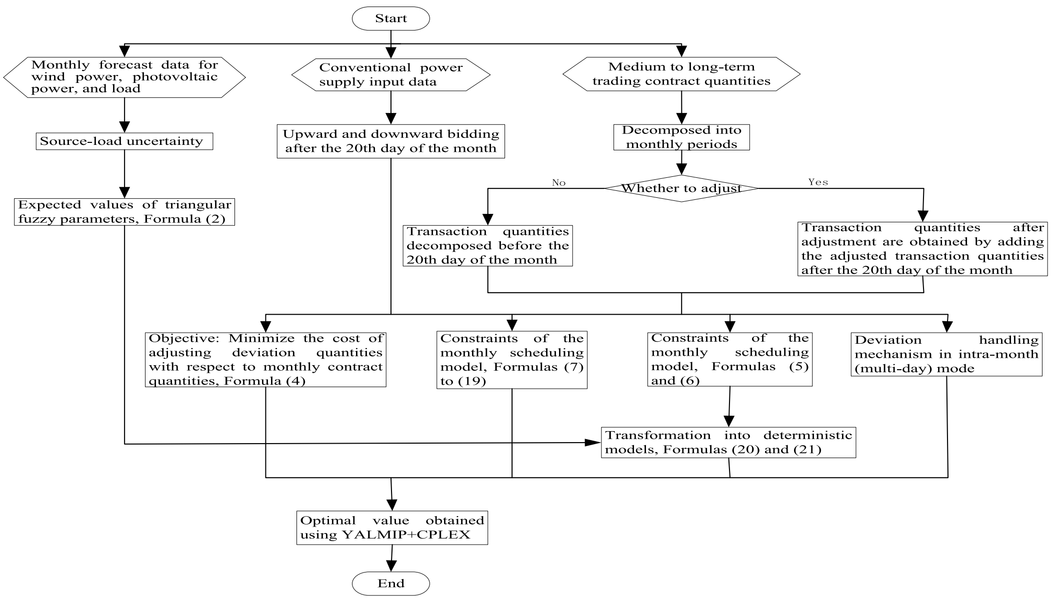

FIGURE 1. Fuzzy chance-constrained programming model solution flowchart.

where E_m represents the upper limit of maintenance projects that can be carried out at the same time.

(f) Relationship between maintenance status and operating status

When the power generation unit is under maintenance, the operating status is 0. The coupling relationship between the operating status and the maintenance status is expressed as:

$$u_{i,t} \leq 1 - \sum_{m=1}^{M} \sum_{k=1}^{K} A_{i,m} y_{m,k} B_{k,t} \tag{19}$$

where $A_{i,m}$ represents the association matrix between maintenance project m and power generation unit i, and $B_{k,t}$ represents the association matrix between maintenance time k and unit combination time t.

C. CONVERSION TO A DETERMINISTIC MODEL

The system power balance constraint and reserve capacity constraint involve fuzzy variables and chance constraints. Following the approach in reference [18], the fuzzy chance-constrained planning can be transformed into a deterministic model with crisp equivalence. The crisp equivalence expression for the system power balance constraint is:

$$\begin{aligned}&(2-2\alpha)\left[P_{L2,t}-P_{W2,t}-P_{V2,t}\right]\\&\quad+(2\alpha-1)\left[P_{L3,t}-P_{W1,t}-P_{V1,t}\right]-\sum_{j=1}^{N_G}u_{j,t}P_{j,t}\\&=0\end{aligned} \tag{20}$$

The crisp equivalence expression for the reserve capacity constraint is:

$$\begin{aligned}&(2-2\alpha)\left[P_{L2,t}-P_{W2,t}-P_{V2,t}\right]\\&\quad+(2\alpha-1)\left[P_{L3,t}-P_{W1,t}-P_{V1,t}\right]-\sum_{j=1}^{N_G}u_{j,t}P_j^{\max}\\&\leq 0\end{aligned} \tag{21}$$

V. MODEL SOLUTION FLOWCHART

The input data in the model involves three parts: the contract trading electricity quantity decomposed into monthly periods provided by the trading center, the conventional power supply input data provided by the regulatory agency, and the predicted data for monthly wind power, photovoltaic power, and load. After the 20th day of the month, the contract electricity quantity for wind power and photovoltaic power can be adjusted based on the deviation of generation electricity quantity before the 20th day within the month, while the conventional thermal power units need to be traded in the market through bidding with deviation electricity quantity adjustments. During the model solving process, the uncertainty of source-load is transformed into deterministic form using triangular membership functions, and the fuzzy variables in the system power balance constraint and reserve capacity constraint are transformed into deterministic models. Finally, the model is solved using the YALMIP+CPLEX solver to obtain the optimal value of the objective function. The specific flowchart of the model solution process is shown in Figure 1.

VI. IMPROVED IEEE30-NODE SYSTEM CASE STUDY ANALYSIS

A. SYSTEM PARAMETERS

In this study, we used the improved IEEE30-node system case study. The parameters of conventional thermal power

TABLE 1. Parameters of thermal power units.

Output Limit/ MW	Lower Limit Of Output/ MW	Minimum Start-Stop Time/h	Fuel Cost Coefficient		
			$a_i\left[\$/(MW)^2\right]$	$b_i(\$/MW)$	$c_i/\$$
460	230	8	0.0211	21.05	1313.6
300	150	6	0.0375	23.9	372.5
243	121	5	0.079	21.62	480.29
120	60	3	0.048	23.23	639.4
130	65	1	0.063	16.51	502.7

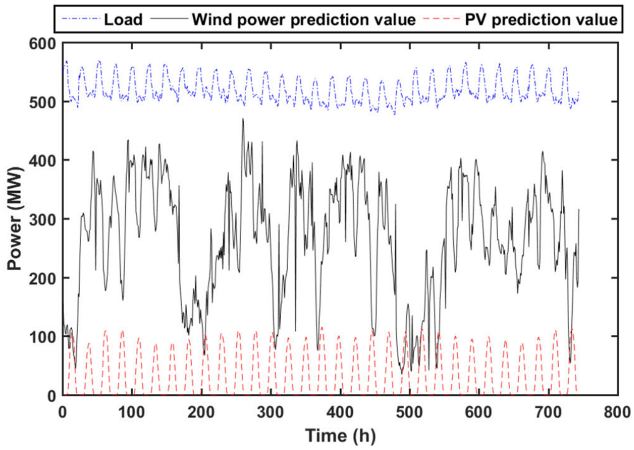

FIGURE 2. Monthly forecast for wind, PV and load.

units are shown in Table 1, and the monthly forecasts of wind power, photovoltaics, and load are shown in Figure 2.

Using the MATLAB 2015b software environment, we established a monthly generation and maintenance joint optimization scheduling model based on the deviation electricity quantity processing mechanism, and used the CPLEX solver for solving. The case study analysis consists of four parts: comparative analysis of different modes, joint optimization scheduling for maintenance, comparative analysis at different confidence levels, and comparative analysis at different wind power contract quantities.

B. COMPARATIVE ANALYSIS OF DIFFERENT MODES

Based on the deviation electricity quantity processing mechanism, we proposed a monthly joint optimization scheduling model with fuzzy opportunity constraints to handle the uncertainty on both supply and demand sides. To verify the feasibility and effectiveness of the model, we established three modes for comparative analysis.

Mode 1: Handling uncertainty on both supply and demand sides by reserving a fixed percentage of reserve capacity based on load, wind power, and photovoltaics' power, with the optimization objective of minimizing the curtailed wind power and photovoltaics.Mode 2: Handling uncertainty on both supply and demand sides using fuzzy opportunity constraints, with the optimization objective of minimizing the curtailed wind power and photovoltaics.Mode 3: Handling uncertainty on both supply and demand sides using fuzzy opportunity constraints, incorporating upward and downward price incentives based on the deviation electricity quantity processing mechanism, with the optimization objective of minimizing the deviation in the monthly contract completion rate.

TABLE 2. Comparison of scheduling results under three modes.

Mode	Abandoned Wind Rate/%	Photovoltaic Curtailment Ratio/%	System Cost/RMB	Reserve Capacity /MW
1	22.55%	33.97%	10425916	171736
2	15.25%	18.37%	9907376	102128
3	6.07%	1.25%	9655178	134873

Results of the optimization scheduling for Mode 2 and Mode 3, considering a confidence level of 0.95, are shown in Table 2.

From Table 2, it can be observed that Mode 3, which handles uncertainty using fuzzy opportunity constraints, achieves the lowest curtailed wind power and photovoltaics rates as well as the lowest system cost compared to the other modes. Compared to Mode 1, which handles uncertainty by reserving a fixed percentage of reserve capacity, Mode 3 reduces the system cost by 7.39%, decreases the reserve capacity by 21.47%, and reduces the curtailed wind power and photovoltaics rates by 16.48% and 32.72% respectively. By introducing the price incentives for the deviation electricity quantity in the electricity market, Mode 3 adjusts the optimization objective and achieves a 2.55% reduction in system cost compared to Mode 2, improving the economic efficiency of the system. The curtailed wind power and photovoltaics rates are reduced by 9.18% and 17.12% respectively, and the reserve capacity increases by 32.06%, further ensuring the safety of the system operation.

C. JOINT OPTIMIZATION SCHEDULING FOR MAINTENANCE

In Mode 3, the planned maintenance periods for Unit 1 and Unit 2 are during the first two weeks of the month, with a maintenance period of 5 days. Using the monthly generation and maintenance joint optimization scheduling model based on the deviation electricity quantity processing mechanism, the operational statuses of the conventional units are shown in Figure 2, and the daily generation amounts of the power generation equipment throughout the month are shown in Figure 4. In Figure 3, black represents the operational status of the units, while white represents the shutdown status. From Figure 3 and Figure 4, it can be observed that Unit 1 and Unit 2 have mutually exclusive maintenance periods, and the maintenance is scheduled during the period of relatively high

TABLE 3. Monthly scheduling optimization results under different confidence levels.

Confidence Level	Abandoned Wind Rate/%	Photovoltaic Curtailment Ratio/%	System Cost/RMB	Reserve Capacity /MW
0.60	47.04%	0.16%	9688883	117406
0.65	42.79%	0.00%	9801039	79415
0.70	37.33%	0.04%	9698125	98612
0.75	32.19%	0.08%	9663675	129351
0.80	26.12%	0.06%	9598621	127024
0.85	18.95%	0.11%	9569510	129418
0.90	11.93%	0.00%	9585676	127955
0.95	6.07%	1.25%	9655178	134873

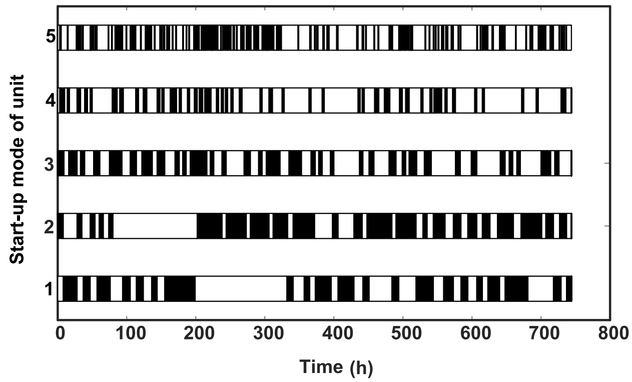

FIGURE 3. Boot mode of conventional unit.

wind power generation, which is beneficial for wind power integration and system safety.

D. COMPARATIVE ANALYSIS AT DIFFERENT CONFIDENCE LEVELS

The optimization results of the monthly dispatch at different confidence levels are shown in Table 3. It can be seen from Table 3. that as the confidence level increases, the wind curtailment rate decreases continuously. Since the installed capacity of photovoltaic power is relatively small compared to wind power, the curtailment rate of photovoltaic power is less than 1.5% and its variation trend is not significant. The system cost shows a trend of "first increasing, then decreasing, and then increasing" as the confidence level changes. The trend of reserve capacity is opposite to that of system cost. When system security increases, economic efficiency decreases. The main reason is that in this paper, the goal is to minimize the adjustment cost of the monthly contract deviation in the electricity market environment, which leads to a non-linear correlation between system cost, reserve capacity, and confidence level.

E. COMPARATIVE ANALYSIS AT DIFFERENT WIND POWER CONTRACT VOLUMES

To simplify the calculation, wind power and photovoltaic power do not participate in the bid adjustment for upward and downward regulation. The bid price for deviation power is executed based on the clearing price, while the bid prices for upward and downward regulation of conventional units and the completion of monthly contracts are shown in Table 4. From Table 4, it can be seen that the bid prices for reduction by Units 2 to 5 are higher than the bid price for upward regulation by Unit 1, resulting in a completion rate of less than 100% for Unit 1's monthly contract. Wind power and photovoltaic power are executed at the unified clearing price in the market, and the bid prices for upward and downward regulation are the lowest in the electricity market, ensuring the completion of the monthly contract without deviation and maximizing the benefits in the market. Compared with Mode 2, in Mode 3, except for Unit 1, all other power plants achieve their contract volumes, resulting in a relatively balanced completion rate for monthly contract volumes.

The optimization dispatch results when the wind power contract volume is decreased by 10% and increased by 10% and incorporated into the monthly generation plan are shown in Table 5. From Table 5, it can be seen that both the decrease and increase of the wind power contract volume in the monthly generation plan result in deviations in the completion of the wind power contract volume. The wind curtailment rates after executing the dispatch for the two scenarios of decreased and increased monthly contract volumes are 7.07% and 3.16% respectively.

VII. ANALYSIS OF A PROVINCIAL POWER GRID CASE IN NORTHWEST CHINA

To further validate the effectiveness of the proposed method, a simulation analysis is conducted on a provincial power grid case in Northwest China. During the optimization of the medium and long-term dispatch plan, the network structure of the provincial power grid is complex, with numerous power sources, transmission lines, and substations. The scheduling institution has already completed the operation mode and major equipment maintenance arrangements for the current year, annual plan, and special periods before the dispatch plan is formulated, a simplified schematic of the large power grid is shown in Figure 5.

Different operation modes consider situations such as equipment overload or overlimit, stability limits of interconnection lines and transmission sections, etc. In actual operation of the power grid, based on the allocated power output values from the AGC system and the operating limits of the modes, the power grid equipment does not exceed power limits under normal operation. Therefore, detailed modeling of the power grid equipment is not necessary when formulating medium and long-term dispatch plans. Only the restrictions caused by limited renewable energy due to interconnection lines need to be considered, and the power source and grid structure of the power grid are simplified to meet the calculation requirements of medium and long-term dispatch plans. The schematic diagram of the simplified power grid is shown in Figure 4.

TABLE 4. Completion of monthly contract electricity quantity under different modes.

Unit	Installed Capacity/MW	Monthly Contract Electricity Quantity/MW.h	Mode 3				Mode 2	
			Upgrade Quotation/(RMB/MW.h)	Downgrade Quotation/(RMB/MW.h)	Monthly Actual Completion Of Electricity/MW.h	Contract Completion Rate/%	Monthly Actual Completion Of Electricity/MW.h	Contract Completion Rate/%
1	460	100000	200	-180	99500	99.5	110688	110.7
2	300	90000	220	-205	90296	100.3	81476	90.5
3	243	50000	240	-210	50333	100.7	52066	104.1
4	120	15000	250	-235	15667	104.4	13232	88.2
5	130	20000	280	-260	20500	102.5	24102	120.5
Wind Power	450	200000	180	-180	200000	100.0	196238	98.1
PV	150	30000	180	-180	30000	100.0	24801	82.7

TABLE 5. Scheduling results of wind power under different monthly contract quantities.

Uint	The monthly contract power of wind power is 10 % smaller			The monthly contract power of wind power is 10 % larger.		
	Monthly Contract Electricity Quantity/MW.h	Monthly Actual Completion Of Electricity/MW.h	Contract Completion Rate/%	Monthly Contract Electricity Quantity/MW.h	Monthly Actual Completion Of Electricity/MW.h	Contract Completion Rate/%
1	100000	100500	100.5%	100000	99500	99.5%
2	90000	90667	100.7%	90000	89333	99.3%
3	50000	50333	100.7%	50000	49667	99.3%
4	15000	15667	104.4%	15000	14333	95.6%
5	20000	20500	102.5%	20000	19500	97.5%
Wind Power	180000	197858	109.9%	220000	206192	93.7%
PV	30000	30000	100.0%	30000	30000	100.0%

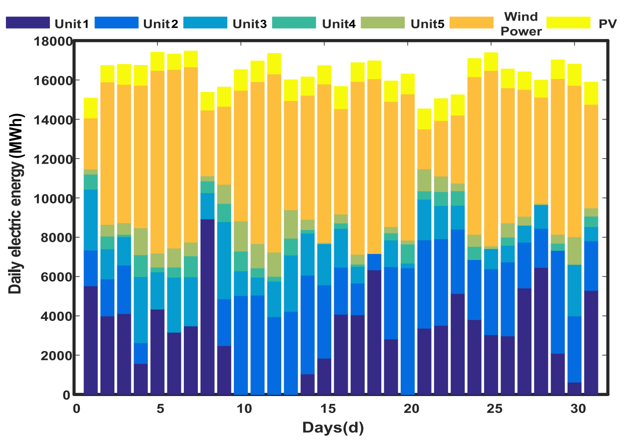

FIGURE 4. Monthly daily output of power generation equipment.

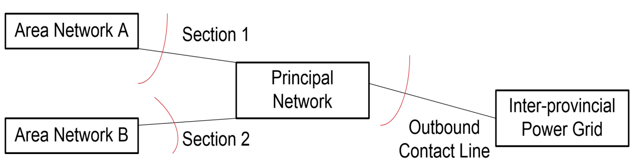

FIGURE 5. A simplified diagram of the grid

Specifically, the wind farms, photovoltaic power stations, and load within the designated region are aggregated, while the thermal power units are aggregated by the thermal power plants. The transmission capacity limitations of the lines within the designated region are ignored, and only the transmission capacity limitations between the designated region and the main power grid are considered. The simplified power grid is divided into three sub-grid regions: the main grid, regional network A, and regional network B. The main power sources in each sub-grid region include thermal power, wind power, and photovoltaic power, with a smaller proportion of hydropower and other small power sources. After offsetting the monthly planned power with the load of each sub-grid, only the net load time series is retained. The power sources and loads in each sub-grid region are shown in Table 6. The transmission limits for section I and section II are 1.2 million kilowatts and 1.4 million kilowatts respectively, and the maximum transmission capacity for outbound interconnection lines is 14.5 million kilowatts.

The simplified power grid has a total installed capacity of 61,798 MW, with 23,398 MW from thermal power, involving 43 power plants, 26,250 MW from wind power, and 12,150 MW from photovoltaic power.

A. MONTHLY DISPATCH PLAN EXECUTION RESULTS

Considering the uncertainties on both the supply and demand sides, a fuzzy chance-constrained joint optimization dispatch model is used to verify the feasibility and effectiveness of the model, whether the deviation power handling mechanism is considered or not. Mode 2 and Mode 3 are used for verification. The monthly forecast values of wind power, photovoltaic

TABLE 6. Installed capacity and load scale of large power grid Unit:10MW.

Area	Thermal Power	Wind Power	PV	Total Power Supply	Maximum Load	Minimum Load
Principal Network	1874.8	2449	730	5053.8	1502	1112
Area Network A	40	176	199	415	80	47
Area Network B	425	0	286	711	261	153

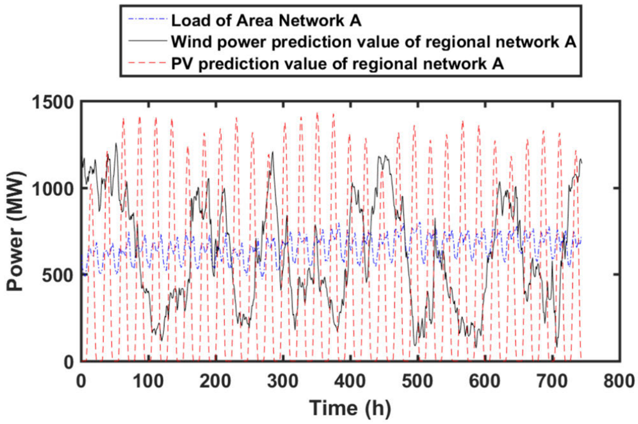

FIGURE 6. Monthly wind, PV and load forecasts for regional network A.

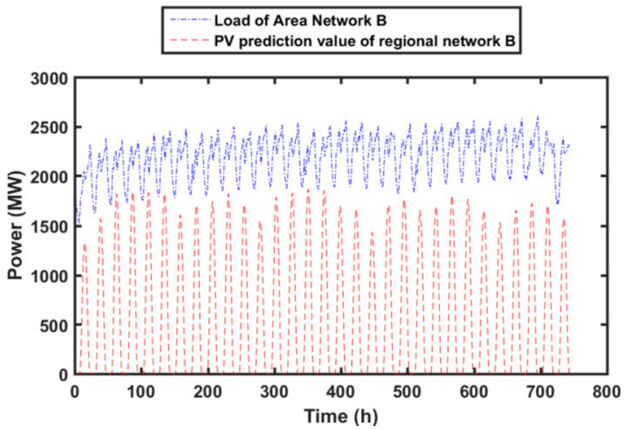

FIGURE 7. Monthly wind, PV and load forecasts for regional network B.

power, and load in the three sub-grid regions are shown in Figure 6 to Figure 8.

The execution results of the monthly dispatch plan for the simplified power grid obtained using Mode 2 and Mode 3 are shown in Table 7. It can be seen from Table 7 · that by considering the deviation power handling mechanism and using Mode 3, which utilizes fuzzy chance constraints to handle the uncertainties on both the supply and demand sides, the wind curtailment rate and photovoltaic curtailment rate for the principal network, area network A, area network B, and the entire power grid are minimized compared to Mode 2, which does not consider the deviation power handling mechanism. Under Mode 3, the wind power curtailment rate and photovoltaic curtailment rate in the simplified power grid are reduced by 10.56% and 10.39% respectively. In Mode 3, through the price incentive of deviation contract for the electricity market,

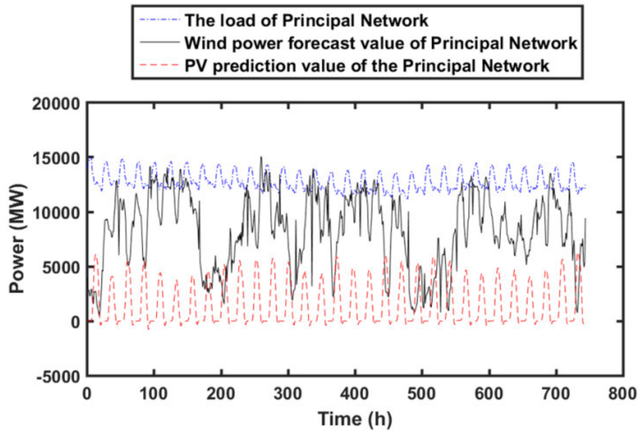

FIGURE 8. Monthly forecast of wind, PV and load for the main.

TABLE 7. Implementation result of monthly dispatching plan of large power grid.

Type	Mode 2		Mode 3	
	Abandoned Wind Rate/%	Photovoltaic Curtailment Ratio/%	Abandoned Wind Rate/%	Photovoltaic Curtailment Ratio/%
Principal Network	19.80%	20.62%	9.25%	10.17%
Area Network A	21.61%	22.33%	10.92%	11.12%
Area Network B	--	23.38%	--	13.28%
Large Power System	19.91%	21.21%	9.35%	10.82%

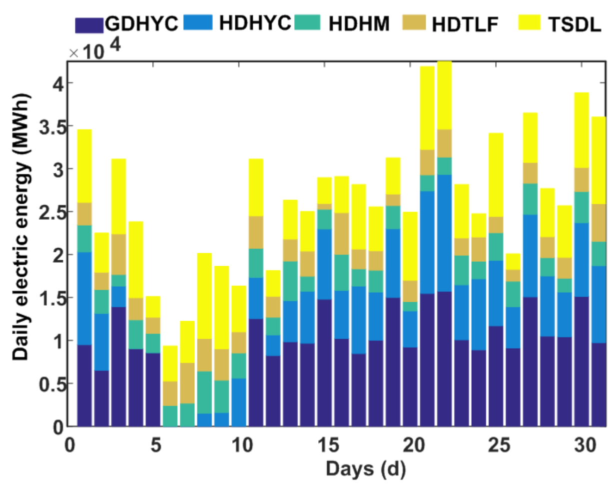

FIGURE 9. Monthly daily output of thermal power equipment in large power grids.

TABLE 8. Results of monthly (multi-day) dispatching plan execution in large power grid.

Uint	Installed Capacity/ MW	Monthly Contract Electricity Quantity/MW.h	Mode 3				Mode 2	
			Upgrade Quotation/(RMB /MW.h)	Downgrade Quotation/(RMB /MW.h)	Monthly Actual Completion Of Electricity/MW.h	Contract Completion Rate/%	Monthly Actual Completion Of Electricity/MW.h	Contract Completion Rate/%
GDHYC	660	288000	200	-180	287500	99.8%	156310	54.3%
HDHYC	800	178450	280	-260	177950	99.7%	192314	107.8%
HDHM	270	86400	250	-235	85733	99.2%	104836	121.3%
HDTLF	270	86400	250	-235	85733	99.2%	111543	129.1%
TSDL	600	192000	250	-235	191333	99.7%	209163	108.9%
HK	400	106350	240	-210	106017	99.7%	133773	125.8%
JZ	660	261880	200	-180	261380	99.8%	239799	91.6%
GDYC	700	134020	280	-260	133520	99.6%	205841	153.6%
KSSQ	700	224000	250	-235	223333	99.7%	266798	119.1%
TDQH	700	344350	200	-180	343850	99.9%	279263	81.1%
TF	270	86400	250	-235	85733	99.2%	99794	115.5%
HNQBK	700	139560	280	-260	139060	99.6%	205384	147.2%
Wind Power	26250	7000000	180	-180	6450300	92.1%	5698975	81.4%
PV	12150	2025000	180	-180	2025000	100.0%	1789130	88.4%

the monthly dispatch optimization objectives are adjusted, resulting in improved utilization of renewable energy compared to Mode 2.

In Mode 3, the planned maintenance periods for Unit GDHYC and Unit HDHYC are the first two weeks of the month, with a maintenance duration of 5 days for both units. The daily operating generation of the thermal power equipment within the month is shown in Figure 9. From Figure 9, it can be observed that Unit GDHYC and Unit HDHYC have mutually exclusive maintenance periods.

B. MONTHLY EXECUTION RESULTS OF PLANS (MULTIPLE DAYS)

The simplified implementation results of the monthly dispatch plans for the large-scale power grid obtained using Mode 2 and Mode 3 are shown in Table 8. Due to space limitations, only the results of 12 power plants are retained. From Table 8, it can be observed that compared to Mode 2, Mode 3 achieves a relatively balanced monthly contract fulfillment rate for all units, with wind power and photovoltaic achieving contract completion rates of 92.1% and 100% respectively, which are 10.7% and 11.6% higher than Mode 2.

Under Mode 2, Power Plant GDYC achieved an actual monthly electricity production of 206 million kilowatt-hours, with the highest contract fulfillment rate of 153.5% among thermal power plants. After implementing Mode 3, the contract fulfillment rate decreased by 54%. Under Mode 2, Power Plant GDHYC achieved an actual monthly electricity production of 156 million kilowatt-hours, with the lowest contract fulfillment rate of 54.3% among thermal power plants. After implementing Mode 3, the contract fulfillment rate increased by 46%. In the market environment, the consistency and uniformity of contract fulfillment rates in Mode 3 is superior to Mode 2. Apart from wind power and photovoltaic, Power Plant GDHYC has the lowest bid price among thermal power units, which is beneficial for prioritizing the completion of monthly contract electricity production. In the large-scale power grid, wind power and photovoltaic follow a unified market clearing electricity price, maximizing market dividends and facilitating the market-based integration of renewable energy.

VIII. CONCLUSION

This study considers uncertainties in supply and demand as well as maintenance scheduling in the joint dispatch of the monthly electricity production and maintenance plans. A joint optimization dispatch model is established based on the deviation electricity quantity handling mechanism. Through comparative analysis of different scenarios, the following conclusions are drawn:

The method of adopting a fuzzy chance constraint to handle uncertainties on both the supply and demand sides, compared to the traditional approach of reserving fixed percentages for contingencies, can reduce system costs and backup capacity, while also decreasing the curtailment rates of wind and photovoltaic power.

By introducing a deviation electricity quantity handling mechanism, with the implementation of upward and downward price incentives, the consistency of the monthly contract completion rates for conventional thermal power units is ensured, enhancing the economic and operational security of the system. The adjustment costs for system deviation electricity quantities are supported by wind and photovoltaic power, and the reasonable declaration of monthly contract electricity volumes for wind and photovoltaic power can achieve completion without deviation, unlocking market dividends.

In the comparative analysis of different scenarios, the model considering the deviation electricity quantity handling mechanism (Model 3) outperforms the model without this mechanism (Model 2) in reducing wind and photovoltaic curtailment rates as well as system costs. This is particularly evident in the improved IEEE 30-bus system and a provincial grid in Northwest China, where Model 3 demonstrates better scheduling results, including lower curtailment rates and more balanced monthly contract completion rates.

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