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RESEARCH ARTICLE

Flexibility Demand Analysis and Regulation Capacity Sharing Decisions Between Interconnected Power Systems Considering Differences in Regulation Performance

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ABSTRACT To cope with the demand for large amount of flexibility regulation caused by high penetration of intermittent renewable energy, it is necessary to classify and measure the demand capacity for different regulation performance, and to reasonably allocate flexibility resources for different regions and different regulation capacities. This study proposes a flexibility demand analysis and regulation capacity sharing decisions between interconnected power systems considering differences in regulation performance. Firstly, the empirical mode decomposition (EMD) method is used to decompose the historical operating load curves of each sub-region, and the demand capacities of different regulation performances are calculated based on the obtained decomposition results of trend components and fluctuation components. Then, the probability density and the regulation demand capacity interval at different confidence levels are calculated based on the regulation capacity statistics of the sample of historical operation days. Finally, the regulation capacity sharing decisions between the interconnected regions are made based on the cost of various regulation resources in different sub-regions and the confidence level requirements of internal resources in sub-regions to meet regulation demand. A scenario based on the interconnection operation of two regional grids and the self-sufficiency rate of regulation capacity in each sub-region is no less than 0.95 confidence level is used to verify the effectiveness and feasibility of the proposed method. The simulation results demonstrate that the regulation capacity demand considering the difference in regulation quality can provide a detailed basis for the cross-region deployment of different quality flexibility resources, and the total cost of regulation capacity of the regional grid after adopting the cross-region sharing decision model is reduced by about 4.51% compared with the system independent optimization model.

INDEX TERMS Flexibility, regulation performance, regulation demand, sharing decisions.

I. INTRODUCTION

A. BACKGROUND

In order to cope with the energy crisis and global climate change, energy transition is the inevitable trend of energy development. In this context, the proportion of intermittent renewable energy generation represented by wind power and photovoltaic to all installed power generation is growing rapidly. The World Energy Outlook report released by British Petroleum states that the share of oil, gas and coal in primary energy will decrease from 85% in 2018 to 65%-20%, respectively, by 2050, and renewable energy will

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grow to 20%-60% accordingly [1]. Since the power output of intermittent renewable energy has obvious fluctuation characteristics, the power system regulation capacity needs to be configured according to the net load creep demand caused by new energy to continuously ensure the power balance of the system [2]. If the regulation capacity configuration is inadequate or the regulation performance cannot meet the rapidly changing demand of net load, it may may cause intermittent renewable energy curtailment or power supply gap [3], [4]. Conversely, if the configured regulation capacity is excessive, the economic efficiency of grid operation will be compromised [5], [6]. Therefore, a reasonable configuration of the flexibility regulation capacity of the power system is the key to guarantee the reliable and economic operation of the power system.

B. LITERATURE REVIEW

Accurate assessment of regulation capacity requirements is fundamental and central to the optimal configuration of flexibility resources. In the existing studies on the demand analysis of flexibility regulation capacity of power systems, typical indicators such as the variation of net load [7], [8], the variation of renewable energy output [9], [10], or power curtailment [11] are mainly selected as references for demand capacity calculation. Reference [7] uses Monte Carlo sampling method to evaluate the flexibility demand capacity based on the actual data and forecast deviations of system load at different time periods and considering the variation factors such as temperature correlation, load growth trend, and new energy penetration rate. Reference [8] proposes a multi-time scale flexibility requirement analysis method based on historical data of wind power, photovoltaic, and load, which takes into account medium to long term and day-ahead operating scenarios. Reference [9] proposes evaluation methods for flexible regulation capacity requirements from the perspectives of grid operation and grid planning, respectively, in response to the output fluctuation characteristics of wind power and photovoltaic power. Reference [10] also analyzes the fluctuation and deviation characteristics of intermittent renewable energy output from a multi time scale perspective, in order to determine the flexibility regulation demand of the power system during various periods of operation. Reference [11] proposed a flexibility requirement analysis method that considers wind power curtailment, which uses the probability distribution results of wind power abandonment under different operating scenarios as the basis for setting flexibility regulation capacity. The above method mainly evaluates the flexibility regulation demand from the perspective of new energy output or net load variation of the whole power system, and does not differentiate the regulation quality of the flexibility demand capacity from the perspective of different frequencies and different directions.

Scholars have conducted extensive research on the optimal allocation of flexible resources in the power system. In the study of flexibility resource allocation within the system region, literature [12] proposed a stochastic optimization model for day-ahead dispatching of power systems, which can realize the joint optimization of electric energy and flexibility reserve capacity, thus improving the matching of flexibility resources reserved for dispatching plans with net load changes. Literature [13] uses a robustness framework to find the optimal set of scenarios for renewable energy generation, and then completes the allocation of flexibility regulation capacity resources such as energy storage units, slow-start and fast-start units. Literature [14] utilizes the feature that battery electric vehicles (BEVs) can provide flexible resources for grid operation and constructs an optimal charging schedule model considering charging frequency and user behavior factors. The literature [15] proposed a joint optimization method of flexibility resources and electric energy resources based on main network-distribution network synergy in order to facilitate the full utilization of resources at the distribution network level to enhance the flexibility of main network operation. The literature [16] proposed an optimization method for flexibility regulation capacity allocation based on opportunity constraints by considering the cost of flexibility regulation resources and system operation risks. The established method makes full use of the regulation capacity of multiple types of resources such as slow-start units, fast-start units, energy storage, and demand-side response, which significantly improves the flexibility regulation capacity in power system operation. However, the above-mentioned approach for the allocation of flexible regulation resources is developed from the perspective of the total demand for regulation of the entire power system and does not significantly distinguish the demand components with differences in regulation performance. In general, flexibility resources with faster regulation rates and the ability to change regulation direction frequently are relatively more costly, while those with poorer regulation performance are relatively less costly [17], [18]. If the demand components with different performance in terms of regulation frequency and regulation rate are not significantly distinguished from the total flexibility regulation demand, it will, to a certain extent, lead to the mismatch of flexibility demand and flexibility resources with different regulation qualities, thus limiting the economy of flexibility regulation capacity allocation.

In addition, different regions have different resource endowments, and thus the attributes of flexible regulation capacity costs vary. For example, in regions rich in water and adjustable load resources, the capacity cost of the more flexible regulation resources is relatively low [19], [20]; in regions rich in thermal power resources, the capacity cost of the less flexible regulation resources is also relatively low [21], [22]. For interconnected power systems, it will help to improve the economy of system operation if the dispatch plan or capacity resource allocation plan can be arranged by the complementary capacity of resources in different sub-regions [23], [24]. Many researchers and scholars have adopted the model of inter-regional mutual cooperation to improve the system economics. Reference [25] constructed a cross regional interconnected power grid operation optimization model for wind power consumption based on decomposition and coordination theory, which enhances the economic benefits of system operation through the complementary utilization of wind power resources in different subregions. In the literature [26], a dispatching decision method considering hydropower flexibility regulation capacity mutualization is proposed to achieve cross-regional mutualization of flexibility resources under the scenario of considering DC contact line constraints. Literature [27] first measures the operational standby demand within the sub-region through the probability indicators of lost load and wind power surplus in different regions, and then considers the security constraints of the sub-region grid to achieve joint optimization of cross-region generation standby capacity, which effectively improves the allocation effect of network-wide standby capacity resources. However, the existing methods mentioned above have not yet meticulously taken into account the differences in flexibility regulation needs of different regulation qualities in the process of carrying out the optimal allocation of resources across regions.

C. RESEARCH GAPS, AIMS AND CONTRIBUTIONS

With the increasing penetration of intermittent renewable energy sources, the demand for flexible regulation capacity for power system operation is gradually increasing, and the range of subjects providing flexible resources is expanding. Therefore, it is necessary to analyze and optimize the configuration of flexibility capacity demand in a more detailed way. Based on the aforementioned analysis in the sectionsubsection I-B, the following research gaps still exist in the existing relevant studies:

- The analysis of the regulation demand for power system flexibility is mainly carried out from the perspective of renewable energy output or load power of the whole power system, e.g. [9] and [11], and the regulation components with differences in regulation quality are not identified from the total regulation demand for the time being. Therefore, the relatively coarse flexibility demand analysis method is not conducive to the fine-grained allocation of flexibility resources with differences in regulation performance.
- For the allocation method of flexibility regulation capacity, the existing studies mainly focus on how to optimize the synergy of multiple types of resources such as units, controllable loads, and energy storage within the sub-regional grid to fully utilize the flexibility potential of each type of regulation resources to meet the flexibility regulation capacity demand, e.g. [14] and [15]. Few existing studies have addressed how to complementarily utilize flexibility resources distributed within different regions with different regulation qualities to further enhance the economic efficiency of operation.

Based on the above analysis, this study proposes a flexibility demand analysis and regulation capacity sharing decisions between interconnected power systems considering the difference in regulation performance. The aims of this study is to identify the components with different regulation quality from the total system flexibility regulation demand, and calculate the corresponding regulation capacity demand and probability distribution characteristics, so as to facilitate the refined demand analysis and resource matching of flexibility regulation capacity. Based on this, the characteristics of flexibility demand and resource supply in different sub-regions are considered to make sharing decisions for regulation capacity. On the premise of securing the flexibility regulation demand, the situation of insufficient flexibility resources for a certain type of regulation quality or high flexibility regulation cost is avoided, so as to enhance the economic efficiency of power system operation.

The contribution of this study can be summarized as follows:

- The flexibility regulation demand measurement method considering flexibility energy differences based on time series decomposition is proposed to improve the accuracy of flexibility demand analysis. Firstly, the time series of the net system load is decomposed into different trend components, so that each series component can correspond to the flexibility demand of different regulation performances respectively, and thus the total regulation demand can be reasonably split into demand components of different qualities. Then, based on a variety of historical operation scenarios, the regulation demands under different confidence are calculated to provide a detailed basis for the allocation of flexibility resources.
- The regulation capacity resource allocation method between the interconnected regions is proposed to reduce the flexibility regulation costs. Based on the demand components of different regulation performances calculated by time series decomposition, the regulation demands of different regulation performances within the sub-region are optimally matched. Through the proposed cross-sub-region flexibility resource sharing method, the flexibility regulation cost of the power system can be reduced while satisfying the confidence level of the flexibility resource sufficiency in the sub-region is not lower than the set level.

The rest of the study is organized as follows. Section II covers the impact of new energy access on power system operation and regulation. Section III presents in detail the flexibility regulation demand analysis method based on time series decomposition. Based on the analysis of Section III, a flexible resource allocation method that considers the mutual support among sub-regions is proposed in Section IV. Section VI provides simulation analysis to verify the effectiveness and feasibility of the proposed method. The conclusions are drawn in Section VII.

II. THE IMPACT OF HIGH PENETRATION OF INTERMITTENT RENEWABLE ON THE OPERATION AND REGULATION OF THE POWER SYSTEM

A. THE VOLATILITY OF INTERMITTENT RENEWABLE ENERGY OUTPUT AND THE FLEXIBLE REGULATION REQUIREMENT FOR SYSTEM

Intermittent renewable energy generation has the characteristics of "volatility" and "randomness", which may lead to more drastic power output changes between different operating days or different operating periods, thus causing the net load of the power system to creep up and down more obviously. The net load of the power system may show more obvious climbing and sliding phenomena. Sufficient flexible regulation resources need to be allocated to cope with this change. For the system regulation demand caused by the volatility and randomness of intermittent renewable energy output, if it is coped with entirely by resources with better regulation performance but higher regulation costs (e.g. gas-fired units, energy storage, etc.), it will not be conducive to giving full play to the regulation complementary capacity of various dispatching resources and reducing the economy of the system.

Therefore, it is necessary to extract the flexibility demand components for different regulation qualities based on the net load variation patterns in historical operation scenarios, so that capacity resources with different regulation performances can be allocated in a reasonable manner.

B. POTENTIAL FOR RESERVE MUTUAL SUPPORT BETWEEN INTERCONNECTED POWER SYSTEMS

Considering the differences in power supply structures and load characteristics within different sub-regional grids, the flexibility regulation demands of different sub-regions and the regulation capacity resources that can be invoked also have differences [28], [29]. If in the demand calculation session, the flexibility demands of different regulation qualities are first distinguished, and the probability characteristics of the flexibility demands of different qualities are analyzed to obtain the flexibility demand value intervals corresponding to different confidence levels in the historical operation scenarios. Then, based on the flexibility demand within different sub-regions, the supply of regulation resources, and under the condition that the adequacy of flexibility resources within the sub-regions is not lower than the set confidence condition, the flexibility regulation demand of each sub-region will be further responded by the mutual assistance of regulation resources between sub-regions. This approach will help to realize the potential of mutual support between interconnected power systems and improve the overall level of system operation and regulation.

In summary, this paper proposes a flexibility demand analysis method for high penetration renewable energy power systems, and the results of the analysis are used to guide the flexibility resource allocation under the interconnected power systems. Firstly, based on the decomposition results of the system load time series, the demand capacity for different regulation qualities is calculated separately; Then, considering the probability characteristics of demand capacity with different regulatory qualities, as well as the cost differences of various flexible resources possessed by different subregions, flexible resource sharing decisions across subregions are made. The research framework of this study is shown in Figure 1.

III. FLEXIBILITY REGULATION REQUIREMENT ANALYSIS METHOD BASED ON TIME-SERIES DECOMPOSITION

A. EMPIRICAL MODE DECOMPOSITION OF THE NET LOAD TIME SERIES

In the fields of power generation and load forecasting, in order to reveal the pattern of intermittent renewable energy generation curve or power load curve, the time series of power generation or load is usually decomposed to form several "trend components" reflecting long-period and continuous changes, and "fluctuation components" reflecting frequent changes in the short term [30], [31]. Then, more obvious regular features are extracted for each component to improve the prediction accuracy.

In order to distinguish the total demand capacity of flexibility regulation caused by net load volatility into demand components with different regulation quality, the idea of processing time series in the field of power system forecasting can be borrowed to perform empirical mode decomposition of the actual net load curves of historical operation dates to obtain trend and fluctuation components with different variation patterns [32]. The specific operation method is as follows:

1) STEP 1

Based on the original net load time series $\overline{L}_t = \left[L_1, \ldots, L_t, \ldots, L_{Nt}\right]$, the maximum value series $\overline{L}_{\max,t} = \left[L_{\max,1}, \ldots, L_{\max,t}, \ldots, L_{\max,U_T}\right]$ and the minimum value series $\overline{L}_{\min,t} = \left[L_{\min,1}, \ldots, L_{\min,t}, \ldots, L_{\min,U_T}\right]$ are extracted respectively, where, N_T denotes the number of load time series; U_T indicates the number of extreme value points, and $U_T < N_T$.

2) STEP 2

For the maximum value series $\overline{L}_{\max,t}$ and the minimum value series $\overline{L}_{\min,t}$, the coefficients of the segmented spline interpolation function are solved to obtain the following expressions for the interpolation function:

$$\begin{cases} \overline{S}_{\max,j}(t) = a_j + b_j(t-t_j) + c_j(t-t_j)^2 + d_j(t-t_j)^3 \\ \overline{S}_{min,j}(t) = v_j + w_j(t-t_j) + x_j(t-t_j)^2 + y_j(t-t_j)^3 \end{cases} \quad (1)$$

where, a_j, b_j, c_j, d_j, v_j, w_j, x_j and y_j are the coefficient of the j-th segment of the spline interpolation function; $\overline{S}_{\max,j}(t)$ and $\overline{S}_{min,j}(t)$ represent the values of the interpolation function of the j-th segment of the sequence of maximal and minimal values at time slot t, respectively.

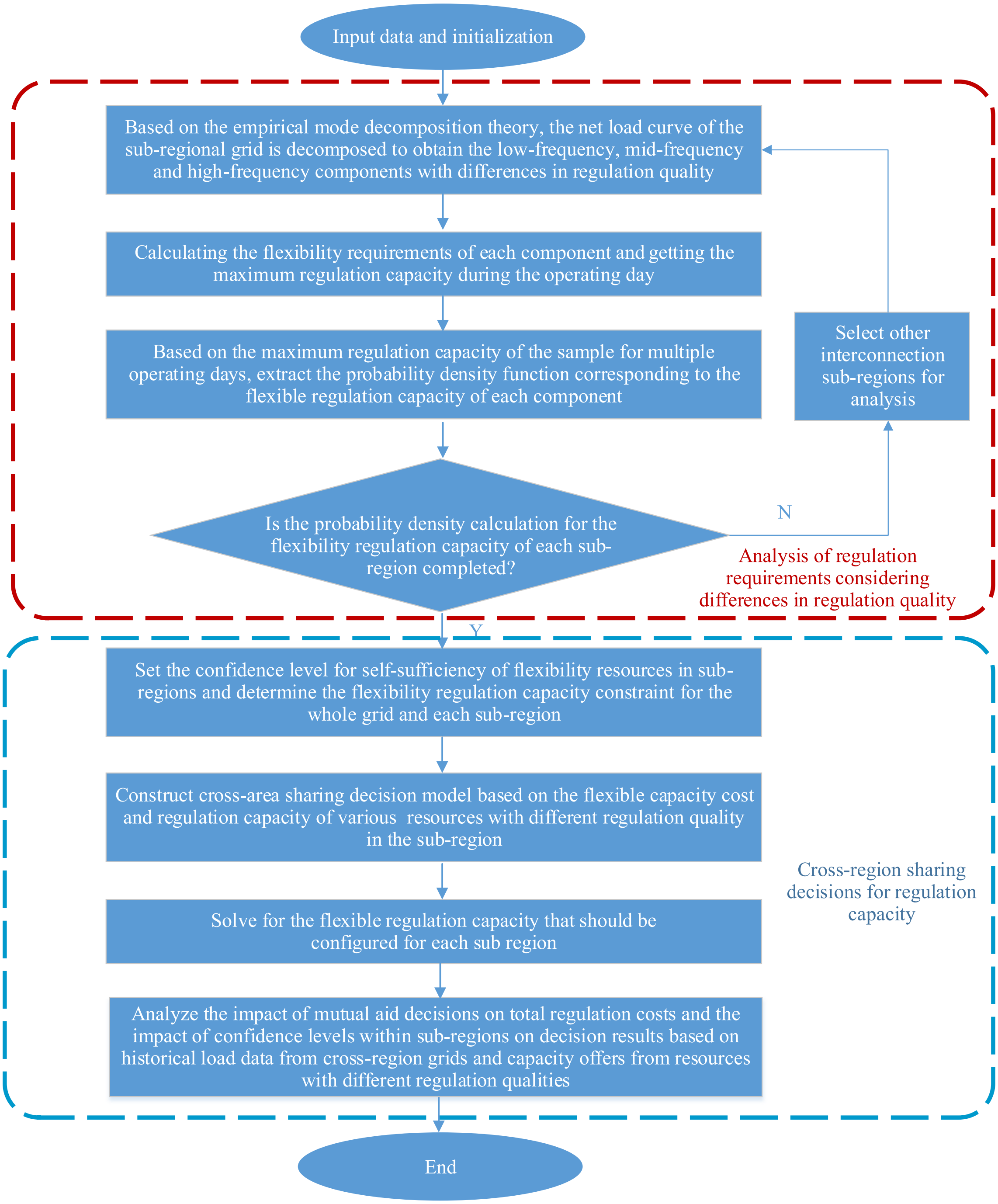


FIGURE 1. The framework for flexibility demand analysis and regulation capacity sharing decisions between interconnected power systems considering differences in regulation performance.

3) STEP 3

Based on the interpolation function of the net load maxima and minima, the net load components are calculated as follows:

$$D_1(t) = \sum_{j=1}^{U_T-1} \frac{\overline{S}_{\max,j}(t) + \overline{S}_{min,j}(t)}{2} \tag{2}$$

where $D_1(t)$ denotes the net load in time period t taken at the 1-th component. By subtracting $D_1(t)$ from the original net load $\overline{L}_t$, the remaining net load value, $L_t - D_1(t)$, also contains the remaining fraction to be decomposed.

4) STEP 4

$L_t - D_1(t)$ is regarded as the time series components to be decomposed, and then repeat the steps from step 1 to

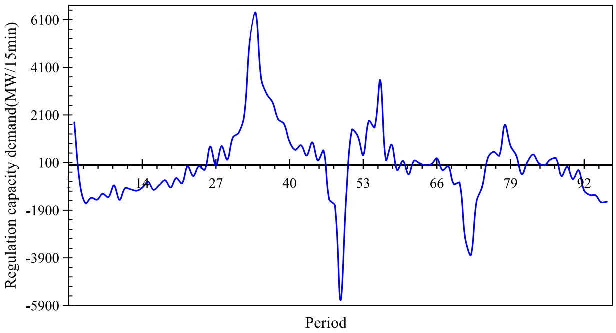


FIGURE 2. Regulated power demand for each period corresponding to the original system load curve for a typical day.

step 3 until the total number of net load components reaches the established requirement, then the decomposition of the net load time series is completed. The final correspondence between the net load curve and several components can be obtained as follows:

$$L_t = \sum_{i=1}^{n} D_i(t) \tag{3}$$

where, $D_1(t)$ denotes the net load in time period t taken at the i-th component; n indicates the total number of components corresponding to the original net system load.

B. CALCULATION AND PROBABILISTIC CHARACTERIZATION OF FLEXIBILITY REGULATION REQUIREMENTS

As mentioned above, if the complete system load time series is used directly for regulation demand analysis and resource allocation, it is highly likely that frequent large amounts of active regulation demand in opposite directions will occur between short intervals. For example, the climbing and sliding power demand between time periods based on system load statistics for a typical day in a provincial of China is shown in Figure 2, with forward or reverse regulation demand reaching about 6000 MW/15 min in some time periods.

When conducting flexibility regulation demand analysis and resource allocation based on the original load curve, it is difficult to accurately assess the possible creep and slippage power values for each time period. For this reason, it is necessary to reserve a large number of flexibility resources with good regulation performance. This makes it hard to manage and allocate resources with different regulation qualities in a fine-grained manner.

After decomposing the time series of the original system load, the up-regulation and down-regulation capacity demands for each time period are counted separately. Then probabilistic feature analysis based on historical operation samples can provide detailed references for rational allocation of flexible resources with different regulation performances. For a certain operation day, the up-and down-regulated capacity demand of the system in each time period can be expressed as:

$$\begin{cases} R_{s,i,t}^U = \max\{D_i(t) - D_i(t-1), 0\} \\ R_{s,i,t}^D = \min\{D_i(t) - D_i(t-1), 0\} \end{cases} \tag{4}$$

where, $R_{s,i,t}^U$ and $R_{s,i,t}^D$ denote the upward/downward demand capacity of the i-th load time series component corresponding to time period t on operating day s, respectively.

For the historical system load data, after the demand capacity for each time period of the operating day is calculated from equation (4), the extreme value series for the upward and downward capacity corresponding to the historical sample number m are obtained as follows:

$$\begin{cases} \overline{R}_i^{U,\max} = \left[R_{1,i}^{U,\max}, \cdots, R_{s,i}^{U,\max}, \cdots, R_{m,i}^{U,\max}\right] \\ \overline{R}_i^{D,\max} = \left[R_{1,i}^{D,\max}, \cdots, R_{s,i}^{D,\max}, \cdots, R_{m,i}^{D,\max}\right] \end{cases} \tag{5}$$

where, $R_{s,i,}^{U,max}$ and $R_{s,i}^{D,max}$ denote the maximum upward capacity demand and the downward capacity demand of the i-th component of the system load during the operating day s, respectively.

Calculate the kernel density functions corresponding to the extreme value time series $\overline{R}_i^{U,max}$ and $\overline{R}_i^{D,\max}$ for m sample days:

$$\begin{cases} f_i^U(r) = \frac{1}{m}\sum_{s=1}^{m} K\left(\frac{r-R_{s,i}^{U,max}}{h}\right) \\ f_i^D(r) = \frac{1}{m}\sum_{s=1}^{m} K\left(\frac{r-R_{s,i}^{D,max}}{h}\right) \end{cases} \tag{6}$$

where, $f_i^U(r)$ and $f_i^D(r)$ are the probability density functions corresponding to the i-th upper and lower regulation components at the capacity value r, respectively; h denotes the kernel width; K denotes the kernel function, which can be taken as uniform kernel function, triangular kernel function, Gaussian kernel function, etc.

Based on equation (6), the probability density function of each regulation component under the historical operation scenario is calculated, and the regulation capacity demand under a certain confidence level $1-\sigma$ can be obtained as follows:

$$\begin{cases} R_{i,\sigma}^U = \int_{\frac{\sigma}{2}}^{1-\frac{\sigma}{2}} f_i^U(r)rdr \\ R_{i,\sigma}^D = \int_{\frac{\sigma}{2}}^{1-\frac{\sigma}{2}} f_i^D(r)rdr \end{cases} \tag{7}$$

where, $R_{i,\sigma}^U$ and $R_{i,\sigma}^D$ denote the up-regulated capacity and down-regulated capacity of the i-th component under the confidence level $1-\sigma$ condition, respectively.

IV. FLEXIBLE RESOURCE ALLOCATION CONSIDERING CROSS-REGION REGULATION CAPACITY SHARING

A. PRINCIPLES FOR FLEXIBLE RESOURCE ALLOCATION

Flexibility resources belong to a class of resources for auxiliary services of the power system. In actual dispatching operation, in order to ensure the reliability of power system operation, it is necessary to reserve a certain capacity of regulating resources within the region to cope with the demand in most operation scenarios. For scenarios with lower probability and larger flexibility regulation demand, consider meeting flexibility regulation demand through inter-regional mutual assistance to utilize flexibility resources with better regulation capacity and lower cost outside the region, so as to better realize the optimal utilization of resources in the global scope.

According to the historical system load of each region, the statistics obtained the regulation capacity demand of different components and their probability distribution characteristics. On this basis, cross-region flexibility resource allocation decisions are formed. The principles to be followed in the decision include: 1) the flexibility regulation demand of each regional grid under the specified confidence level should be met by the adjustable resources in the region, and the part of regulation demand outside the confidence level will then be considered for cross-region mutual assistance; 2) the resources with better regulation quality can match the flexibility regulation demand with poorer regulation quality, and vice versa.

B. A RESOURCE ALLOCATION DECISION MODEL CONSIDERING CROSS-ZONE REGULATION CAPACITY SHARING

For the flexible resource allocation problem of the cross-region power system, firstly, the time series decomposition is performed based on the historical load operation data within each sub-region, and the probability density function of the flexibility regulation demand corresponding to each component is obtained statistically from equation (7). Then, a certain confidence level $1-\sigma$ within each sub-region is set according to the reliability requirement of resource supply within the sub-region and the power grid transmission channel capacity across the sub-region. Finally, according to the capacity cost of each type of flexibility resource within each sub-region, the following decision model is constructed and solved with the lowest flexibility resource cost for the whole region as the goal:

$$\min \sum_{e=1}^{E}\sum_{i=1}^{\Delta}\sum_{j=1}^{Si}\left(a_{e,i,j}X_{e,i,j}^{U}+b_{e,i,j}X_{e,i,j}^{D}\right) \tag{8}$$

where, E denotes the number of sub-regional grids included in the whole network scope, Δ and S_i denote the number of components of flexibility demand and the number of subjects of flexibility resources of type i in the whole network scope, respectively; e, i and j denote the numbers of sub-regional grids, types of flexibility resources and subjects of flexibility resources, respectively. It should be noted that in the latter expression, the larger the value of i is, the better the regulation character performance of the flexibility resources. For example, the flexibility regulation resource of type $i+1$ can go to meet the regulation demand of the flexibility resource of type i. $X_{e,i,j}^{U}$ and $X_{e,i,j}^{D}$ denote the up-regulation and down-regulation capacity of the flexibility resource subject allocated to each sub-region, respectively, which belong to the decision variables to be solved by the model; $a_{e,i,j}$ and $b_{e,i,j}$ denote the capacity cost of the flexibility resource of up-regulation and down-regulation, respectively.

According to the allocation principles described above, it is necessary to meet the total regulation requirements of all types of flexibility resources for the whole network, as well as the flexibility regulation requirements for each sub-region at the specified confidence level $1-\sigma$.

1) CONSTRAINTS ON THE TOTAL FLEXIBILITY REQUIREMENTS OF THE POWER GRIDS

$$\sum_{e=1}^{E}\sum_{j=1}^{Si}X_{e,i,j}^{U}+\sum_{e=1}^{E}\sum_{j=1}^{Si}X_{e,i+1,j}^{U}+\ldots+\sum_{e=1}^{E}\sum_{j=1}^{Si}X_{e,\Delta,j}^{U} \geq \sum_{e=1}^{E}R_{e,i}^{U}+\sum_{e=1}^{E}R_{e,i+1}^{U}+\ldots+\sum_{e=1}^{E}R_{e,\Delta}^{U} \tag{9}$$

$$\sum_{e=1}^{E}\sum_{j=1}^{Si}X_{e,i,j}^{D}+\sum_{e=1}^{E}\sum_{j=1}^{Si}X_{e,i+1,j}^{D}+\ldots+\sum_{e=1}^{E}\sum_{j=1}^{Si}X_{e,\Delta,j}^{D} \geq \sum_{e=1}^{E}R_{e,i}^{D}+\sum_{e=1}^{E}R_{e,i+1}^{D}+\ldots+\sum_{e=1}^{E}R_{e,\Delta}^{D} \tag{10}$$

Eqs. (9) and (10) denote, respectively, the total flexibility resource allocation capacity considering the downward compatibility of the flexibility resource regulation quality, which should meet the system-wide upward and downward regulation capacity demand. Where, $R_{e,i}^{U}$ and $R_{e,i}^{D}$ denote the demand capacity of the type i up-regulation and down-regulation resources of sub-region e, respectively, approximating the values of the extreme regulation capacity under the historical operation scenarios.

2) CONSTRAINTS ON THE INTERNAL FLEXIBILITY REGULATION DEMAND OF EACH SUB-REGION AT A CERTAIN CONFIDENCE LEVEL

$$\sum_{j=1}^{Si}X_{e,i,j}^{U}+\sum_{j=1}^{Si}X_{e,i+1,j}^{U}+\ldots+\sum_{j=1}^{Si}X_{e,\Delta,j}^{U} \geq R_{e,i,\sigma}^{U}+R_{e,i+1,\sigma}^{U}+\ldots+R_{e,\Delta,\sigma}^{U} \tag{11}$$

$$\sum_{j=1}^{Si}X_{e,i,j}^{D}+\sum_{j=1}^{Si}X_{e,i+1,j}^{D}+\ldots+\sum_{j=1}^{Si}X_{e,\Delta,j}^{D} \geq R_{e,i,\sigma}^{D}+R_{e,i+1,\sigma}^{D}+\ldots+R_{e,\Delta,\sigma}^{D} \tag{12}$$

where, $R_{e,i,\sigma}^{U}$ and $R_{e,i,\sigma}^{D}$ denote the up-regulated and down-regulated capacity demand of the type i flexibility resources in sub-region e, respectively, which can be calculated by equation (7). Equations (11) and (12) show that the capacity of the flexibility resources configured within each sub-region should be able to meet the regulation capacity demand within the sub-region at the confidence level.

After obtaining the flexibility regulation demand of each sub-region and its probability distribution characteristics, the models of Eqs. (7) to (12) are solved based on the capacity cost information of different types of regulation resources in each sub-region. In this way, the results of the flexible resource allocation considering the cross-region regulation capacity sharing can be obtained.

V. CASE STUDY

The actual system load curves of two Chinese provinces in 2022 were selected for the study. The system load lines for each operating day are decomposed based on the empirical mode decomposition method to obtain the high-frequency, mid-frequency, and low-frequency regulation components. The up-regulated and down-regulated capacities of each component are counted and probabilistic characterization is developed, which is described in V-A. Then, the cost of flexibility resources for the two sub-region power grids is set as shown in Figure 3. Sub-region B has a cost advantage in the allocation of resources with higher flexibility, while sub-region A has a cost advantage in the allocation of resources with lower flexibility requirements.

To further verify the effect of cross-region regulation capacity mutual assistance on flexibility resource allocation enhancement, the flexible resource allocation results considering cross-region regulation capacity mutual assistance are compared with the results under the independent allocation model of intra-region flexibility resources, and the impact of confidence level on the above results is explored, as elaborated in subsection V-B.

A. ANALYSIS OF FLEXIBILITY REGULATION DEMAND AND THE PROBABILISTIC CHARACTERISTICS

1) FLEXIBILITY CAPACITY DEMAND BASED ON TIME SERIES DECOMPOSITION

After the empirical mode decomposition of the historical system load curves of the two sub-regions, the maximum value of the regulation capacity corresponding to the system load components in each historical operation day (the upward regulation capacity is an example) is calculated according to the equation (4), as shown in Figure 4.

As can be seen from Figure 4, the mid- and low-frequency flexibility regulation demands of the two sub-regional power grids have similarities, mainly showing relatively larger regulation demands in spring and winter seasons and smaller regulation demands in summer and autumn. However, there are large differences in the distribution of high-frequency regulation demand in the two sub-regions, which indicates the potential for cross-fertilization of flexibility resources in different regions.

2) PROBABILISTIC CHARACTERIZATION OF THE FLEXIBILITY REGULATION DEMAND

The kernel density distribution of the maximum upward capacity demand within the operating day corresponding to the system load components of the two sub-regions is calculated by equation (6), as shown in Figure 5. Based on the probability density function curve, the value of the maximum upward capacity under any confidence level regulation can be obtained.

In addition, compared to conducting regulation demand analysis directly for the original system load, calculating the intra-day maximum upward capacity based on the results obtained from time series decomposition, the probability concentration of the regulation demand capacity corresponding to each component is higher, and conducting the allocation of flexibility resources on this basis contributes to improving the coverage level of deterministic regulation capacity allocation results for uncertain operation scenarios.

Based on this, the maximum distribution intervals of the high-frequency, mid-frequency, and low-frequency regulation components of the two sub-regional grids during the operation days at different confidence levels are statistically obtained, as shown in Figure 6. From Figure 6, it can be seen that as the confidence level increases, the regulation capacity demand shows a growing trend of increasing slope. This indicates that pursuing an excessively high level of confidence can lead to a sharp increase in the total allocation of regulated capacity resources.

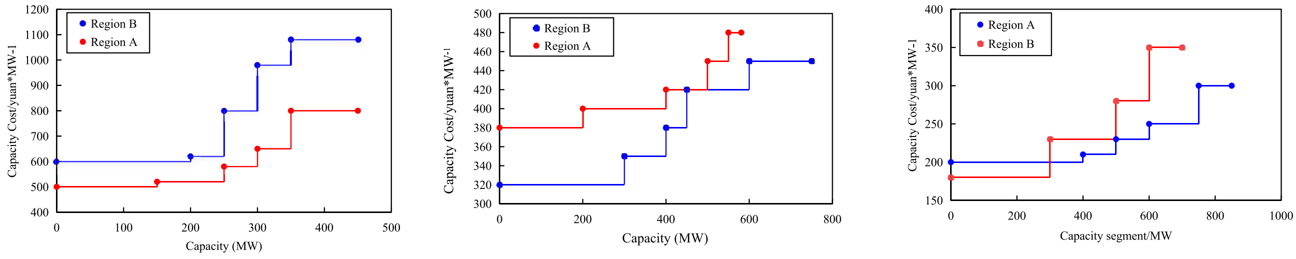
B. THE RESULTS OF FLEXIBLE REGULATED RESOURCE SHARING DECISIONS

1) COMPARISON OF THE REGULATION CAPACITY COSTS

To further verify the enhancement effect of regulation capacity sharing of regulation resources with different regulation performances on flexible resource allocation, the calculation results of the proposed method (M1) in this paper are compared with the method of independent optimal allocation of resources within sub-regions (M2), specifically in terms of regulation capacity cost and resource allocation.

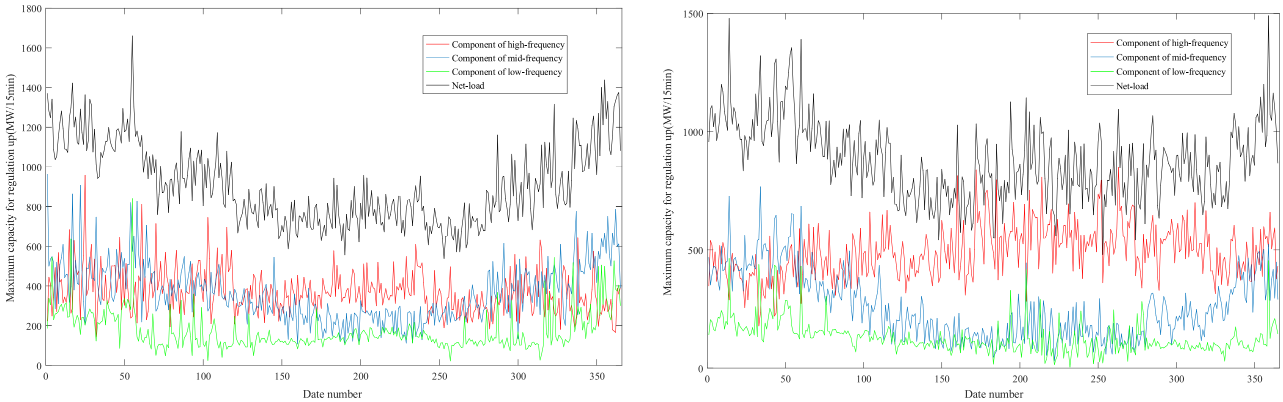
The upper limit of the regulation capacity range corresponding to the confidence level of 95% is used as the total regulation capacity demand of each sub-region (the required capacity of the extreme scenarios of historical operation is not considered for the time being), and the regulation capacity resources of high frequency, mid frequency, and low frequency are allocated by the M1 and M2 methods respectively. The M1 method requires that the self-sufficient capacity in the sub-region should not be lower than the upper limit of the regulation capacity interval corresponding to the 85% confidence level, and the regulation capacity demand beyond the 85% confidence level could be satisfied by sharing within the region.

The regulation capacity costs for the different components of the two approaches are shown in Table 1. It can be seen that the total regulating capacity cost decreases by about 4.51% because the sharing mode contributes to the complementary potential of flexibility resources in different regions. This is specifically due to the fact that some of the higher performance flexibility resources in sub-region B can be used to meet the regulation demand in sub-region A, provided that the 85% confidence level of self-sufficiency of flexibility resources within the sub-region is met. Similarly, some of the



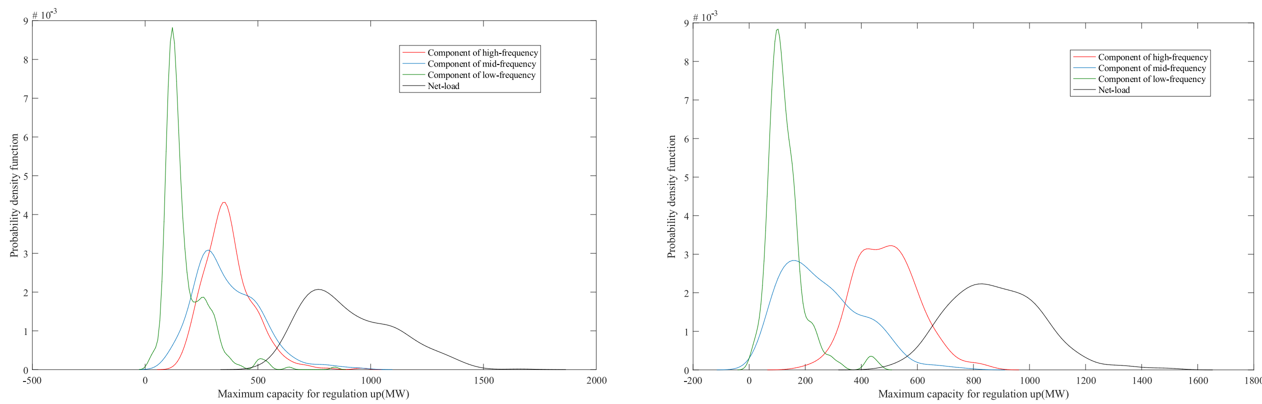
(a) (b) (c)

FIGURE 3. Capacity costs for various types of flexibility resources in both sub-regional power grids: (a) Regulation capacity cost (To meet high-frequency regulation demand). (b) Regulation capacity cost (To meet mid-frequency regulation demand). (c) Regulation capacity cost (To meet low-frequency regulation demand).



(a) (b)

FIGURE 4. Maximum regulation capacity in each operating day: (a) Maximum upward regulation capacity of sub-region A in each operating day. (b) Maximum upward regulation capacity of sub-region B in each operating day.



(a) (b)

FIGURE 5. Probability density function of the maximum upward regulation capacity within an operating day: (a) Probability density of the maximum upward capacity of sub-region A in the operating day. (b) Probability density of the maximum upward capacity of sub-region B in the operating day.

low-frequency regulation capacity resources of sub-region A can be used to meet the demand of sub-region B, thus avoiding the procurement of some of the more expensive flexibility resources.

In addition, the results of the M1 method solution show that using the cross-area sharing model can, to a certain extent, avoid using high-performance regulation resources to meet the situation where only low-performance regulation resources are required to meet the regulation demand. On the contrary, the flexibility regulation demand within each sub-region in the M2 method is satisfied by the resources within the sub-region, and in the case of insufficient supply of a certain type of flexibility resources, the flexibility resources with better performance but also higher cost need to be called,

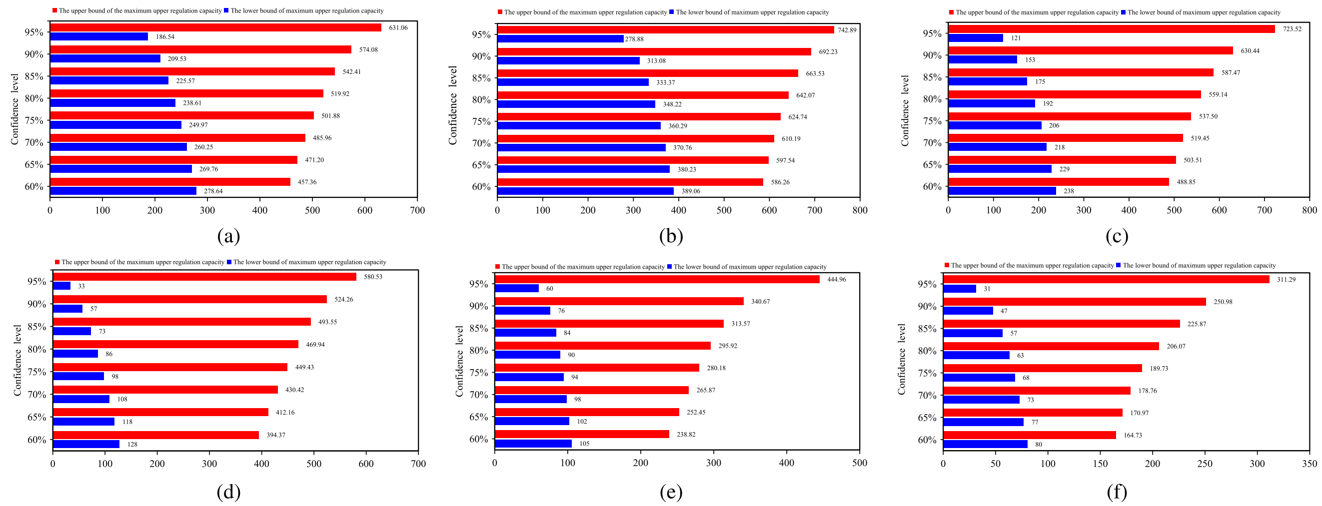


FIGURE 6. Maximum upward capacity distribution interval within operating days at different confidence levels: (a) and (b) are Regulation demand distribution intervals (low-frequency components) for sub-regions A and B, respectively. (c) and (d) are Regulation demand distribution intervals (mid-frequency components) for sub-regions A and B, respectively. (e) and (f) are Regulation demand distribution intervals (high-frequency components) for sub-regions A and B, respectively.

TABLE 1. Comparison of flexibility regulation capacity cost for two optimization methods.

Method	Region	Cost of high frequency regulation capacity (yuan)	Cost of mid-frequency regulation capacity (yuan)	Cost of low frequency regulation capacity (yuan)
Independent optimization mode (M2)	A	342,600	268,800	131,750
	B	163,150	235,380	186,550
	Total		1,328,230	
Sharing mode (M1)	A	304,120	268,800	131,750
	B	163,150	235,380	165,150
	Total		1,268,350	

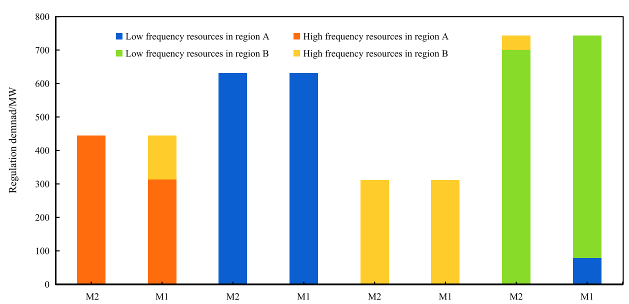


FIGURE 7. Comparison of matching results of flexibility resources for M1 and M2 methods.

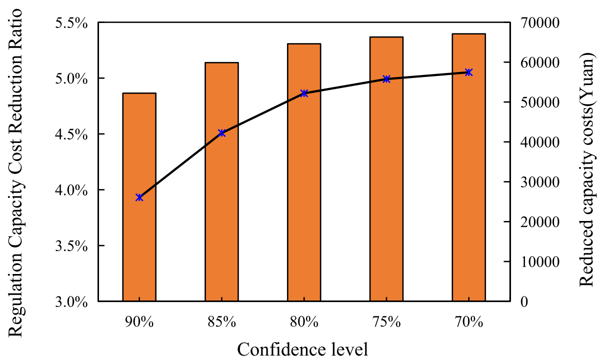


FIGURE 8. Comparison of economic effects of cross-region sharing of flexible resources under different confidence levels.

which will raise the total cost of system regulation to a certain extent. For example, in the scenario of M2 method in this example, the total demand of low-frequency regulation capacity in sub-region B is 743MW, but the supply margin of low-frequency regulation resources in region B is only 700MW, and the remaining 43MW can only be satisfied by high-frequency regulation resources within the sub-region, which will indirectly increase the cost of balancing flexibility resources in the region too much. The flexibility resource matching results calculated by the two methods are shown in Figure 7.

2) THE EFFECT OF DIFFERENT CONFIDENCE LEVELS ON THE EFFECTIVENESS OF DECISION MAKING

The confidence level involved in using the M1 approach is mainly used to reflect the degree to which the flexibility resources allocated within the sub-region meet the regulation demand within the sub-region. The regulation capacity demand beyond the confidence level is the space for the cross-region sharing decision. Based on the scenario in V-B1, different confidence level requirements are chosen to optimize the cross-region regulation capacity resources using the M1 method and compare their total regulation capacity costs and cost reduction rates with those using the M2 method, as shown in Figure 8.

In general, the economic optimization effect obtained through cross-region sharing is more prominent in the scenario with a high degree of self-sufficiency matching of flexibility resources in the sub-region, but this economic optimization effect has a marginal decreasing effect as the degree of self-sufficiency matching decreases. In practical application, the cross-region sharing of flexibility resources should be carried out by selecting appropriate setting confidence parameters according to the transmission capacity of cross-region transmission channels and the differences in flexibility resource endowments of each sub-region.

VI. CONCLUSION

In order to cope with the regulation demand of complex and variable power system operation under high penetration intermittent renewable energy scenarios, this study firstly proposes an analysis method of flexibility demand considering different regulation performances, based on the idea of time series decomposition, and obtains the regulation capacity demand corresponding to different trend components from the curve of system load of historical operation days by solving. Then, a probabilistic characteristic analysis is performed on the maximum regulation capacity demand within the operating day to obtain the distribution interval of various regulation demand capacities at different confidence levels, which is used as a reference benchmark for flexibility resource allocation. Moreover, considering the potential of cross-region regulation resource sharing, the allocation decision of flexibility resources is carried out to further reduce the capacity cost of system operation regulation through coordinated allocation of cross-region flexibility resources under the condition that the self-sufficiency level of flexibility resources in each sub-region is not lower than a certain confidence level. The results show that the proposed method can improve the precision of regulation demand analysis and the coverage of deterministic regulation resources for uncertain scenarios, and the cross-region sharing decision can reduce the system regulation capacity cost while meeting the system regulation demand.

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