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# Reactive Voltage Partitioning Method for the Power Grid With Comprehensive Consideration of Wind Power Fluctuation and Uncertainty

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**ABSTRACT** When large-scale wind power is connected to the power grid, the fluctuation and uncertainty in the wind power reduce the stability and accuracy of the grid's reactive voltage division results based on the electrical distance matrix and affect the grid's reactive power regulation. This paper proposes a grid reactive voltage partitioning method that considers the wind power stability and accuracy in a comprehensive manner. The wind power uncertainty and zoning results are characterized by the distribution of wind power forecast error intervals and changes in the zoning result nodes at different moments when the wind power is connected. Regarding volatility, according to the discretization of the probability distribution of the active power output at a certain time based on the wind power prediction, a calculation interval of the wind power output under a single cross-section is formed, and multiple sequential power flow sections within a long time scale are clustered and partitioned by an agglomeration hierarchical clustering method. Finally, an optimal zoning model of reactive voltage is established over a long time scale with the minimum comprehensive stability serving as the objective function. A simulation analysis of the improved IEEE39 node system shows that the partition combination can effectively increase the stability and accuracy of the reactive partitioning.

**INDEX TERMS** Wind power active prediction interval, wind power fluctuation, wind power uncertainty, hierarchical clustering algorithm, reactive voltage partitioning.

## I. INTRODUCTION

With the increasing scale of grid interconnection and improvements in online automation, automated voltage control (AVC) in grid hierarchical partitioning has been widely applied to ensure the safety and stability of grid operation. Reactive voltage division has become an important issue for secondary voltage control in AVC [1].

At present, there are mainly three modes of reactive power hierarchical voltage control, namely, the three-stage voltage control mode first proposed by EDF, the two-stage voltage control mode proposed by Deutsche Power and the "soft" three-stage voltage control mode that is widely applied in China. Among these modes, the main research content for secondary voltage control is on dividing the control area. It is found that in both theoretical analysis and practical operation, due to the serious loss of reactive power when transmitting over a long distance, the local control of the layered partition is conducive to the near balance of the reactive power and accurate control of the node voltage. The research idea of reactive power partitioning is to adopt the corresponding optimization algorithm based on the electrical distance between the system nodes and the partitioning index. Partitioning algorithms are mainly divided into expert algorithms [2], modern heuristic algorithms [3], clustering algorithms [4], [5], complex network theory algorithms [6] and hybrid algorithms [7].

The clustering method is widely used in reactive voltage control partitioning, which is a very classic partitioning method. The idea is to first obtain the electrical distance

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between the nodes in the power grid and to then classify the nodes with a close electrical distance into a class through the corresponding clustering algorithm. The clustering method has been widely used in the fields of pattern recognition and data mining. Data are usually clustered according to the principle of minimum coupling in the same region and maximum coupling between regions. The clustering algorithm mainly includes the density-based clustering algorithm, the analytic hierarchy process, the division method, the graph theory method, the K-means method, the fuzzy C-mean method and the complex network-based method. The advantage of the hierarchical clustering algorithm is that as long as the electrical distance between each node in the system is defined in advance and defined according to the distance similarity, the hierarchical relationship between each node can be found without specifying the number of clusters in advance, which can be used for clustering multiple local areas. The existing reactive power partition method has a favorable effect on the traditional power grid partition and can obtain the static partition result according to the electrical distance between nodes, which is beneficial to reactive power optimization in the power grid region, improves the online computing speed and reduces the consumption of memory.

With wind power as a typical representative of renewable energy with large-scale access to the grid, the reactive power partition method must address the challenges brought by new conditions. First, wind power output has a strong volatility, causing the power flow state of the system to fluctuate after wind generation is connected to the power grid and making it difficult to realize the zoning algorithm based on the stable power flow section in traditional two-stage voltage control. In addition, the effect of voltage control is difficult to guarantee. Second, the uncertainty in wind power's active power prediction also leads to uncertainty in the electric distance matrix based on the reactive power-voltage sensitivity between nodes, thus making it impossible to obtain accurate and reliable reactive power partition results, which increases the difficulty of day-ahead dispatching of the power system.

To address the contradiction between the fluctuation in the fan output and the requirement that the partition results be as stable as possible, PV nodes and PQ nodes in the system were separated in ref. [8], and the expected electric distance matrix between nodes in the system was taken as the partition basis. Affine propagation (AP) clustering was adopted to partition the grid nodes. In addition, the evaluation indexes of the partition quality were defined to evaluate the partition quality from the aspects of coupling, interval decoupling and zonal voltage control sensitivity. In ref. [9], the wind power output probability distribution was discretized into multiple scenarios; a full-dimensional voltage/reactive power sensitivity matrix corresponding to the scenario was obtained based on the idea of a reactive power source control space, and partitioning was carried out by using a fuzzy clustering method based on transitive closure. In ref. [10], the expected scenario of multiple wind power discrete scenarios was obtained, and an immune-centerpoint clustering algorithm was applied to classify each node and transform the problem into a mathematical spatial clustering problem. In ref. [11], a method of voltage control region division that included a wind power grid and considered the randomness in the wind speed was proposed, which was based on the sum of the submatrices of partial derivatives of the active and reactive power with respect to the voltage amplitude in the Jacobian matrix.

In summary, after wind power and other new energy sources are connected to the power grid, the current research plan is mainly to replace the electric distance matrix under a single power flow section by equating the volatility of active wind power in the electric distance expectation matrix through a probabilistic method to reduce the influence of wind power fluctuations on the partition stability to a certain extent. However, this approach is based mainly on the probabilistic statistics of the historical output data of wind farms, so accurate real-time partition results cannot be obtained. In addition, the current in the power grid control widely undergoes active scheduling based on wind power prediction to reduce the influence of wind power uncertainty and volatility, but for reactive partitions that rely only on real measured data, the accuracy and effectiveness are poor, which can cause a change in the partition that is larger when the wind is more volatile. In addition, the boundary nodes change frequently, affecting the area of the reactive power optimization control effect.

To make full use of wind power prediction results and reduce the influence of wind power grid access on reactive power partitioning, this paper proposes a reactive voltage partitioning method for power grids that takes the wind power volatility and uncertainty into consideration. The uncertainty is represented by the prediction error interval of the wind power, and the resulting node change scale of the power grid partition under the wind power connection at different times is characterized by the volatility. Based on the discretization of the probability distribution of the active power output at a certain time in wind power prediction, a calculation interval of the downwind power output of a single section is formed. By constructing the optimal partition model of the reactive voltage under a long time scale with the minimum comprehensive stability of the partition serving as the objective function, the variation in the partition results is reduced, and the stability of the reactive power partition is improved. Further, the accuracy of power grid dispatching is effectively improved.

## II. REACTIVE POWER PARTITIONING METHOD BASED ON AGGLOMERATIVE HIERARCHICAL CLUSTERING

### A. THE ESTABLISHMENT OF AN ALL-DIMENSIONAL ELECTRICAL DISTANCE MATRIX OF THE SYSTEM

The power flow calculation in the power grid satisfies the following equation:

$$\begin{bmatrix} \Delta \boldsymbol{P} \\ \Delta \boldsymbol{Q} \end{bmatrix} = - \begin{bmatrix} \boldsymbol{J}_{\mathrm{P}\theta} & \boldsymbol{J}_{\mathrm{PV}} \\ \boldsymbol{J}_{\mathrm{Q}\theta} & \boldsymbol{J}_{\mathrm{QV}} \end{bmatrix} \cdot \begin{bmatrix} \Delta \boldsymbol{\theta} \\ \Delta \boldsymbol{V} \end{bmatrix} \tag{1}$$

In (1), $\Delta\theta$ and $\Delta V$ are the phase angle and amplitude changes of the node voltage, respectively; $\Delta P$ and $\Delta Q$

represent the amount of change in the active and reactive power injected into a node, respectively; and $J_{P\theta}$, $J_{PV}$, $J_{Q\theta}$ and $J_{QV}$ are four submatrices of the Jacobian matrix.

The coupling relationship between the voltage and active power needs to be considered in the case of a heavy system load. To accurately account for the effect of the active power on the voltage, the complete decoupling of PQ here is not considered. Letting $\Delta \boldsymbol{P} = 0$, we can obtain the following equation:

$$\boldsymbol{S}_{\mathrm{VQ}} = \left[\boldsymbol{J}_{\mathrm{QV}} - \boldsymbol{J}_{\mathrm{Q}\theta}\boldsymbol{J}_{\mathrm{P}\theta}^{-1}\boldsymbol{J}_{\mathrm{PV}}\right]^{-1} \tag{2}$$

In (2), $S_{VQ}$ is the sensitivity matrix of the change in the voltage amplitude of the PQ node relative to the change in the reactive power of the node in the system.

Because the sensitivity matrix in equation (2) does not include the PV node, this paper builds a voltage/reactive full-dimensional sensitivity matrix containing all nodes except the balancing node on the basis of reactive voltage sensitivity between PQ nodes.

For an n-node system, let 1-m be the PQ node, (m + 1)−(n−1) be the PV node and n be the balanced node. First assume that the m + 1th node is a PQ node, and the other power supply nodes are PV nodes. The augmented sensitivity matrix S 'is calculated as follows:

$$\boldsymbol{S}' = \begin{bmatrix} s_{11} & \cdots & s_{1m} & s_{1(m+1)} \\ \vdots & \ddots & \vdots & \vdots \\ s_{m1} & \cdots & s_{mm} & s_{m(m+1)} \\ s_{(m+1)1} & \cdots & s_{(m+1)m} & s_{(m+1)(m+1)} \end{bmatrix} \tag{3}$$

Let $\boldsymbol{S}'$ ( $s_{1(m+1)}$, $s_{2(m+1)}\cdots s_{m(m+1)}$) $= \boldsymbol{a}$, ($s_{(m+1)1}$, $s_{(m+1)2}\cdots s_{(m+1)m}$) $= \boldsymbol{b}$. The physical meaning indicates the voltage/reactive sensitivity of the other PQ nodes to the (m + 1) nodes, and the voltage/reactive sensitivity of the (m + 1) nodes to the other PQ nodes, respectively. $s_{(m+1)(m+1)}$ is the voltage/reactive sensitivity of the (m + 1) node to itself, and the rest are the elements of the voltage/reactive sensitivity of the PQ node. By analogy, each power supply node is successively and recursively listed as this type of node, and the corresponding a and b vectors are obtained to form the $\boldsymbol{A}_{m\times(n-m-1)}$ and $\boldsymbol{B}_{(n-m-1)\times m}$ matrices, respectively. The diagonal matrix $\boldsymbol{C}_{(n-m-1)\times(n-m-1)}$ composed of a corresponds with each power supply to $s_{(m+1)(m+1)}$. The m-th order matrix in the upper left corner of $\boldsymbol{S}'$ is defined as $S$VQ. Formation, combine the above matrices into a full-dimensional augmented sensitivity matrix $\boldsymbol{S}$:

$$\boldsymbol{S} = \begin{bmatrix} \boldsymbol{S}_{\mathrm{VQ}} & \boldsymbol{A}_{m\times(n-m-1)} \\ \boldsymbol{B}_{(n-m-1)\times m} & \boldsymbol{C}_{(n-m-1)\times(n-m-1)} \end{bmatrix} \tag{4}$$

Based on the obtained full-dimensional sensitivity matrix, the voltage sensitivity $\alpha_{ij}$ *between* nodes $i$ and $j$ is obtained:

$$\alpha_{ij} = \frac{\partial U_i}{\partial U_j} = \frac{\partial U_i / \partial Q_j}{\partial U_j / \partial Q_j} \tag{5}$$

In (5), $\partial U_i/\partial Q_j$ and $\partial U_j/\partial Q_j$ are the voltage-reactive power sensitivity of node $i$ to node $j$ and that of node $j$ to itself, respectively.

To reflect the interactions among all nodes in the system, we map each node of the system to a multidimensional space to establish a full-dimensional electrical distance matrix. The European distance is used to express the electrical distance between nodes $i$ and $j$:

$$d_{ij} = \sqrt{\sum_{k=1}^{n-1} (\alpha_{ik} - \alpha_{jk})^2} \tag{6}$$

The $(n-1) \times (n-1)$-dimensional $D$ matrix is composed of $d_{ij}$, which is the full-dimensional electrical distance matrix of the system.

### *B. THE AGGLOMERATIVE HIERARCHICAL CLUSTERING METHOD*

#### 1) HIERARCHICAL CLUSTERING ALGORITHM

The hierarchical clustering method [13] is a commonly used clustering algorithm that divides the electrical distance matrix between nodes in the system at different levels, divides the power grid into several subregions according to certain rules, and forms a tree-like cluster structure. According to the different directions of hierarchical decomposition, the prospective approach can be divided into bottom-up aggregation methods and top-down splitting methods. Because there is no need to specify the number of clusters in advance, this technique is simple and widely used.

This paper uses a bottom-up agglomeration algorithm. Each node in the system is considered as a different cluster, and the two clusters with the closest mutual distance are merged until all nodes belong to a cluster. Commonly used intercluster distances are the single linkage, complete linkage, average linkage and ward linkage. When a ward linkage is used, the relative distance of each merge is smaller than the distance between the other clusters, and the accuracy is the highest of all the linkages. Therefore, this paper uses the ward link algorithm for cluster analysis.

If there is a particular node in the clustering process, when using the clustering method to form an area separately, such as for some large power plants far from the load center, expert partitioning results should be adjusted appropriately.

#### 2) EVALUATION INDEX OF CLUSTERING ALGORITHM

Given that the reactive power zoning of wind power not only needs to meet the traditional zoning requirements, such as regional connectivity and coupling, but also considers whether the distribution of reactive power in each area after the zoning is reasonable. For this reason, the intraregion coupling degree and interregion coupling were used. The three indicators of the degree and the degree of regional reactive power balance are used to quantify and evaluate the quality of the partition.

Among them, the strong coupling degree in the area is defined as:

$$A = \sum_{l=1}^{N} A_l = \sum_{l=1}^{N} \frac{2\sum_{j=1}^{M_l}\sum_{i=j+1}^{M_l} D_{ij}}{M_l(M_l-1)} \tag{7}$$

The weak coupling between regions is defined as:

$$B = \sum_{l=1}^{N} B_l = \sum_{l=1}^{N} \frac{1}{M} \sum_{K=1}^{M} \frac{\sum_{j=1}^{L_j} \sum_{i=1}^{L_i} D_{ij}^K}{L_i \cdot L_j} \tag{8}$$

In the formula, $A_l$ represents the strong coupling index in the area $l$, the physical meaning is the average value of the electrical distance between the nodes in zone $l$; the smaller the value, the stronger the coupling between the nodes in the area. $N$ is the number of system partitions, $M_l$ is the number of nodes in the area $l$, $D_{ij}$ is the electrical distance between the nodes in the area, $B_l$ represents the strong gold index between the areas, the physical meaning is that the area $l$ and the adjacent area are connected to the connected node pair area, which is the average electrical distance of all nodes in the zone. The larger the value, the weaker the coupling between regions. $L_i$ indicates the number of nodes in zone $K$ adjacent to zone $l$. $L_j$ represents the number of nodes in zone $l$ directly connected to neighboring zone $K$. $M$ is the number of areas directly connected to area $l$.

According to the reactive power partition balance principle, in actual operation, each area needs at least enough reactive power reserve to ensure not only the voltage stability of each area but also that the reactive power distribution is balanced in each area to avoid unreasonable reactive power distribution. Economical reduction. The regional reactive power balance index is defined as:

$$\tau_l = \frac{Q_{Gl} - Q_{Ll}}{Q_{Gl}} \times 100\% \tag{9}$$

$$\eta = \sqrt{\frac{1}{N} \sum_{l}^{N} |\tau_l - \bar{\tau}|^2} \tag{10}$$

In the formula, $Q_{Gl}$ is the sum of the maximum reactive power output of each reactive power source in area $l$, $Q_{Ll}$ is the sum of the reactive power load in area $l$, $\tau_l$ is the reactive power reserve of area $l$ and $\eta$ is the regional reactive power imbalance. The physical meaning is the degree of balance of the system's reactive power sources in each area after the detection of the partition. The smaller the value, the more reasonable the distribution of reactive power sources and the higher the degree of resource utilization.

## III. A POWER GRID PARTITION MODEL THAT COMPREHENSIVELY considerS THE FLUCTUATION AND UNCERTAINTY OF WIND POWER

### A. DETERMINATION OF THE WIND POWER PREDICTION ERROR DISTRIBUTION

Wind power prediction information is widely used in day-ahead scheduling models, and the prediction information is usually of two types: deterministic information and uncertain information. Point value prediction is associated with deterministic information and is easy to obtain and apply, but the single numerical prediction result contains limited information [14]. The uncertainty and fluctuation in the wind power can be fully considered by using the uncertainty prediction information, which is the mainstream research direction of wind power active output prediction, including interval prediction and probability prediction.

The probability interval prediction of wind power usually requires prior assumptions, and the prediction errors of the general active power output of wind power follow a normal distribution, beta distribution, Cauchy distribution or piecewise exponential distribution. The probability density function of the normal distribution is:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{11}$$

When taking the predicted and actual wind power values of EirGrid from February to November 2010 as an example, the normal distribution can be used to fit the predicted relative error sequence, and the obtained probability density function is shown in Figure 1. Therefore, the normal distribution can represent the trend of the wind power prediction error distribution as a whole [15]. Furthermore, the normal distribution is also applicable to the prediction error distribution of large-scale wind farms, and the prediction time is 12-24 h, so the wind power prediction error distribution in this paper is based on this framework.

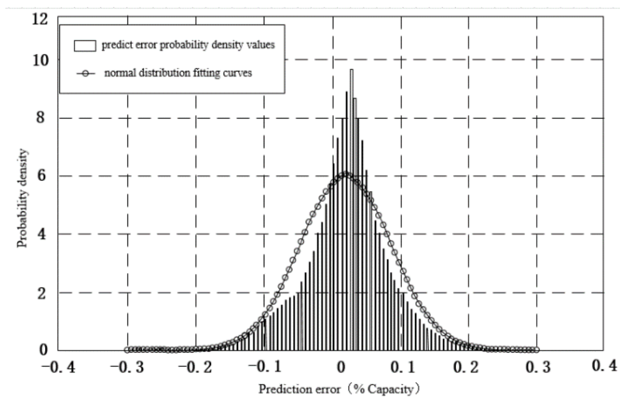



**FIGURE 1. Schematic diagram of the fitting power prediction error distribution using a normal distribution curve.**

### B. ESTABLISHMENT OF A REACTIVE POWER PARTITION MODEL OF THE POWER GRID

When the forecast error of wind power adopts a normal distribution, the active output range of wind power can be simulated according to Figure 2, and the error distribution shown in Figure 2 adopts the normal distribution heat map. Among them, the abscissa indicates the time axis, and the ordinate indicates the active output corresponding to the wind power output. The model is used as an input to connect to the grid to be partitioned.

As seen from the figure, the partition result corresponding to the times from $t_1$ to $t_2$ and according to the partition situation of the probability distribution represents the uncertainty in the partition result, and the result with the highest probability represents the partition situation that is most likely to

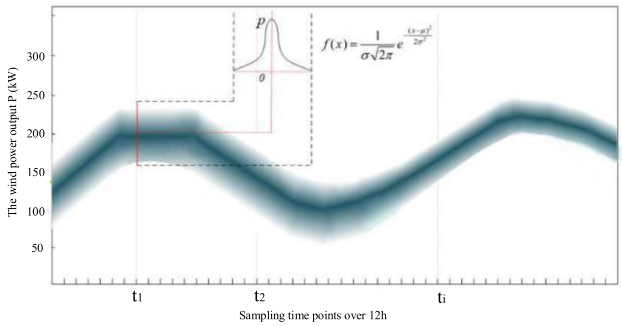



**FIGURE 2.** Wind power active prediction interval.

occur in this period. The partition distributed according to the changing nodes of the partition represents the fluctuation in the partition result, and the result with the least node change represents the most stable partition in this period. However, the result with the highest possibility is not necessarily the most stable, so the result with the highest possibility and the most stability needs to be considered comprehensively. This paper proposes a grid partition method that takes the wind power fluctuation and uncertainty into account as follows:

(1) In a single time period, the purpose is to propose a zonal representation model that comprehensively represents the fluctuation and uncertainty in the wind power in a single time period. The normal distribution represents the probability density function of the wind power error, so the probability of the active power interval at time $t$ is:

$$p(x) = \frac{1}{\sigma\sqrt{2\pi}}\int_{P_1}^{P_2} e^{-\frac{x^2}{2\sigma^2}}dx \tag{12}$$

In (12), let $4\sigma = \frac{\Delta P}{2}$; then $\sigma = \frac{\Delta P}{8}$. Assuming that the probability density functions at times $t_1$ and $t_2$ both meet the normal distribution, then the probability of the active power output interval of the wind power at both moments can be expressed by equation (12), and the number of nodes changing the result of the reactive power partition at time $t_1$ to $t_2$ is $\Delta n_{12}$. Then, the comprehensive stability degree of the partition result change in a single time period is defined as

$$\min f(\Delta t_{12}) = \min\frac{\Delta n_{12}}{p_{12}} = \min\frac{\Delta n_{12}}{p_{t1}\cdot p_{t2}} \tag{13}$$

The physical meaning expressed by equation (13) is that when the partition result node changes at the last two moments of the current time are the least and the probability of occurrence is the greatest, the partition result changes are the most stable of all the changes.

(2) Long time scale:

Because the wind power fluctuation range is large over a long time scale and the optimal partition result of each time period is also the initial partition result of the next time period, it is necessary to comprehensively consider the optimal partition result of multiple time periods, which is expressed by the following equation:

$$\min\int_{t_1}^{t_n} f(\Delta t)dt \tag{14}$$

In (14), $f(\Delta t)$ represents the change degree of nodes within a unit time period; and $t_1$ and $t_n$ represent the start and end time nodes of the long time scale, respectively. This equation and the minimum value are the comprehensive optimization results under a long time scale. Considering the single period of the uncertainty in the probability density function of the characterized wind power, the number of nodes in the changing representation of the partition results at the different times is the wind volatility, so the partition results considering the two kinds of wind characteristics can effectively increase the access under the background of the wind power grid reactive voltage accuracy and stability of the partition.

## IV. THE SOLUTION OF THE POWER GRID PARTITION MODEL WHEN COMPREHENSIVELY CONSIDERING THE WIND POWER FLUCTUATION AND UNCERTAINTY

### A. DISCRETIZATION OF THE ACTIVE POWER OUTPUT INTERVAL OF THE WIND POWER

To quantitatively describe the effect of wind power on the reactive power partition of the power grid, the active power output of the wind power at a single time point is sampled to obtain $N$ smaller prediction intervals of the active wind power. $P_{ti1}$ and $P_{ti2}\cdot$ $P_{tiN}$ are used as the median values of the wind power bands of different probabilities at time $t_i$ and represent the output levels of each wind power probability interval. Table 1 shows the median value of the wind power active power prediction output interval and the probability of the wind power active power output interval corresponding to different moments.

**TABLE 1.** Median and output interval probabilities of active wind power predictions corresponding to different moments.

| Moment | Median | Output interval probability |
|---|---|---|
| | $P_{t11}$ | $k_{t11}$ |
| $t_1$ | $\vdots$ | $\vdots$ |
| | $P_{t1N}$ | $k_{t1N}$ |
| | $P_{t21}$ | $k_{t21}$ |
| $t_2$ | $\vdots$ | $\vdots$ |
| | $P_{t2N}$ | $k_{t2N}$ |
| $\vdots$ | $\vdots$ | $\vdots$ |
| | $P_{ti1}$ | $k_{ti1}$ |
| $t_i$ | $\vdots$ | $\vdots$ |
| | $P_{tiN}$ | $k_{tiN}$ |

In the table, from the perspective of the active power output interval of each wind power at times $t_1$ to $t_2$, there are $N^2$ kinds of changes in the mean value of the active power output interval, and there are also $N^2$ kinds of corresponding probabilities of occurrence. Then, the mean value of the $N^2$ kinds of active power output of the wind power at times $t_1$ to $t_2$ corresponds to the variation in the $N^2$ kinds of partitions and the number of node changes before and after partitioning. Similarly, the variation in the partition results at times $t_i$ to $t_{(i+1)}$ is constant.

As shown in Figure 3, for long-timescale power grid reactive power optimization, partitioning applies at every moment due to the $N$ partition results under different probabilities, so there are a total of $N^n$ kinds of optimal portfolio models. There are a variety of models, and the only model that applies in the $t_1 \sim t_n$ period is the one with the highest probability of the minimal partition result ranges at the same time, which can effectively solve the wind power active power caused by unstable partitioning and the problem of inaccuracy. Therefore, the mathematical model of reactive power partitioning considering the uncertainty and fluctuation in the wind power can be expressed as follows:

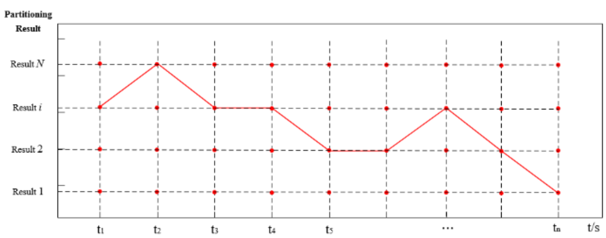



**FIGURE 3. Optimal graph of the results of reactive power partitioning over a long time scale.**

#### 1) OBJECTIVE FUNCTION

When the probability of the reactive power partitioning result is maximized and the fluctuation is minimized over a long period of time, the comprehensive stability is minimized, as shown in equation (15):

$$\min \sum_{i=1}^{n} \frac{\Delta n_{\Delta t_i}}{p_{\Delta t_i}} \tag{15}$$

#### 2) CONSTRAINT CONDITION

a. The active and reactive power of each node in the grid is subject to the following conditions:

$$\begin{cases} Q_{ti.\min} \leq Q_{ti} \leq Q_{ti.\max} \\ P_{ti.\min} \leq P_{ti} \leq P_{ti.\max} \end{cases} \tag{16}$$

In (16),.. $P_{ti.\max}$, $P_{ti.\min}$ are the upper and lower limits of the active power output of each node of the system, respectively; and $Q_{ti.\max}$, $Q_{ti.\min}$ are the upper and lower limits of the reactive power output of each node of the system, respectively.

b. The active power output of the wind farm is subject to the following condition:

$$P_{\mathrm{W}ti.\min} \leq P_{\mathrm{W}ti} \leq P_{\mathrm{W}ti.\max} \tag{17}$$

In (17), $P_{\mathrm{W}ti.\max}$, $P_{\mathrm{W}ti.\min}$ are the upper and lower limits of the active power output range of the wind farm, respectively.

c. Operational safety constraint:

$$V_{i.\min} \leq V_i \leq V_{i.\max} \tag{18}$$

In (18), $V_{imax}$ and $V_{imin}$. represent the allowable upper and lower limits of the node-I voltage, respectively.

d. The N smaller wind power active power prediction interval obtained by sampling is subject to the following condition:

$$1 \leq N \leq N_{\max} \tag{19}$$

In (19), $N_{\max}$ represents the maximum value of the number of smaller intervals obtained by sampling the active power output interval of the wind power, which can be calculated according to the minimum active power output interval $\Delta P_{\min}$, where the result of the rigid reactive power partition changes; i.e., $N_{\max} = \frac{\Delta P}{\Delta P_{\min}}$.

e. The change amount $\Delta n_{\Delta t_i}$ of the result node of the partition at the adjacent time is subject to the following condition:

$$0 \leq \Delta n_{\Delta t_i} \leq \Delta n_{\Delta t_i.\max} \tag{20}$$

In (20), $\Delta n_{\Delta t_i}$. max represents the maximum value of the change amount of the result node of the partition at the adjacent time, that is, the number of nodes of the power system.

f. The optimal partition result of each time period is also the initial partition result of the next time period; that is, the output curve in the active power output error distribution interval of wind power has cohesion as follows:

$$\Delta W_{ij}^{(k)} = W_{ki} - W_{(k+1)j} \tag{21}$$

$$\Delta W_{jh}^{(k+1)} = W_{(k+1)j} - W_{(k+2)h} \tag{22}$$

In (21) and (22), $k \in [1, n]$, and $i, j, h \in [1, N]$; $W_{ki}$, $W_{(k+1)j}$, and $W_{(k+1)h}$ represent the partition results at times $k$, $(k+1)$, and $(k+2)$, respectively. $\Delta W_{ij}^{(k)}$ represents the change in the partition result node from time k to time $(k+1)$; and $\Delta W_{jh}^{(k+1)}$ represents the change in the partition result node from time $(k+1)$ to time $(k+2)$.

### *B. SOLUTION STEPS OF THE POWER GRID PARTITION MODEL WITH COMPREHENSIVE CONSIDERATION OF THE WIND POWER FLUCTUATION AND UNCERTAINTY*

The steps of the power grid partition model with comprehensive consideration of the wind power fluctuation and uncertainty is shown as Figures 4.

## V. ANALYSIS OF EXAMPLES

### *A. EXAMPLE SETTING*

#### 1) EXAMPLE MODEL

To confirm that the proposed wind power grid partition method considering uncertainty and fluctuation is feasible, in this paper, the IEEE 39 system is improved using the simulation analysis with wind farm access 37 as the PQ node, the reactive load and circuit topology are evaluated in accordance with the standard IEEE 39 node set, and a MATLAB R2014a partition model is established for solution.

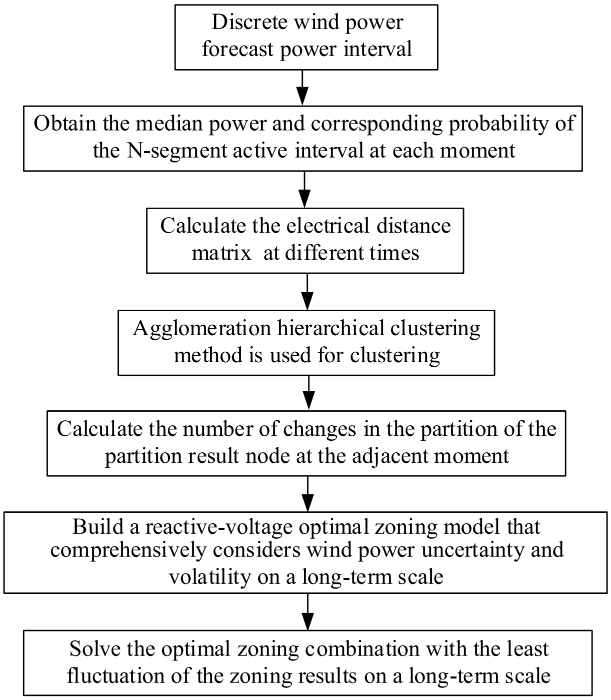



**FIGURE 4. Solution steps of the power grid partition model.**

#### 2) DETERMINATION OF THE SAMPLING PERIOD AND DISCRETE QUANTITY OF THE WIND POWER OUTPUT INTERVAL

The determination of the reactive power division cycle needs to refer to the AVC calculation cycle; there are two main cases for the AVC startup method in China's actual power grid. 1) One case is the regular timing startup. This startup method needs to calculate the power flow every 15 min, for a total of 96 calculations in 24 h. 2) The other case is the emergency start method. When the power flow state of the power grid changes greatly in a short time, to quickly restore the power grid to a stable state, AVC can manually start the partition calculation according to the specific situation. This is a special case. The partition method proposed in this paper can adopt the calculation method with a smaller period; the smaller the period, the denser the calculation points, and the more accurate the calculated partition scheme. However, through communication and discussion with the power grid dispatcher and considering the zoning situation of the large power grid, the regulation and management scope changes too frequently to avoid too many changes in the boundary node, and the active power output of the wind power does not change significantly within 30 min. Therefore, the partition period is set to be calculated every 30 min, for a total of 48 times in 24 h.

Because the wind power error prediction interval is in accordance with the normal distribution, it is analyzed by simulation in the IEEE 39 system. When the active power fluctuation range of the wind farm connected to the system is less than 40 MW, it will not cause changes in the zoning results. There are few climbing events with a 50% power change, and the method in this paper can be divided into more intervals in the application. This scenario is only used to show the effect of the calculation example. Therefore, the prediction interval of wind power output at a single moment can be discretized into the three cells. The median value of the active power between the three cells is taken as the active power input between each cell, that is, $N = 3$.

### B. ANALYSIS OF THE RESULTS

#### 1) REACTIVE POWER PARTITION EFFECT VALIDATION

Within the value range of the wind power output interval number, a higher interval number corresponds to more accurate results. Therefore, $N = 3$ can be set. At this point, the mean value and probability of the output interval of the wind power active power prediction at each time are calculated every 15 min within 12 h, and the electric distance matrix of the power flow section of the grid connected to the median value of the active power of each wind power interval at different times is calculated.

After clustering, the partition results under different probability intervals at each moment are obtained, as shown in Table 2, where $W_{tij}$ represents the partition results corresponding to the access of the JTH interval of wind power to the grid at time $t_i$. The power grid at the initial time of wind power connection is partitioned by means of condensed hierarchical clustering, and the partitioning results are shown in Table 3.

**TABLE 2. Median and output interval probability of active wind power prediction corresponding to different moments.**

| Moment | Median (kW) | Output interval probability | Results of zoning |
|---|---|---|---|
| | 92 | 0.16 | $W_{t11}$ |
| t1 | 128 | 0.68 | $W_{t12}$ |
| | 162 | 0.16 | $W_{t13}$ |
| | 101 | 0.16 | $W_{t21}$ |
| t2 | 138 | 0.68 | $W_{t22}$ |
| | 180 | 0.16 | $W_{t23}$ |
| ⋮ | ⋮ | ⋮ | ⋮ |
| | 110 | 0.16 | $W_{t31}$ |
| t48 | 146 | 0.68 | $W_{t32}$ |
| | 192 | 0.16 | $W_{t33}$ |

Using the condensed hierarchical clustering method to partition the grid at the initial moment of wind power access, the partition results are shown in Table 3, and Table 4 is the partition quality evaluation index of the initial partition results. The result of reactive power partitioning by this kind of algorithm can meet the requirements of the partitioning principle. By calculating the number of change nodes in the partition result of each adjacent time period, an optimal partition model that takes into account the wind power uncertainty and fluctuation over a long time scale is constructed, and the

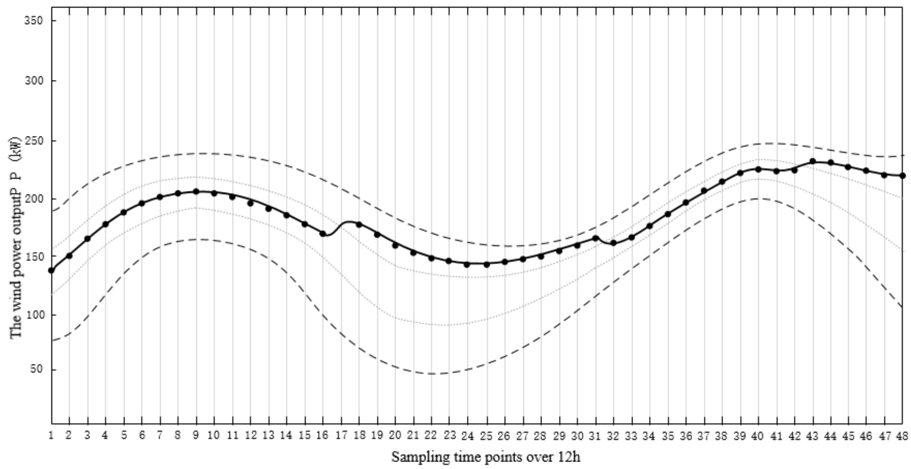



**FIGURE 5.** Wind power output curve when the zone is most stable over long time scales.

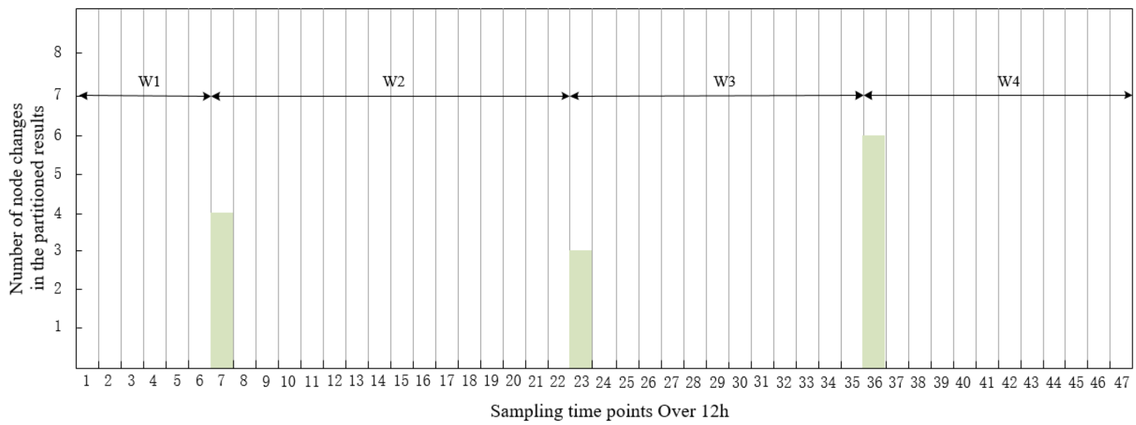



**FIGURE 6.** Number of node changes in the reactive partition results over long time scales.

**TABLE 3.** Results of reactive power zoning at the initial moment when wind power is connected to the grid.

| Zone index | Node index within zones |
|---|---|
| 1 | 2, 3, 17, 18, 25-27, 30, 37 |
| 2 | 1, 9, 39 |
| 3 | 4-8, 10-14, 31, 32 |
| 4 | 28, 29, 38 |
| 5 | 15, 16, 21-24, 35, 36 |
| 6 | 19, 20, 33, 34 |

**TABLE 4.** Evaluation index of partition quality of initial partition.

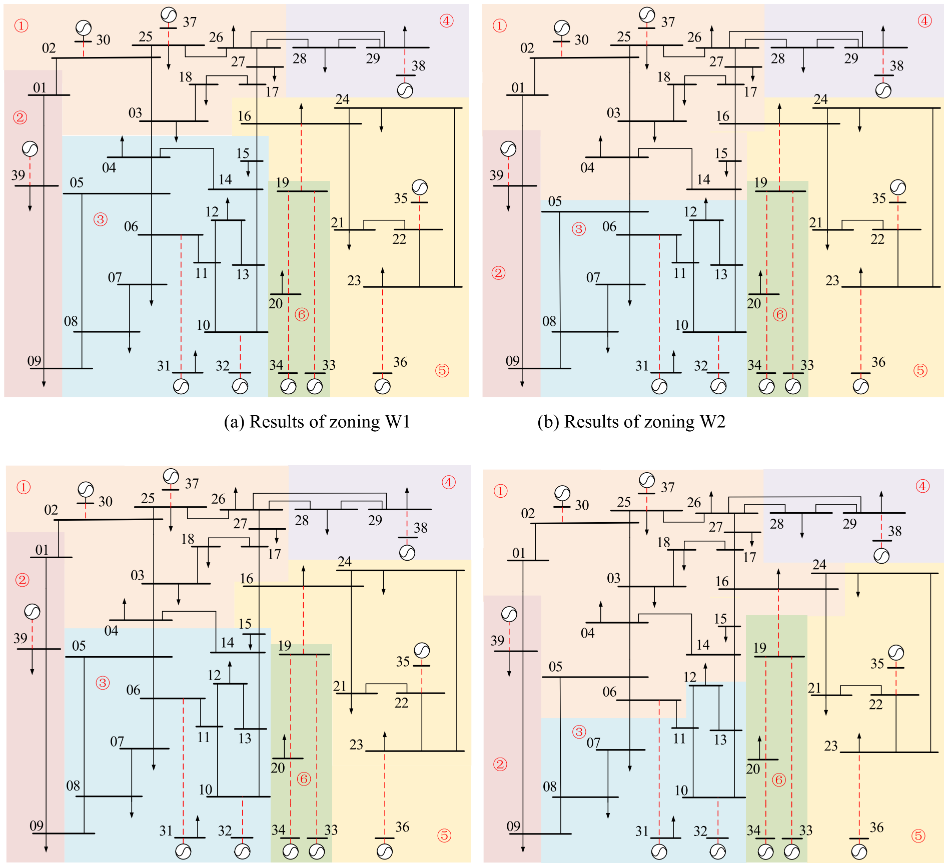
| Partition | $A_l$ | $B_l$ | $\tau_l$ |
|---|---|---|---|
| 1 | 2.04 | 2.88 | 0.65 |
| 2 | 2.25 | 2.74 | 0.77 |
| 3 | 2.16 | 2.98 | 0.44 |
| 4 | 1.55 | 3.05 | 0.79 |
| 5 | 1.91 | 3.12 | 0.58 |
| 6 | 1.49 | 2.69 | 0.84 |
| The whole system | 1.90 | 2.91 | 0.1382 |

minimum result is 91.67. The corresponding optimal partition scheme is shown in Figures 5, 6, and 7.

Figure 5 shows the active power output curve of wind power that is the most stable within 12 h when the uncertainty and fluctuation are taken into account. To ensure the stability of the partition results, the wind power output curve deviates from the curve of the wind power output probability maximization at moments 16 and 42, which can consider the stability and uncertainty in the partition results. Figures 6 and 7 show the four partition results planned within 12 h; the node changes when the partition changes. The four partition results are W1, W2, W3, and W4, and each partition result conforms to the principle of reactive power partitioning.

### 2) EFFECT ANALYSIS OF THE PARTITION METHOD

To verify the effectiveness and advancement of the method proposed in this paper, the wind power uncertainty and fluctuating power grid are taken into account.



(a) Results of zoning W1 (b) Results of zoning W2

(c) Results of zoning W3 (d) Results of zoning W4

**FIGURE 7. Variation chart of the results of reactive power partitioning over a long time scale.**

The results are compared with the output of the wind power probability maximization of the wind power output curve and the wind power output curve with the minimum variation in the partition result when wind generation is connected to the power grid. Among the results, the curve with the maximum probability of wind power output is the output curve that connects the median of the active power output corresponding to the distribution interval of the wind power prediction error at each moment, and the curve with the minimum change in the partition results is the wind power output curve that exhibits the minimum change in the partition results within 12 h.

Figure 8 shows the wind power output curves corresponding to three different zoning results. Among them, the blue wind power output curve is solved according to the objective function proposed in this paper, which can comprehensively consider the uncertainty and volatility of wind power on the zoning results. The red wind power output curve only considers the influence of wind power fluctuations on the stability of the zoning results. The objective function of the zoning model is set to minimize the change of the final zoning results. The probability of occurrence is very small. The green wind power output curve represents the maximum wind power output probability and only considers the impact of wind power uncertainty on the zoning results; it does not consider the impact of wind power volatility on the zoning in the long-term scale.

The three zoning result indicators in Table 5 correspond to the three wind power output curves in Figure 8. The wind power probability maximization output method only considers the factors of wind power uncertainty, and the corresponding zoning result is the situation with the highest probability of occurrence, but it does not consider the volatility of wind power. As seen from Table 5, there are six kinds of zoning results. Six times is too frequent to lead to continuous adjustment of the zoning-based reactive power optimization model,

**TABLE 5. Comparison of zoning results of three wind power output methods over a long time scale.**

| Index | Comprehensive stability | Numbers of zones |
|---|---|---|
| The wind power output method obtained in this paper | 91.67 | 4 |
| Wind power probability maximization method of wind power output | 126.45 | 6 |
| Wind power output method with the minimum variation in the partition results | 115.3 | 3 |

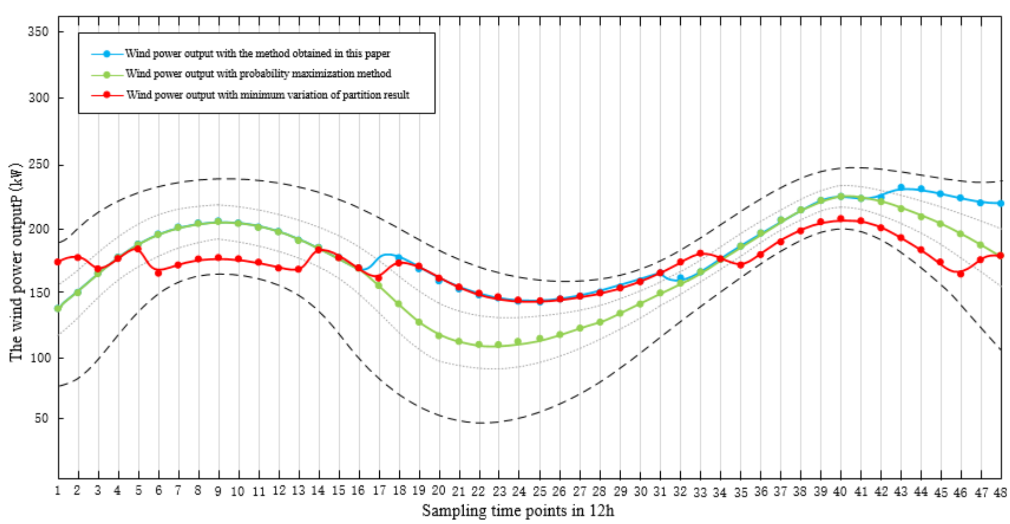



**FIGURE 8.** Wind power output curves corresponding to three different zoning methods over a long time scale.

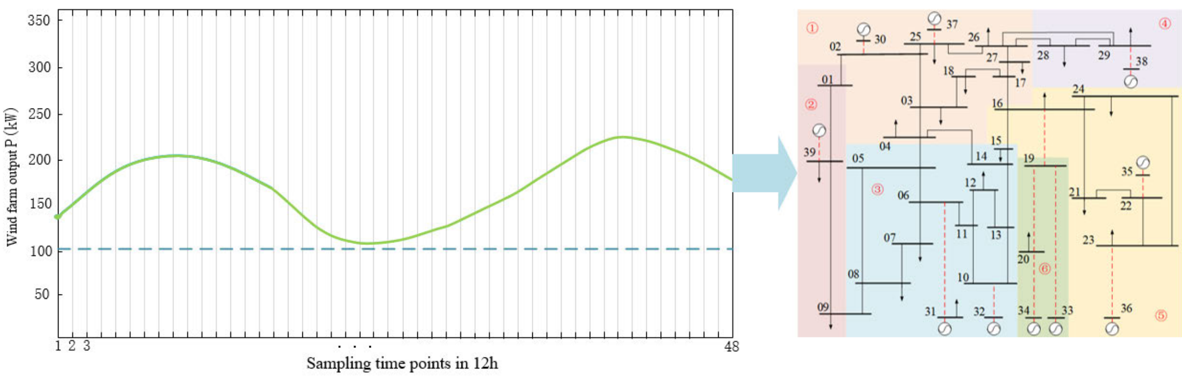



**FIGURE 9.** Schematic diagram of the partition method only considering wind fluctuations.

thereby reducing the economics of grid dispatching. The zoning method with the smallest change in the zoning results corresponds to the red wind power output curve in Figure 8. It mainly considers the impact of wind power volatility on the zoning of the power grid. Although the zoning results will be very stable, there are only three results, but because of the uncertainty in the wind power in this case, the wind power output curve is mainly distributed in the interval with a small probability, so the comprehensive stability will be low. The zoning results obtained by the zoning model proposed in this paper comprehensively consider the volatility and uncertainty of wind power. Therefore, its comprehensive stability is the lowest, and the partition effect is the best within 12 h.

(iii) Contrast analysis with classical zoning method that only considers wind power fluctuations

To reflect the effectiveness of the partition method proposed in this paper, we now compare it with a method that only considers wind power volatility. Reference [8] uses a probabilistic method to equate the wind power active volatility in an electrical distance expectation matrix to replace a single power flow profile. To reduce the impact of wind power fluctuations on the stability of the partition, this method is a typical method for the problem of connecting wind power to the power grid at this stage. Therefore, this paper compares the results with those from reference [8] for the treatment of wind power.

As shown in Figure 9, the wind power output curve of the partition method only considers the wind power fluctuation and does not consider the error distribution of the active output. According to the treatment of the wind power curve in [8], the wind power active probability is now reduced to five scenarios to find the occurrence probability of each scene. The results are shown in Table 5.

To compare the output methods for wind power in [8], the electrical distance between the PQ nodes in each scenario is calculated, the expected matrix of the electrical distance between the PQ nodes in the entire network is calculated according to the probability, and the agglomerative hierarchical clustering algorithm is used for clustering to obtain the result of reactive power zoning under wind power access, as shown in Table 6.

According to Table 6 and Figure 7, comparing the two zoning methods to consider the results of the zoning of wind power access within 12 h, it can be seen that reference [8]

**TABLE 6. Partitioning result for ieee 39 bus system.**

| Partition number | Node number within the zone |
|---|---|
| 1 | 2-4，17，18，25-27，30，37 |
| 2 | 1，9，39 |
| 3 | 5-8，10-15，31，32 |
| 4 | 28，29，38 |
| 5 | 16，21-24，35，36 |
| 6 | 19，20，33，34 |

has only one zoning result under the wind power access within 12 h, which can maintain the stability of the partition. When considering the uncertainty of wind power while considering the volatility, there are four partition results in 12 h from the partition method proposed in this paper, and reference [8] only obtains one of the partition results (W3), which can be obtained from Figure 6. The zoning results are accurate only in the 23-36 time period, inaccurate zoning results in other periods will cause two nodes with a longer electrical distance to be divided into one area, and nodes with a shorter electrical distance will be divided into different areas. This does not meet the requirements of the partitioning principle, and the resulting partitioning results are meaningless.

## VI. CONCLUSION

This paper presents a method of zoning reactive power voltages that comprehensively considers the uncertainties and fluctuations of wind power.

(1) First, the uncertainty of the wind power forecast error interval is used to characterize the uncertainty, and the variation in the node of the grid division result at different times is used to characterize the volatility to quantify the two characteristics of wind power.

(2) Then, the predicted power output of the wind power at a certain time is discretized to form a calculation area for the wind power output under a single section. The electrical distance matrix corresponding to multiple sequential power flow sections in the long-term scale is obtained, and the hierarchical clustering method is used for each section. Partitioning is performed to obtain the partitioning results corresponding to different sampling intervals at different times.

(3) Finally, based on the zoning results that correspond to different moments, a reactive power optimal zoning model that comprehensively considers wind power uncertainty and volatility at a long time scale is constructed, and an optimal zoning that can meet the stability and accuracy of the zoning is obtained.

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