frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 18 January 2024
DOI 10.3389/fenrg.2024.1355606

OPEN ACCESS

EDITED BY
Zhengmao Li,
Aalto University, Finland

REVIEWED BY
Xinyue Chang,
Taiyuan University of Technology, China
Mingfei Ban,
Northeast Forestry University, China

*CORRESPONDENCE
Rouyu Lin,
22310065@zju.edu.cn
Wei Tian,
wtian@zju.edu.cn

RECEIVED 14 December 2023
ACCEPTED 05 January 2024
PUBLISHED 18 January 2024

CITATION
Ye J, Li X, He Y, Lin R and Tian W (2024), A dynamic hierarchical partition method for optimal power balance of urban power system with high renewables.
Front. Energy Res. 12:1355606.
doi: 10.3389/fenrg.2024.1355606

A dynamic hierarchical partition method for optimal power balance of urban power system with high renewables

Jun Ye[1], Xianfeng Li[1], Yibing He[1], Rouyu Lin[2]* and Wei Tian[2]*

[1]Hangzhou Electric Power Design Institute, Hangzhou, China, [2]College of Electrical Engineering, Zhejiang University, Hangzhou, China

With the development of new urban power systems, the centralized-distributed hierarchical partition management architecture has gradually become a consensus. Existing hierarchical partition methods are mostly static. And if the partition results are determined, it will remain unchanged for a relatively long time. However, the new type power system experiences more frequent and larger fluctuations in power generation and load, requiring dynamic responses to the system's real-time operation. In this case, traditional partition methods are no longer applicable, and new hierarchical partition methods for system operation need to be adopted. Therefore, this paper proposes a power balance mechanism of urban power system based on dynamic hierarchical partition method, including dynamic hierarchical partition method and corresponding decoupling power balance models. The former can continuously change the results of hierarchical partition according to the real-time state of the power system, so as to reduce the inter-regional liaison cost and improve the economy. The latter improves the independence of the region and the security of the power system through decoupling power balance. Eventually, the proposed method is validated with an modified Hawaii 37-node system.

KEYWORDS

hierarchical partition, power balance, urban power system, high renewables, hierarchical clustering

1 Introduction

With the development of renewable energy technologies, the generation cost of wind power and photovoltaic power continues to decrease while their generation efficiency continues to improve. The cleanliness and low-cost characteristic of new energy make their installed capacity in the power system continue to rise, and promote the development of power system into a new phase. However, at the same time, the volatility and uncertainty of new energy, as well as their different operational characteristics compared with traditional power sources, have made the operating environment of urban power systems more complex and the management more challenging, which poses risks to the reliability of the power system (Li et al., 2021; Li et al., 2022; Yang et al., 2023a; Hou et al., 2023). In this situation, traditional grid morphology and management architecture can no longer meet the operational requirements of new urban power systems (Xu et al., 2019; Chen et al., 2023).

As a result, scholars at home and abroad have made many attempts and gradually reached a consensus that the urban power systems will be managed in a hierarchical and partitioned manner in the future (Lai et al., 2014; Hao et al., 2020; Adeyanju and Canha, 2021; Wang et al., 2022). The hierarchical partition management architecture which combines the advantages of centralized management and distributed management (Li et al., 2023), aligns more with the requirement of safe and reliable operation of urban power systems (Pan et al., 2023; Zhao et al., 2023; Yang Y. et al., 2023b).

As for the hierarchical partition methods for urban power systems, heuristic methods and clustering methods have been extensively studied. Heuristic methods include simulated annealing (Irving and Sterling, 1990; Gil et al., 2006), genetic algorithms (Orero and Irving, 1996; Hu et al., 2005), tabu search (Chang et al., 1999; Liu et al., 2002), evolutionary computation (Li et al., 2009), etc. In reference (Irving and Sterling, 1990), the simulated annealing algorithm was used to determine the network partition, and the cost function was set to find the global optimal. But it took a lot of time to seek out the solution. So Orero and Irving (1996) used genetic algorithms to partition the system by balancing the number of lines and nodes between partitions. Obviously, the main issues with heuristic algorithms are slow optimization and difficult selection of control parameter, which necessitates a considerable number of prior experiments for parameter selection on specific problems.

Clustering methods have been widely used in hierarchical partitioning of power systems, including k-means clustering (Biserica et al., 2013; Wang et al., 2013; Li et al., 2014), hierarchical clustering (Zhang et al., 2021; Han et al., 2023), fuzzy clustering (Yang et al., 2006; Dai et al., 2011; Mezquita et al., 2011), etc. Biserica et al. (2013) applied k-means clustering for power grid partitioning, and used the minimum sum of squared electrical distances within each cluster as the objective function, ensuring that the injection or outflow power from any node in the same partition has an approximately effect on the area. Reference (Dai et al., 2011) employed both the spectral coefficient averaging and fuzzy C-means clustering for grid partitioning, and selected a weighted objective function by node controllability and representativeness indexes to determine the dominant nodes. The aforementioned k-means clustering and fuzzy clustering methods require given and sensitive values, while the hierarchical clustering method does not require the given cluster trees (Y. Zhang, 2018). Zhao et al. (2023) performed hierarchical partitioning of the grid based on hierarchical clustering and determined the partitioning results with the objective of minimizing the average value of the net load value and geographical proximity.

Once the above hierarchical partitioning methods are determined, the partitioning results will remain unchanged for a relatively long period of time (Sánchez-García et al., 2014; Zhao et al., 2023). Therefore, most of these methods are merely applicable to power system planning in the new type power system with a large amount of wind and solar energy integration. When applied to power system operation, they may lead to a large number of problems such as wind and light abandonment, tidal overruns, etc., due to the inability to respond to system source load changes in a timely manner, and increase the liaison cost of power scheduling. However, with further advancement in renewable energy generation technologies, the future generation costs of new power systems will continue to decrease, while the proportion of system interconnection costs and accident maintenance costs in the overall operating costs of power systems will gradually increase. In this regard, the traditional static hierarchical partition methods are neither economical nor safe for the urban power system in the future.

Therefore, this paper proposes a hierarchical partitioned electric power balance mechanism for urban power systems applicable to system operation, including a dynamic hierarchical partition method and a partitioned decoupled electric power balance mechanism, which can improve the overall economy and security of future urban power system by exchanging small power generation cost for large reduction of interconnection cost. The main contributions of this paper are as follows:

1) Propose a partitioning result determination method that comprehensively considers the consumption of interconnection coordination resources and the independent operation capability within each partition, achieving dynamic hierarchical partitioning of the power grid;
2) Achieve the partitioned decoupling operation of the power balance model by decoupling the constraints;
3) Introduce a dynamic operation mechanism to ensure that the hierarchical partitioning as well as the power balance model meets the system operation requirements.

The rest of the paper is organized as follows. Section 2 describes the dynamic hierarchical partitioning method for urban power system. Section 3 presents partitioned decoupling power balance model. Power balance mechanism of urban power system based on dynamic hierarchical partition method is described in Section 4. Case study of modified Hawaiian 37-node system is presented in Section 5. Section 6 summarizes the observations through the case study and Section 7 concludes this paper.

2 A dynamic hierarchical partition method for urban power system

The hierarchical partition management architecture of future urban power system is shown in Figure 1. The centralized layer coordinates and controls the distribution layer, implementing power dispatch among different zones in the distribution layer to improve the efficiency of interconnection resource allocation and the economy of the power grid operation. The different partition in distribution layer operates independently from each other, which, on one hand, facilitates the local consumption of renewable energy and enhances the flexibility of the power grid operation, and on the other hand, assist in reducing the regional net load density to ensure that the power shortage caused by partitioned islanding is minimized in the event of an accident, thus avoiding chain reactions and reducing the cost of accidents.

2.1 Hierarchical method

The centralized layer and distribution layer are the main entities that distinguish the control authority levels in urban power systems. The centralized layer consists of network nodes in the 110 kV and above, which are connected to the transmission network and high-voltage distribution network. The distribution layer consists of

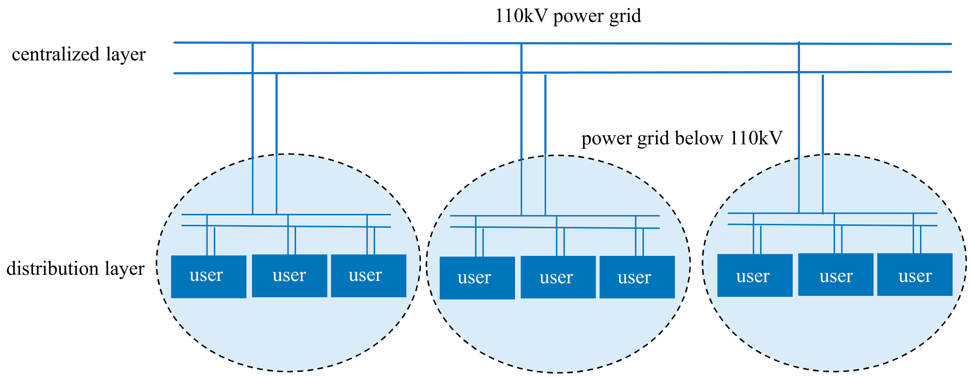

FIGURE 1
The hierarchical partitioning management architecture of future urban power system.

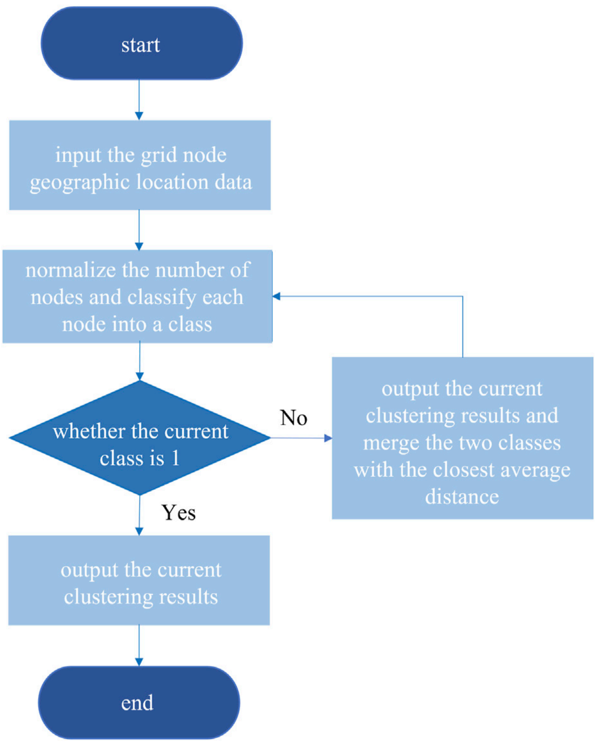

FIGURE 2
Partition cluster process diagram.

network nodes in the 110 kV and below, directly connected to the low-voltage distribution network and end-users.

2.2 Partition method

Distribution layer partitions are the fundamental units for the operation and control of urban power systems, and as shown in Figure 2, the division of partitions should be consistent with the physical reality. Therefore, based on the principle of geographic proximity, the hierarchical clustering method is used to cluster the grid nodes participating in the partition, and a clustering tree is obtained. Afterwards, the number of partitions is determined, i.e., the level of the clustering tree, and the final partition results are obtained.

The specific hierarchical clustering process is described as follows:

1) Step1: Input the two-dimensional geographical location data for each node in the power grid and normalize the data;
2) Step2: Consider each grid node as a class and then identify the two classes with the closest average distance to be merged;
3) Step3: Repeat the merging process until all grid nodes are merged into one class, and output the clustering results after each merge.

Through the aforementioned partition clustering process, the clustering tree shown in Figure 3 is obtained. The branches of the clustering tree represent the lower level, indicating that each node is a separate partition, while the trunk of the clustering tree represents the top level, indicating that all nodes are merged into one partition.

In Figure 3, the number of intersections between the dashed lines and the clustering tree represents the number of partitions, which is denoted as k, $k = 1, 2 \ldots, N-1$. N represents the total number of nodes involved in the partitioning. By determining the position of the dashed lines, which corresponds to the number of partitions, the final system partitioning results can be obtained.

The determination of the number of partitions needs to consider the following issues:

1) Having no partition (number of partition is 1) or too few partitions, which is not conducive to the flexibly local consumption of renewable energy and independent operation of partitions.
2) Having excessive number of partitions, which leads to a significant increase in the number of inter-regional liaison lines, and excessive consumption of resources.

It can be seen that too many or too few partitions are not favorable to the flexible and economical operation of the power grid. Therefore, it is necessary to find a reasonable partition scheme that takes into account the independent operational capacity within each

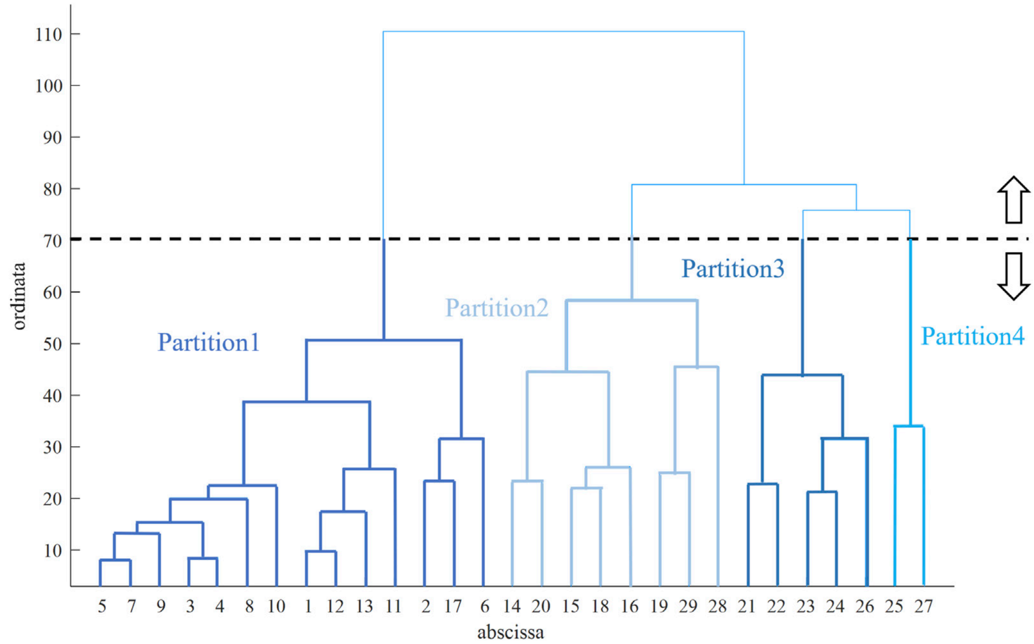

FIGURE 3
Clustering tree diagram.

partition and the consumption of interconnection resources. To this end, the following objective function is proposed to determine the number of partitions, as shown below.

$$\min f(k,t) = \lambda\left(Q^{*}_{k+1,t} - Q^{*}_{k,t}\right) + (1-\lambda)\left(C^{*}_{k+1,t} - C^{*}_{k,t}\right) \quad (1)$$

$$Q^{*}_{k,t} = \frac{Q_{k,t}}{\|Q_t\|_2} \quad (2)$$

$$Q_{k,t} = \sqrt{\sum_{a=1}^{k}\left(\sum_{j=1}^{n_a} q^{k}_{aj,t}\right)^2} \quad (3)$$

$$C^{*}_{k,t} = \frac{C_{k,t}}{\|C_t\|_2} \quad (4)$$

$$C_{k,t} = \frac{1}{2}\sum_{a=1}^{k} c^{k}_{a,t} \quad (5)$$

Where $Q_{k,t}$ is the square root of the sum of the squares of the total predicted net load values of nodes in each partition at time t, when the number of partitions is k; $q^{k}_{aj,t}$ is the predicted net load value of the node j in the partition a at time t, when the number of partitions is k; n_a is the number of nodes in partition a; $Q^{*}_{k,t}$is the value of $Q_{k,t}$ after being normalized by the L_2 norm; $C_{k,t}$ is the total number of interconnection lines in each partition at time t when the number of partitions is k; after normalizing it with the L_2 norm, we obtain $C^{*}_{k,t}$; $c^{k}_{a,t}$ is the number of interconnection lines in the partition a at time t when the number of partitions is k; λ is the weighting coefficient.

The partition number k obtained through (1) has the following implications. When the number of partitions decreases from $k+1$ to k, the weighted value of the reduction in interconnection line quantity and the sum of the square of the total net load in each partition is maximized due to partition merging. The interconnection line quantity and the square of the total net load can respectively estimate the consumption of interconnection resources and the independent operational capability of that partition. The closer the regional net load sum of squares is to zero, the smaller the inward or outward transfer of electricity from the partition, indicating a stronger capability of independent operation. Therefore, when the partition number changes from $k+1$ to k, the rate of reduction in resource consumption of interconnection lines and the rate of improvement in comprehensive independent operation capability of each partition are maximized, indicating that the partition merging process has the greatest overall impact on the power balance.

3 Partiton decoupling power balance model

In the hierarchical partition control framework of centralized-distributed form, when the urban power system operates in practice, the distribution layer operates independently in each partition, thus the power balance is ensured by power transmission among network nodes within each partition. If the power balance of the partition cannot be achieved, the centralized layer will coordinate and control interconnection resources to ensure power supply in case of power shortage. In order to realize the hierarchical partition operation process aforementioned, it is necessary to perform calculations of the power balance on a regional basis, which is specifically manifested in the partition weighting of the objective function and the partition decoupling of the constraint conditions.

3.1 Objective function

Taking into account the economy of system operation and the independent operation capability of each partition, the optimization objective of the power balance model is to minimize the weighted sum of the total generation cost of units and the power imbalance of each partition. Specifically, it can be expressed as (6) below.

$$min\sum_{a\in A}\sum_{b\in u^a} f_b^a\left(P_{b,t}^a\right) + \sum_{a\in A}\eta^a S_t^a \tag{6}$$

Where A is the set of partitions obtained by hierarchical partition of the power system; a is a specific partition in the set of partitions; u^a is the set of units in region a; b is a specific unit in the set of units; f_b^a is the cost function of unit b, which is generally a quadratic function; $P_{b,t}^a$ is the output of unit b at time t; S_t^a is the power imbalance of partition a at time t; η^a is the penalty term for power imbalance in partition a.

3.2 Constraint condition

In the hierarchical partition management framework, each partition operates independently, so the system constraints are decomposed into regional constraints. For any partition in the set of partitions, the following regional constraints and operational constraints must be satisfied.

3.2.1 Power balance constraint

$$\boldsymbol{B^a}\boldsymbol{\theta_t^a} + \boldsymbol{R_t^a}\boldsymbol{T_t^a} = P_t^a - D_t^a + P_{w,t}^a + P_{s,t}^a \tag{7}$$

Where $\boldsymbol{B^a}$, $\boldsymbol{\theta_t^a}$, $\boldsymbol{R_t^a}$ and $\boldsymbol{T_t^a}$ are the nodal admittance matrix, nodal phase angle matrix, adjacency matrix, and interconnection line flow matrix of partition a at time t, respectively. P_t^a, D_t^a, $P_{w,t}^a$ and $P_{s,t}^a$ are the sum of conventional unit output, load, actual wind power output, and actual photovoltaic power output in partition a at time t, respectively.

3.2.2 Phase angle constraint of reference node

$$\theta_{ref}^a = 0 \tag{8}$$

where θ_{ref}^a is the reference node phase angle for partition a. If there is no reference node in partition a, this equation does not need to be considered.

3.2.3 Power flow constraints of line in the partition

$$\left|\boldsymbol{B_f^a}\boldsymbol{\theta_t^a}\right| \le \boldsymbol{FL^{a,max}} \tag{9}$$

Where $\boldsymbol{B_f^a}$ is the power flow transfer matrix of partition a, which is the product of the inverse of the branch reactance matrix and the transpose of the node-branch incidence matrix; $\boldsymbol{FL^{a,max}}$ is the matrix of upper power flow limits of intra-partition lines in partition a; $FL_{ij}^{a,max}$ is the upper power flow limit of line ij; $\forall ij \in L_a$, and L_a is the set of lines within the partition a.

3.2.4 Power flow constraints of interconnection line

$$\left|T_{ij,t}^a = \frac{\theta_{i,t} - \theta_{j,t}}{x_{ij}}\right| \le T_{ij}^{a,max}, \forall ij \in \Gamma_a \tag{10}$$

where $T_{ij,t}^a$ is the power flow of interconnection line ij passing through partition a at time t; $T_{ij}^{a,max}$ is the upper limit of the power flow on interconnection line ij within partition a; Γ_a is the set of interconnection lines within partition a; $\theta_{i,t}$ and $\theta_{j,t}$ are the phase angles of node i and j on line ij at time, respectively; x_{ij} is the reactance value of line ij.

3.2.5 Regional power imbalance constraints

$$S_t^a = \left|\sum_{ij\in\Gamma_a} T_{ij,t}^a\right| \tag{11}$$

where S_t^a is the power imbalance of partition a at time t.

3.2.6 Unit operation constraints

$$P_b^{a,min} \le P_b^a \le P_b^{a,max}, \forall b \in u^a \tag{12}$$

$$P_{b,t}^a - P_{b,t-1}^a \le RU_b^a, \forall b \in u^a \tag{13}$$

$$P_{b,t-1}^a - P_{b,t}^a \le RD_b^a, \forall b \in u^a \tag{14}$$

Where (12) is the upper and lower limits constraints of unit output; (13)–(14) are the unit ramping constraints. $P_{b,t}^a$ and $P_{b,t-1}^a$ are the output of conventional unit b at time t and $t-1$, respectively. $P_b^{a,min}$ and $P_b^{a,max}$ are the minimum and maximum values of the output of conventional unit b. RU_b^a and RD_b^a are the maximum upward and downward ramping rates of unit b.

3.2.7 Operational constraints of wind and solar energy sources

$$0 \le P_{w,b,t}^a \le P_{w,i,t}^{a,fore}, \forall b \in u_w^a \tag{15}$$

$$0 \le P_{s,b,t}^a \le P_{s,j,t}^{a,fore}, \forall b \in u_s^a \tag{16}$$

where $P_{w,b,t}^a$ and $P_{s,b,t}^a$ are the actual output of wind power and solar power at time t, respectively; $P_{w,i,t}^{a,fore}$ and $P_{s,j,t}^{a,fore}$ are the theoretical output of renewable unit at time t; u_w^a and u_s^a are the collection of wind power units and solar power units in region a.

3.2.8 Operational constraints of energy storage

$$\left|E_{b,t}^a\right| \le E_b^{a,max}, \forall b \in u_e^a \tag{17}$$

$$SOC_{b,t}^a = SOC_{b,t-1}^a - \frac{E_{b,t}^a}{E_b^{a,max}}, \forall b \in u_e^a \tag{18}$$

$$0 \le SOC_{b,t}^a \le 1, \forall b \in u_e^a \tag{19}$$

Where $E_{b,t}^a$ is the output power of energy storage i at time t, with positive values indicating discharge and negative values indicating charge; $E_b^{a,max}$ is the maximum output power of energy storage b; $SOC_{b,t}^a$ and $SOC_{b,t-1}^a$ are the state of charge of the energy storage b at time t and $t-1$, respectively; u_e^a represents the collection of energy storages in partition a.

4 Power balance mechanism of urban power system based on dynamic hierarchical paetition method

The power balance mechanism of urban power system based on dynamic hierarchical partition method determines the partitioning

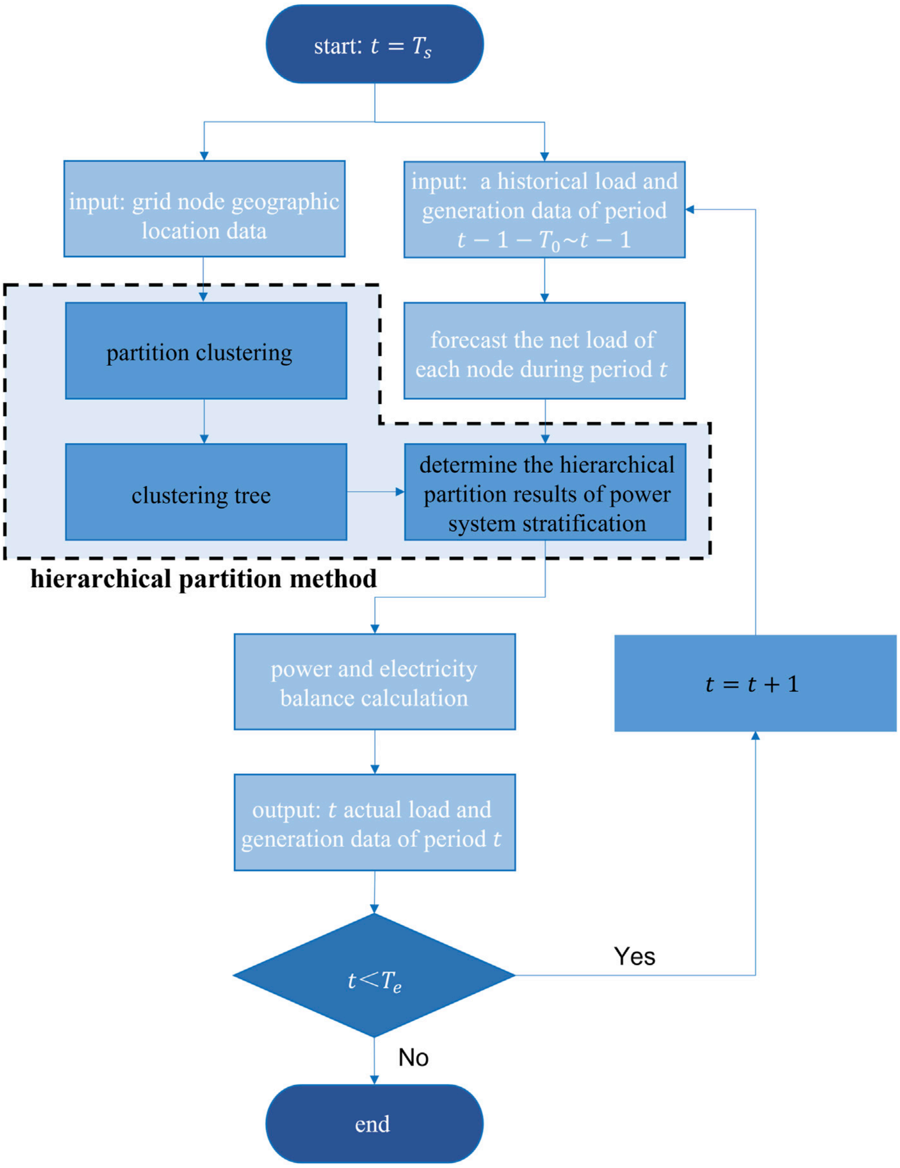

FIGURE 4
Flowchart of the dynamic hierarchical partitioning and power balance mechanism.

results first for each operating moment, and then performs power balancing calculations. The determination of partitioning results is based on both clustering tree and the net load forecast value at the current moment. For clustering tree, as the number of power grid nodes in the same area and their geographical locations remain constant in the long term, it can be considered fixed during the operating phase. Therefore, the partitioning clustering process only needs to be performed once at the beginning of the operation, and the clustering tree remains unchanged during subsequent hierarchical partitioning, eliminating the need for repeated calculations.

As for the current net load forecast value, it is obtained by predicting the historical net load data with a fixed timing length. In this study, the least squares support vector machine based on wavelet packet decomposition is used for net load forecasting. Due to the volatility and uncertainty of renewable energy and power load, the net load of power grid nodes changes in real-time, and the magnitude of the changes can be significant. In order to better meet the real-time absorption demand of renewable energy, improve the real-time independent operation capability of the power grid, and reduce the consumption of interconnection resources, it is necessary to adjust the partitioning results accordingly to achieve an improvement in the optimality of power balance results.

The specific operational process of the dynamic hierarchical partitioning and the power balance mechanism is shown in Figure 4. In the figure, T_s is the starting operating moment; T_0 is the sliding window length, which denotes the length of historical net load data used for predicting the net load data of each node; t is the current operating moment, and T_e is the ending operating moment. The specific process is described as follows:

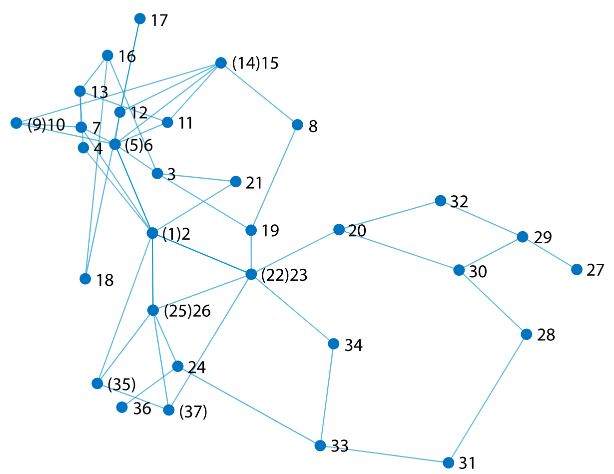

FIGURE 5
Modified Hawaiian 37-node system diagram.

1) Input the geographical location data of the grid nodes and obtain the clustering tree through partition clustering;
2) Input the historical operating data of the time period T_0 before the current running moment t, which includes historical load data and historical generation data. Calculate the net load data of all nodes in the power system at each moment within the time period $(t-1-T_0, t-1)$, and predict the net load value at the current moment based on historical net load data;
3) Based on the clustering tree and the predicted net load values of each node, obtain the hierarchical partitioning results of the power system at the current moment using (1–5);
4) Based on the hierarchical partitioning results of the power system at the current moment, calculate the power balancing results of the power system using (6–19) and output them;
5) Determine if the current moment t is the ending operating moment T_e. If yes, end the operation; if no, set $t = t + 1$ and go to Step 2, which is to enter the calculation of hierarchical partitioning and power balance for the next moment.

5 Case study

As shown in Figure 5, this section analyzes the dynamic hierarchical partitioned power balance mechanism based on the modified Hawaiian 37-node system, which consists of two voltage levels, 138 and 69 kV, and the nodes in parentheses in the figure are all 138 kV.

The total duration of the data is 48 h with a granularity of 1 h, and the base capacity is $100MVA$. The initial operating time is 25 h, using data from 1 to 24 h as historical data. And the final operating time is 48 h, using data from 24 to 47 h as historical data. The weighting coefficient λ is set to 0.4, and the penalty term η^a for power imbalance in each partition is 1,000.

In order to analyze and validate the effectiveness of the dynamic operating mechanism proposed in this paper, the following three operating modes are established. The problem is modeled and solved by MATLAB.

1) Mode 1: no hierarchical partitioning, which can be considered as all nodes belonging to a single partition or each node being a separate partition;
2) Mode 2: static hierarchical partitioning, i.e., the partitioning result is fixed during operation, which can be used to simulate the hierarchical partitioning method proposed in existing studies for system planning;
3) Mode3: dynamic hierarchical partitioning, which refers to mechanism proposed in this paper.

5.1 System operation results study

Based on the aforementioned system parameters and data, the system operating results under three different operating modes are analyzed. The total generation cost and the tie-line power of the 24-h system under different operating modes are shown in Table 1.

From the results in Table 1, it can be observed that the ynamic hierarchical partitioning reduces the total power transmission on tie lines (i.e., the sum of absolute values of power imbalances in each partition) by 21.57% and 1.21% compared with the non-partitioned and static hierarchical partitioning modes, respectively. Meanwhile, the generation cost increases by 0.422% and 0.082% respectively, indicating that the percentage reduction in total power transmission on tie lines is 51 times and 14 times higher than the percentage increase in generation cost. This demonstrates that through dynamic hierarchical partitioning, a large reduction in total power transmission on tie lines can be achieved at a relatively small increase in generation cost, which implies lower interconnection costs.

5.2 Partition operation results study

The total tie-line power under different operating modes in some periods are shown in Table 2. The clustering tree for the partitioning process is illustrated in Figure 2. Based on the clustering tree and (1)–(5), the final static and dynamic partitioning results are determined and depicted in Figures 6, 7, respectively. The 138 kV node is located in the central layer and does not participate in the partitioning process. The new energy units are connected to nodes 23, 26, 27, 28, and 33.

In Table 2, "k" represents "power number". It can be observed from Table 2 that after implementing hierarchical partitioning (including static and dynamic partitioning), the total power transmission on tie lines in the system is always lower than that without partitioning. And in most operating time periods, the total power transmission on tie lines under dynamic partitioning is lower than that under static partitioning. The net load values for each partition under different modes during the 40-h period are shown in Table 3.

Comparing the net load values of different partitions under the two hierarchical partitioning methods in Table 3, it can be observed that the dynamic partitioning process follows the change of the system source-load operation state, and merges partition 1, partition 2, partition 3 and partition 4, which are geographically close to each other and have opposite signs of net load values. After the merger of

10.3389/fenrg.2024.1355606

TABLE 1 System operation results in different modes.

Operation modes	Total generation cost/$	Tie-line power/100 MVA
Mode 1	115,458.10	272.48
Mode 2	115,850.07	216.33
Mode 3	115,944.99	213.71

TABLE 2 Total tie-line power under different operating modes in some periods.

Time/h	Mode1	Mode2		Mode3	
	Tie-line power/100 MVA	k	Tie-line power/100 MVA	k	Tie-line power/100 MVA
38	9.9206	6	7.7679	6	7.7679
39	9.6368		8.1023	6	8.1023
40	11.0015		10.7478	4	9.4274
41	13.3739		9.0022	4	8.4586
42	14.4043		12.0514	6	12.4107
43	14.8631		11.6698	6	11.4045
44	15.0425		10.0469	6	10.0175

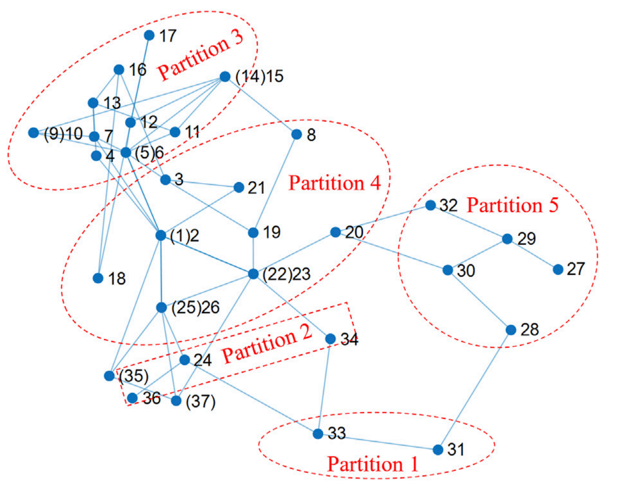

FIGURE 6
Static partition results.

partition 3 and partition 4, the partition decoupling power balance process fully utilizes the regulation capability of the units, reducing the output of units in the original partition 4, so that the 0.00022 MVA of new energy generation capacity, which was not consumed in the static partitioning of partition 4, is fully consumed after the dynamic partitioning, and reduces the total net load value of the merged partition B by 9.48% compared with the original partition 3.

It can be seen that the dynamic hierarchical partitioning and partition decoupling power balance processes complement each other, enabling the system to adapt to operational changes, improve the local accommodation capacity of new energy, and reduce regional power imbalance. In the event of an accident scenario, a smaller amount of regional power imbalance implies a smaller instantaneous power variation in the system, resulting in reduced losses, which is crucial for the safe operation of the system.

6 Conclusion

This paper proposes a power balance mechanism of urban power system based on dynamic hierarchical partition method, which can be applied to the operation of future urban power systems. Compared with the existing static method, the dynamic hierarchical partition method proposed in this paper can change the partition result according to the real-time operation state of the power system, which aims to reduce the coordination cost at the cost of smaller generation cost, improve the local consumption capacity of new energy, and enhance the regional independent operation ability. In addition, a partition decoupling power balance model is proposed in this paper, which make the power balance process can be carried out in a hierarchical way and further improve the independent operation ability of the region.

In this study, the performance of dynamic partitioning results is closely related to the weight coefficient, and the weighting coefficients in the objective function for the determination of the number of partitions may vary for different systems, which needs to be determined in advance. How to choose the appropriate weight coefficient is a difficult point, and the adaptive selection of weight coefficient may be an effective way.

 10.3389/fenrg.2024.1355606

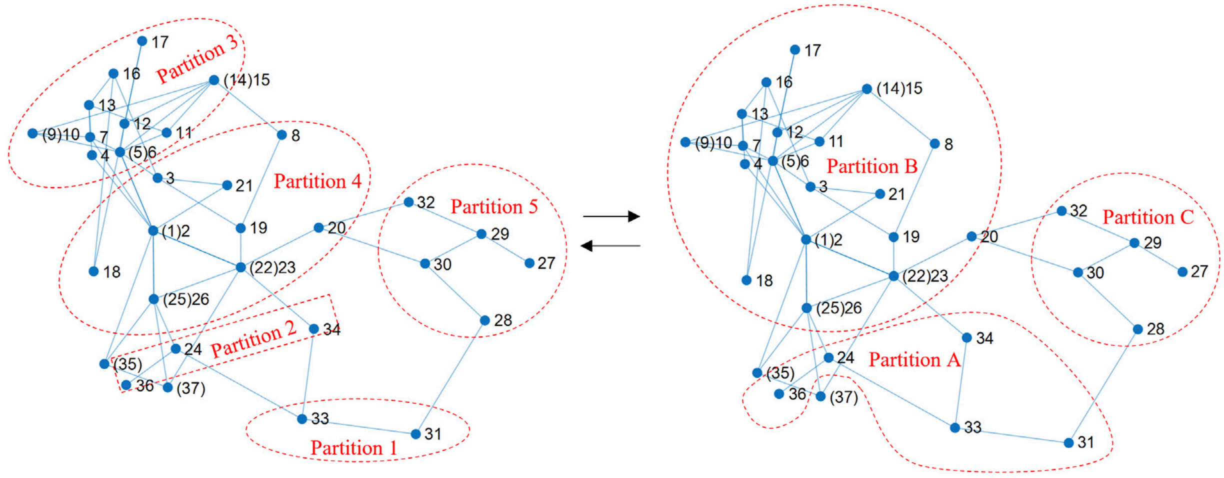

FIGURE 7
Dynamic partition results.

TABLE 3 Net load values for each partition under different modes during the 40-h period.

Net load for partitions/100MVA		
Partition sequence number	Mode 2	Mode 3
1	0.6057	0.6257
2	−0.0263	−0.0263
3	4.3480	4.5668
4	0.0000022	−0.6328
5	0.4002	0.4002
A	—	0.5994
B	—	3.9340
C	—	0.4002

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Author contributions

JY: Conceptualization, Data curation, Investigation, Methodology, Project administration, Writing–original draft. XL: Formal Analysis, Investigation, Software, Writing–original draft. YH: Funding acquisition, Project administration, Resources, Visualization, Writing–original draft. RL: Conceptualization, Methodology, Visualization, Writing–original draft, Writing–review and editing. WT: Data curation, Formal Analysis, Project administration, Software, Writing–original draft, Writing–review and editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This work was supported by the Hangzhou Electric Power Design Institute. Management technology project–Research on macroeconomics and energy consumption forecasting technology based on energy big data (2022YF-113).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Adeyanju, O. M., and Canha, L. N. (2021). Decentralized multi-area multi-agent economic dispatch model using select meta-heuristic optimization algorithms. *Electr. Power Syst. Res.* 195, 107128. doi:10.1016/j.epsr.2021.107128

Biserica, M., Foggia, G., Chanzy, E., and Passelergue, J. C. (2013). "Network partition for coordinated control in active distribution networks," in Paper presented at the 2013 IEEE Grenoble Conference, Grenoble, France, June 2013, 16–20.

Chang, C., Lu, L., and Wen, F. (1999). Power system network partitioning using tabu search. *Electr. Power Syst. Res.* 49 (1), 55–61. doi:10.1016/s0378-7796(98)00119-9

Chen, D., Lu, R., Zhang, S., Zhang, J., Zhang, L., and Zhang, H. (2023). Review of new power system balance calculation and Analysis techniques. *Power Syst. Technol.*, 1–20. doi:10.13335/j.1000-3673.pst.2023.1609

Dai, F., Huang, L., Xv, J., and Sun, Y. (2011). Voltage partition and pilot nodes selecting of Henan power grid based on secondary voltage control. *Power Syst. Prot. Control* 39 (24), 101–105. doi:10.3969/j.issn.1674-3415.2011.24.017

Gil, C., Baños, R., Montoya, M., and Gómez, J. (2006). Performance of simulated annealing, tabu search, and evolutionary algorithms for multi-objective network partitioning. *Algorithmic Operations Res.* 1 (1), 55–64.

Han, P., Guo, J., Dong, W., and Wang, X. (2023). Partiton strategy of power system containing new energy based on system clustering method. *A Publ. Chin. Soc. Univ. Elcetric Power Syst. its Automation*, 1–8. doi:10.19635/j.cnki.csu-epsa.001292

Hao, G., Han, X., Liang, J., and Zhang, X. (2020). Review of dispatch and control methods for tradition power system and highrate renewable energy generation power system. *A Publ. Chin. Soc. Univ. Elcetric Power Syst. its Automation* 32 (09), 10–19. doi:10.19635/j.cnki.csu-epsa.000392

Hou, L., Bai, Y., and Su, J. (2023). Process simulation on the planning of wind-PV-storage for near-zero carbon emission. *Front. Energy Res.* 11, 1217279. doi:10.3389/fenrg.2023.1217279

Hu, Z., Wang, X., Wang, X., and Chen, H. (2005). A two-layered network partition approach for optimal reactive power dispatching. *Power Syst. Technol.* (24), 37–41. doi:10.3321/j.issn:1000-3673.2005.24.008

Irving, M., and Sterling, M. (1990). Optimal network tearing using simulated annealing. *IEE Proc. C (Generation, Transm. Distribution)* 137, 69. doi:10.1049/ip-c.1990.0010

Lai, X., Xie, L., Xia, Q., Zhong, H., and Kang, C. (2014). Decentralized multi-area economic dispatch via dynamic multiplier-based Lagrangian relaxation. *IEEE Trans. Power Syst.* 30 (6), 3225–3233. doi:10.1109/tpwrs.2014.2377755

Li, C., Zhang, J., Yao, D., Li, X., Ge, S., and Lv, Q. (2022). Poer balance method of provincial power system with complex generation structure. *High. Volt. Eng.*, 1–17. doi:10.13336/j.1003-6520.hve.20221942

Li, Z., Li, Y., and D improveuan, X. (2009). A novel partition approach of control variables in cooperative coevolutionary computation for reactive power optimization. *Proc. CSEE* 29 (16), 28–34. doi:10.3321/j.issn:0258-8013.2009.16.005

Li, Z., Lou, Y., Liu, J., Liu, S., Yang, F., and Fu, Y. (2014). "Optimal partition of power distribution network service areas based on improved K-Means algorithm," in Paper presented at the 2014 International Conference on Power System Technology, Chengdu, China, October, 2014.

Li, Z., Wu, L., and Xu, Y. (2021). Risk-Averse coordinated operation of a multi-energy microgrid considering voltage/var control and thermal flow: an adaptive stochastic approach. *IEEE Trans. Smart Grid* 12 (5), 3914–3927. doi:10.1109/TSG.2021.3080312

Li, Z., Xu, Y., Wang, P., and Xiao, G. (2023). Restoration of multi energy distribution systems with joint district network recon figuration by a distributed stochastic programming approach. *IEEE Trans. Smart Grid*, 1. doi:10.1109/TSG.2023.3317780

Liu, D., Tang, G., and Chen, H. (2002). Tabu search based network partitioning for voltage control. *Automation Electr. Power Syst.* (06), 18–22. doi:10.3321/j.issn:1000-1026.2002.06.005

Mezquita, J., Asber, D., Lefebvre, S., Saad, M., and Lagacé, P. J. (2011). "Power network partitioning with a fuzzy C-means," in Proc. IASTED Int. Conf. Power and Energy Systems and Applications (PESA 2011), Pittsburgh, USA, November, 2011.

Orero, S., and Irving, M. (1996). "A genetic algorithm for network partitioning in power system state estimation," in Paper presented at the UKACC International Conference on Control'96, Exeter, UK, September, 1996.

Pan, M., He, X., Ai, Q., and Tang, Y. (2023). Research status and prospect of distributed energy resource dispatching in new distribution system. *Power Syst. Technol.*, 1–16. doi:10.13335/j.1000-3673.pst.2023.0716

Sánchez-García, R. J., Fennelly, M., Norris, S., Wright, N., Niblo, G., Brodzki, J., et al. (2014). Hierarchical spectral clustering of power grids. *IEEE Trans. Power Syst.* 29 (5), 2229–2237. doi:10.1109/TPWRS.2014.2306756

Wang, L., Han, X., and Song, L. (2013). Reactive power voltage control partitioning based on modified shuffled frog-leaping-K-means clustering algorithm. *Transducer Microsyst. Technol.* 32 (06), 18–21. doi:10.13873/j.1000-97872013.06.014

Wang, L., Liu, Y., Wang, X., Wang, H., and Guo, G. (2022). Consensus dispatch of distributed power network based on multi-access edge computing and multi-agent system. *Front. Energy Res.* 10, 907359. doi:10.3389/fenrg.2022.907359

Xu, X., Xue, F., Lu, S., Zhu, H., Jiang, L., and Han, B. (2019). Structural and hierarchical partitioning of virtual microgrids in power distribution network. *IEEE Syst. J.* 13 (1), 823–832. doi:10.1109/JSYST.2018.2821137

Yang, Q., Wang, J., Yang, X., Zhang, Y., Xiao, Y., and Wang, X. (2023a). Development, application, and prospect of power and energy balance Analysis and its speedup computation technologies. *Power Syst. Technol.*, 1–19.

Yang, X., Dong, Z., Tang, B., and Chen, S. (2006). Power network partition based on fuzzy clustering Analysis. *Proc. CSEE* (22), 6–10. doi:10.3321/j.issn:0258-8013.2006.22.002

Yang, Y., Li, Z., Mandapaka, P. V., and Lo, E. Y. M. (2023b). Risk-averse restoration of coupled power and water systems with small pumped-hydro storage and stochastic rooftop renewables. *Appl. energy* 339, 120953. doi:10.1016/j.apenergy.2023.120953

Zhang, H., Long, C., Hu, S., Liao, K., and Gao, Y. (2021). Topology verification method of a distribution network based on hierarchiacal clustering and the Pearson correlation coefficient. *Power Syst. Prot. Control* 49 (21), 88–96. doi:10.19783/j.cnki.pspc.210075

Zhang, Y. (2018). Research overview of reactive voltage control partitioning for power system. *Electrotech. Electr.* (03), 1–6+28. doi:10.3969/j.issn.1007-3175.2018.03.001

Zhao, P., Xie, N., Xie, J., and Wang, C. (2023). Centralized-distributed pattern of distribution network and its hierarchical partition method adapting to development trend of new power system. *Smart Power* 51 (01), 94–100. doi:10.3969/j.issn.1673-7598.2023.01.014