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Real-time distributed dispatch strategy for distribution transformer supply zone cluster based on cloud-edge collaboration architecture

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Aiming at the problem of long-timescale prediction deviation in the distribution network, a fast regulation strategy of cloud-edge coordination based on an intelligent transformer supply zones edge consistency algorithm is proposed. The cloud makes the global initial optimal allocation to the edge transformer supply zone clusters, and then the cluster makes the secondary collaborative optimal allocation to the edge zones. A fast power interaction model within a cluster based on a consensus algorithm is established, and the micro-increase rate of dispatching cost is used as the consistency variable so that the cluster adjustment amount is optimally allocated to each transformer supply zone, and the total dispatch cost of all transformer supply zones is minimized. The simulation example verifies the effectiveness of the cloud-edge collaborative fast control strategy based on the intelligent station cluster edge consensus algorithm in this article.

KEYWORDS

transformer supply zone, coordinate the edge sides, power deviation, distributed dispatch, consensus algorithm

1 Introduction

Under the background of the “double-carbon” goal, China has accelerated the construction of the new electric power system with new energy as the main body. The wide access to a high proportion of distributed new energy and the participation of large-scale resources such as energy storage and flexible load in the regulation and control of the distribution network have affected the safe and stable operation of the system (Peng et al., 2022); how to use the abovementioned resources to coordinate and dispatch is one of the key issues that need to be solved urgently at present (Fang et al., 2019; Zhao et al., 2019).

There have been many studies on the scheduling of using distributed resources. [Tofighi-Milani et al. \(2022\)](#), in order to promote the distributed scheduling of multi-agent systems, proposed a P2P resource management scheme considering network constraints, which can realize that each agent can independently schedule local resources to maximize its own interests. [Huang et al. \(2022\)](#), to manage multiple distributed resources in a microgrid, proposed a two-stage interactive retail electricity market based on interactive energy, which can effectively exploit the flexibility potential of each distributed resource. [Huang et al. \(2021\)](#), in order to promote the free competition of electric energy retailers with multiple distributed resources in the retail market, proposed a transactional retail market mechanism, which reduces the impact of clean energy uncertainty and improves market efficiency. [Yang et al. \(2021\)](#), in order to fully coordinate and utilize flexible resources, proposed a three-timescale coordinated scheduling framework, which can effectively improve the economy of active distribution networks.

With the vigorous development of the Internet of energy ([Liu et al., 2020](#)), the automation and digital transformation of low-voltage distribution transformer supply zone as a unit is gradually carried out in China, and a new generation of intelligent distribution transformer supply zone based on the concept of cloud-edge collaboration and edge computing of the distribution Internet of Things has become one of the construction paths. Cloud-side collaboration can reasonably allocate complex computing tasks. Edge computing implements local data collection and analysis on the side near the data ([Gong et al., 2018](#)), and then uploads to the end. The cloud collects the data transmitted from the edges, makes the optimization decision of the whole system, and then sends the control task to each edge. The cloud-edge cooperative dispatching mode fits the distribution characteristics of new energy in the distribution network ([Li and Song, 2021](#)), and is applied to the optimal regulation of the distribution network ([Ren et al., 2019](#)), which can effectively solve the problem of a large amount of computing and communication data caused by the access of a high proportion of distributed resources.

There have been some research works on the cloud-edge cooperative dispatching strategy. [Peng et al. \(2022\)](#) proposed the dispatching operation mode of two-level fusion of “cloud brain-edge neuron.” [Liu et al. \(2020\)](#), aiming at the problem of peak regulation in virtual power plants, constructed a multi-energy virtual power plant dispatching technical framework of cloud-edge-end hierarchical cooperation. [Si et al. \(2020\)](#) established the physical architecture of Power Internet of Things based on cloud-edge collaboration, built a CPPS unified computing mathematical model based on edge computing and the idea of cooperative autonomy among clusters and cloud-edge collaborative control, and applied the dispatching calculation of virtual power plants. In order to promote the synergistic interaction between distributed resources and distribution

network, [Zhou et al. \(2022\)](#) proposed the Power Internet of Things 5G cloud-edge-end multi-level coordination framework and a cloud-side-end collaborative resource regulation method based on semi-distributed artificial intelligence to achieve collaborative optimization of cloud-side/side-side computing resource allocation. [Zhang and Wang \(2022\)](#) proposed a real-time demand response dispatching strategy of cloud-side collaboration for electric vehicles, and a task unloading strategy of cloud-side collaboration was proposed. A dispatching decision model was established with the goal of minimizing the load difference of the central cloud and maximizing the response benefit of the edge cloud.

Random fluctuation and unpredictability of new energy bring power deviation to distribution network regulation ([Bian et al., 2021](#); [Li et al., 2022](#)). Although the cloud-side cooperative regulation strategy can effectively improve the problems of computation and communication, it is difficult to correct the power deviation in time due to the communication delay in the cloud-edge cooperative control. Therefore, it is necessary to seek an efficient and fast dispatch decision-making method ([Gong et al., 2018](#)). Compared with remote computing in the cloud, edge computing performs data analysis near the device. Compared with cloud-edge information transmission, it is more convenient and faster to directly exchange data between adjacent edges.

A consensus algorithm is a distributed optimization algorithm to solve the task concentration. It only needs the communication data between local and adjacent units, and completes the iterative optimization between each unit, which can effectively reduce the computation and communication burden. At present, the consensus algorithm has been applied to the coordinated control of the distribution network ([Zeraati et al., 2019](#)). [Zhang et al. \(2020\)](#) proposed a distributed energy storage optimization control strategy based on a consensus algorithm for the economic dispatch of autonomous microgrid clusters, and used the consensus algorithm to distribute the output power of energy storage. [Pu et al. \(2017\)](#) proposed a distributed optimization scheduling method based on consistency theory to solve the problem of regional autonomous optimal scheduling in an active distribution network. The incremental cost of distributed power supply was taken as a consistency variable to realize the optimization of power generation cost in the autonomous region. [Li et al. \(2018\)](#), to solve the problem of DC micro-power grid in the centralized control, proposed the multi-objective control strategy based on a consistency algorithm, to realize the voltage stability and power generation cost minimum. [Yang et al. \(2020\)](#) proposed a distributed control strategy based on a consensus algorithm to solve the problem of unbalanced power between photo-voltaic power generation and load in a DC microgrid composed of multiple photovoltaic and battery energy storage units. Taking the control power of batteries as a consistency variable, the unbalanced power can be distributed among batteries according to the real-time state of SoC, avoiding the phenomenon of mutual

charging and discharging between batteries. Lv et al. (2019) established a dynamic economic dispatching model of an independent microgrid with energy storage and controllable loads, and proposed a distributed solution algorithm based on a consensus algorithm to realize the optimal power distribution of distributed power and energy storage.

The abovementioned research applies the consensus algorithm to realize the distributed control of the microgrid or adopts the completely distributed scheme to realize the coordinated regulation of the distribution network. However, due to the lack of coordination of centralized links, the distributed scheme is generally only suitable for distributed control with relatively fixed rules, which is difficult to adapt to changes in the power grid environment, and it is difficult to convert complex optimization problems into distributed algorithms. In this article, aiming at correcting the long-term prediction deviation, combined with the characteristics of the cloud and the edge, a real-time dispatch strategy for distribution transformer supply zone cluster based on cloud-edge collaboration architecture is proposed. Multiple zones with adjacent communication functions are formed into a transformer supply zone cluster. The leader of the transformer supply zone cluster sends the power deviation and dispatching cost signals of the cluster to the cloud, and the cloud optimizes the total power deviation of the distribution network to each cluster based on long-term global control. The study aims to minimize the deviation amendment cost; a real-time power interaction model was established based on the consensus algorithm. The micro-increase rate of the cost was taken as the consistency variable of the transformer supply zone cluster, and the consistency iteration was carried out within the cluster, so the power deviation signal of the cluster was optimally allocated to each zone cluster. When cloud-side communication is interrupted, each cluster can independently implement consistent dispatch according to its own power deviation within the cluster, with autonomous ability. The simulation example verifies the effectiveness of the coordinated control strategy of the transformer supply zone cluster based on the consensus algorithm of the edge nodes of the intelligent transformer supply zones.

The main contributions of this article are as follows:

A distributed real-time control scheme of cloud-edge cooperation is proposed, in which the intelligent terminals of the zones are used as the edge computing nodes, and the cloud-edge cooperation is carried out among multiple zones with adjacent communication functions. The cloud allocates the total dispatch amount to the transformer supply zone clusters for the initial allocation. The transformer supply zone cluster then collaboratively distributes the initial dispatching quantity to each transformer zone for secondary allocation. When the communication between the cloud and the edge is interrupted, the transformer supply zone cluster independently performs secondary optimal allocation according to the

scheduling amount of the cluster to achieve independent operation.

A centralized-distributed scheduling method based on a consensus algorithm is proposed. The cloud optimally distributes the dispatching volume of the distribution network to the transformer supply zone clusters. With the micro-increase rate of dispatching cost as the consistency variable, the consistency iteration is carried out within the cluster, and the dispatch quantity of the cluster is optimally allocated to each transformer supply zone.

2 Distributed fast power regulation strategy for transformer area clusters under the cloud-edge collaboration architecture

2.1 Cloud-side collaborative power dispatching framework

In the cloud-side collaborative control architecture of a new energy distribution network, the cloud is the control center responsible for the global control of the distribution network system. Its main functions include collecting and processing information transmitted by the edge side, making optimization decisions for the whole system, and issuing control instructions to edge side and assisting edge computing. The edge side is each transformer supply zone, equipped with intelligent distribution transformer terminals, which is mainly responsible for intelligent sensing and aggregation of distributed power, energy storage and controllable load in the transformer supply zones, communication with cloud and adjacent side, executing of edge calculation, load dispatching ability of evaluation and control, *etc.* The information exchange between the cloud and the side is carried out through the public channel to realize the cloud-edge cooperation; each transformer supply zone is equipped with an independent local controller to exchange information with adjacent stations to realize edge cooperation.

Based on the flexible load, energy storage, and distributed generation resources output, the day-ahead dispatching is carried out with the objective of minimizing the operation cost of the transformer supply zone. According to the forecast of distributed generation resources output and flexible load, to determine the power generation plan of this transformer supply zone cluster, divide 24 h of a day into T periods, assuming that the power of the constituent unit remains basically unchanged in each period. The objective function of the day ahead dispatching is (Huang et al., 2017)

$$\min F = \sum_{t=1}^T \left\{ \sum_{i=1}^n [C_{DR,i}(t) + C_{ESS,i}(t) + C_{dr,i}(t)] \right\} \quad (1)$$

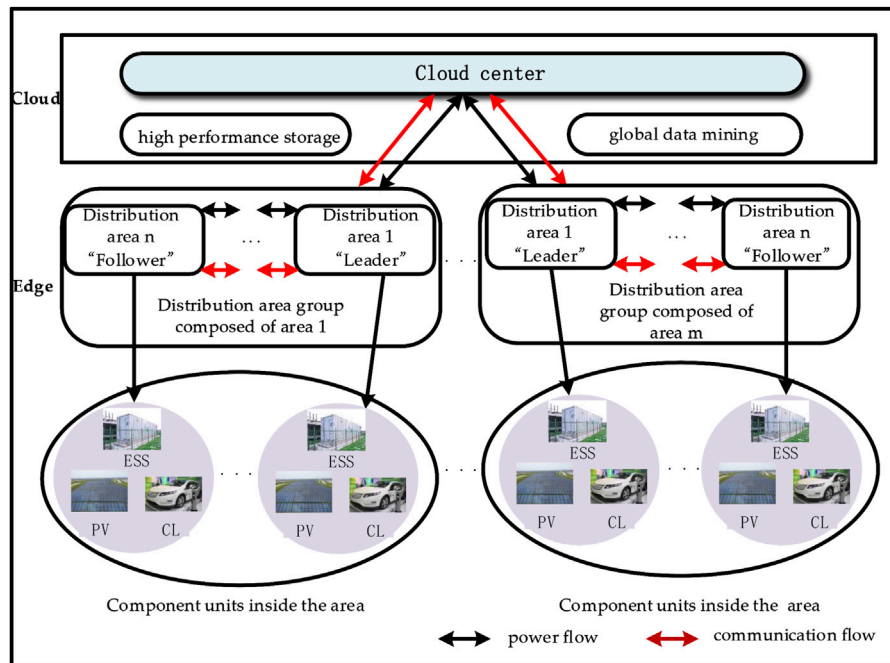


FIGURE 1
Real-time dispatch framework for distribution transformer supply zone cluster based on cloud-edge collaboration architecture.

where $C_{DR,i}(t)$, $C_{ESS,i}(t)$, and $C_{dr,i}(t)$ are, respectively, the operating costs of distributed generation resources, energy storage, and flexible load in transformer i during period t .

In the previous dispatch stage, the cloud performs centralized optimization calculations with the goal of minimizing the cost and optimally allocates the regulation amount to each transformer supply zone cluster because the prediction accuracy decreases with the increase of timescale, and the day ahead scheduling often cannot meet the requirements of power balance. This study takes the optimization value of the long timescale as the reference value to correct the deviation of regulation power from the short timescale. In this study, combined with the characteristics of cloud edge, multiple transformer supply zones with adjacent communication functions are formed into transformer supply zone clusters to form edge nodes, and uses edge computing to adjust and correct the power deviation in real time on a short timescale. Figure 1 shows the real-time dispatch framework for the distribution transformer supply zone cluster based on the cloud-edge collaboration architecture. The “Leader-Follower” distributed dispatching method is adopted within each transformer supply zone cluster (Zhang and Chow, 2011), and the “Leader” of the cluster sends the power deviation and dispatching cost signal of the cluster to the cloud; the cloud summarizes the data information uploaded by all leaders, on a long-term scale; the global centralized dispatch optimization calculation is carried out with the goal of economical

optimization, and distributes the optimized power deviation value to the “leaders” of each transformer supply zone cluster for initial distribution; the transformer supply zone clusters then cooperatively allocate the scheduling amount obtained from the initial allocation to each transformer supply zone for secondary allocation. When the communication between cloud and edges is interrupted, the transformer supply zone cluster can optimize the allocation according to the scheduling volume of the cluster to realize independent operation.

According to the scheduling results of different stages at the transformer supply zone level, the internal resources of the transformer supply zone are finely controlled, and then the ending resources are optimized and managed according to the target dispatching power of the transformer supply zone. With the best global cost as the goal, the resources in the transformer supply zone are classified and participate in the dispatch in stages. The integrated regulation and control requirements of end transformer supply zones are realized.

The total power deviation of the distribution network is

$$\Delta P = \sum_{j=1}^m \Delta P_j \quad (j = 1, 2, \dots, m), \tag{2}$$

$$\Delta P = \sum_{j=1}^m \Delta P_j \quad (j = 1, 2, \dots, m), \tag{3}$$

where ΔP refers to the total power deviation of the distribution network, ΔP_j represents the power deviation of the j th power

distribution cluster being uploaded to the cloud, and $\Delta P_{j,\min}$ and $\Delta P_{j,\max}$ are the upper and lower limits of the regulated power of the j th transformer supply zone cluster, respectively.

According to the power deviation uploaded by the leader of each transformer supply zone cluster, the cloud performs optimization calculations based on the slight increase rate of equal cost. When the equation shown in Eq. 4 is satisfied, the purpose of optimizing power deviation distribution to each power transformer supply zone cluster can be achieved with the goal of economy.

$$\frac{\partial C_1}{\partial(\Delta P_1)} = \frac{\partial C_2}{\partial(\Delta P_2)} = L = \frac{\partial C_m}{\partial(\Delta P_m)} \quad (4)$$

where C_m is the control cost of the m th transformer supply zone cluster and ΔP_m is the power deviation of the m th transformer supply zone cluster.

When the micro-increase rate of cost of all transformer supply zone clusters is consistent, the optimal power deviation value to be corrected for each cluster under the lowest dispatch cost is obtained; that is, it meets the relationship shown in Eq. 5.

$$\sum_{j=1}^m \Delta P_j = \sum_{j=1}^m \Delta P'_j, \quad (5)$$

where ΔP_j represents the power deviation of the j th transformer supply zone cluster and $\Delta P'_j$ represents the power deviation of the j th transformer supply zone cluster after optimization calculation of the cloud equal incremental rate.

2.2 Distribution zone cluster members and functions

There are multiple transformer supply zones in the transformer supply zone cluster, and each transformer supply zone has the resources that can participate in the dispatch. Considering that the type and quantity of distributed power supply, energy storage, and flexible load may be different in each transformer supply zone, for the convenience of expression, the units inside the zone are no longer distinguished here; each transformer supply zone is regarded as an edge node, and in order to ensure that the distribution transformer supply zones cluster has high communication reliability (Zhang and Chow, 2012), the transformer supply zone with good communication and computing capabilities is selected as the “Leader,” and the rest of the transformer supply zones are selected as “followers.”

Leader: As the most important transformer supply zone in the transformer supply zone cluster, it is required to have high communication reliability and good computing capability. It can interact with the cloud for data and information, upload the power deviation of the local transformer supply zone cluster to the cloud, and receive the optimized power deviation value from

the cloud; it can carry out communication exchange with adjacent transformer supply zones, obtain the information transmitted by adjacent transformer supply zones, and update the dispatching information of transformer supply zone in the cluster based on the consensus algorithm.

Follower: All transformer supply zones except “Leader”; they do not need to communicate with the cloud, only interact with adjacent transformer supply zones, and update the dispatching information of the transformer supply zone based on the consensus algorithm.

3 Consistent distributed control method for transformer area cluster

3.1 Consistency theory

3.1.1 Distributed topological graph theory

In this article, optimization is carried out with the goal of minimizing the dispatch cost of all transformer supply zones. It is necessary to coordinate control among multiple zones so that the cost micro-increase rate in the multi-distribution transformer supply zones system tends to a stable common value, which belongs to the consistency of the transformer supply zones.

In the problem of real-time dispatching consistency in transformer supply zones cluster, information is interacted through the communication network between the transformer supply zones, forming a distributed topology, so that can be described by graph theory. The communication relationship between the transformer supply zones of a transformer supply zone cluster can be represented by a directed graph $G = (V, E)$, where $V = \{1, \dots, n\}$ is the set of nodes of the directed graph G and each transformer supply zone can be represented by a node in the directed graph, and $E \subseteq V \times V$ is the set of edges of the directed graph G . Two connected nodes are said to be “neighbors” if and only if there is an information transmission channel between node i and node j . A graph G is said to be a strongly connected graph if, for any two nodes $i, j (i \neq j)$, there exist directed paths from i to j and from j to i .

Define the matrix $A = [a_{ij}]$ as the adjacency matrix of G with diagonal elements of 0 and non-diagonal elements a_{ij} as the number of edges from node i to node j . $D = [d_{ij}]$ is a degree matrix, which is a diagonal matrix of $n \times n$, d_1, d_2, \dots, d_n is the number of degrees corresponding to each node, and the degrees are the number of neighboring nodes of a node. $L = D - A = [l_{ij}]$ is a Laplacian matrix reflecting the topological structure of the power distribution zone, where l_{ij} satisfies the relationship shown in Eq. 6.

$$l_{ij} = \begin{cases} \sum_{j \in N_i} a_{ij}, & (i = j) \\ -a_{ij}, & (i \neq j) \end{cases} \quad (6)$$

3.1.2 Consensus algorithm

In order to effectively reduce the computational and communication burden of cloud-side coordinated control of distribution networks, a centralized-distributed dispatch method based on a consensus algorithm is proposed in this article. In the day-ahead stage, the centralized optimization calculation is performed by the cloud, and in the real-time stage, the coordinated regulation of each transformer supply zone is transformed into a distributed control in the distribution transformer supply zones cluster. The consistency algorithm exchanges information between the local controller and adjacent controllers, and performs iterative calculations in each controller to make the selected consistency variables tend to a common value (Zheng et al., 2022). The calculation process is distributed computing. Therefore, each distribution transformer supply zone can be linked by the consensus algorithm so as to realize the coordinated regulation of the distribution transformer supply zones cluster. The proposed centralized-distributed dispatch method based on the consensus algorithm can not only solve the problem of high computational pressure of the centralized control method but also overcome the global limitation of the distributed control method so that the proposed method combines the advantages of both and overcome the shortcomings of both.

Considering the transformer supply zone as a node, for node i , $x_i(k)$ represents the consistency state information of node i after k iterations, where $i = 1, 2, \dots, n$ and n are the number of nodes, and k is the number of iterations. In the distributed system, using the discrete consensus algorithm, the consistency variables of each node are updated according to the consistency variables of its neighboring nodes. As the number of iterations gradually increases, the consistency variables $x_i(k)$, $x_j(k)$ of any adjacent nodes tend to be consistent and satisfy $x_i(k) = x_j(k)$; at this point, all nodes in the system are considered to converge to a common value, and the first-order consensus algorithm is expressed as

$$x_i(k+1) = \sum_{j=1}^n d_{ij} x_j(k), \quad (7)$$

where $x_i(k+1)$ is the state information of node i after $k+1$ iterations, $x_j(k)$ is the state information of node j after k iterations; $\mathbf{D}(k)$ is the state transition matrix; if matrix $\mathbf{D}(k)$ satisfies two conditions, $\mathbf{D}(k)$ is a non-negative row random matrix and all the eigenvalues are not greater than 1. All intelligent bodies of the system will converge to the same value after enough iterations. d_{ij} are the elements of the i row and j column of the state transfer matrix $i \in n, j \in n$ determined by the topology of the communication network, which can be expressed as

$$d_{ij} = \frac{z_{ij}(k) |l_{ij}(k)|}{\sum_{j=1}^n z_{ij}(k) |l_{ij}(k)|}, \quad (8)$$

where z_{ij} represents the gain weight of node i to node j .

3.2 Consistent and distributed control model for transformer supply zone

3.2.1 Dispatching cost function of zone

For the transformer supply zone, the internal resource attributes are no longer distinguished. The dispatching target is to minimize the dispatching cost of each transformer supply zone in the transformer supply zone cluster, which can be expressed as

$$\min C_i(P_i), \quad (9)$$

where P_i refers to the dispatching power of the i th transformer supply zone and C_i represents the dispatching cost of the i th transformer supply zone.

The flexible resources involved in the real-time dispatch of the transformer supply zone mainly include distributed generation resources, flexible load, and energy storage. Among them, the power dispatch cost function of distributed generation resources can be expressed as (Rahbari-Asr et al., 2014)

$$C_{G,i}(P_{G,i}) = a_i P_{G,i}^2 + b_i P_{G,i} + c_i, \quad (10)$$

where $C_{G,i}$ is the dispatching cost of the i th distributed generation resources; $P_{G,i}$ is the power dispatched by the i th distributed generation resources; a_i , b_i , and c_i are corresponding cost coefficients, respectively.

The operating cost function of the energy storage device is expressed as (Rahbari-Asr et al., 2014)

$$\begin{cases} C_{ESS}(P_{ESS}) = a_c P_{ESS}^2, P_{ESS} < 0 \\ C_{ESS}(P_{ESS}) = a_d P_{ESS}^2, P_{ESS} > 0 \end{cases}, \quad (11)$$

where P_{ESS} is the power dispatched by the energy storage device, $P_{ESS} < 0$ indicates charging the energy storage, $P_{ESS} > 0$ indicates discharging the energy storage, a_c, a_d are corresponding cost coefficients, respectively.

The cost function of flexible load is usually expressed by quadratic function (Liu et al., 2021):

$$C_{dr}(P_{dr}) = -a_{dr} P_{dr}^2 + b_{dr} P_{dr} + c_{dr} \quad (12)$$

where C_{dr} is the control cost of flexible load; P_{dr} is the power consumed by the flexible load; a_{dr}, b_{dr}, c_{dr} are corresponding coefficients, respectively.

According to Eqs 10–12, the dispatching cost function of the i th transformer supply zone can be regarded as the linear convex combination of each component unit in the transformer supply zone:

$$C_i(P_i) = a_i (P_i)^2 + b_i P_i + c_i, \quad (13)$$

where P_i refers to the dispatched power of the i th transformer supply zone, a_i, b_i , and c_i are the corresponding cost coefficients, respectively, which are comprehensively calculated by Eqs 10–12.

The abovementioned calculation method is suitable for the case where the number of distributed resources in the transformer supply zone is small. When the number of distributed resources in the transformer supply zone is large, the K-means algorithm is used to cluster resources with the same response characteristics, which can significantly reduce the amount of calculation.

The power balance constraint of the distribution network is expressed as

$$\sum_{i=1}^n P_i = \sum_{i=1}^n P_L, \tag{14}$$

where P_i refers to the dispatched power of the distribution network and P_L refers to the actual load demand power.

The upper and lower limit constraints of distribution network dispatch power are expressed as

$$P_{i,\min} \leq P_i \leq P_{i,\max}, \tag{15}$$

where $P_{i,\min}$ and $P_{i,\max}$ represent the upper and lower limits, respectively, of the regulated power of the distribution network.

3.2.2 Consistent power dispatching method

According to the principle of the equal cost increment rate, when the adjustment cost increment rate of all stations tends to be the same, the total control cost of the station group can be minimized, and the optimal distribution of the station area control power can be achieved.

According to the equal micro-increase rate of cost, when the micro-increase rate of dispatching cost in all zones tends to be the same, the total control cost of the transformer supply zone cluster can be minimized, and the optimal distribution of the transformer supply zones cluster dispatch power can be achieved. Based on the abovementioned analysis, this article selects the micro-increase rate of cost of each transformer supply zone as the consistency variable, and uses the consistency algorithm to continuously update the consistency variable and update the dispatching power of the transformer supply zone at the same time. When the consistency variables of each transformer supply zone tend to be consistent, the optimal distribution of dispatching power in each transformer supply zone will be realized.

$$\lambda_i = \frac{\partial C_i}{\partial P_i} \quad i = 1, 2, \dots, n \tag{16}$$

It can be obtained from Eq. 17:

$$\lambda_i = 2a_i P_i + b_i \tag{17}$$

The slight increase rate of control cost of station i at $k + 1$ is expressed as

$$\lambda_i(k+1) = \begin{cases} \sum_{j=1}^n d_{ij}(k)\lambda_j(k) + \mu\Delta P_d & \Delta P > 0, \text{ Leader} \\ \sum_{j=1}^n d_{ij}(k)\lambda_j(k) - \mu\Delta P_d & \Delta P < 0, \text{ Leader} \\ \sum_{j=1}^n d_{ij}(k)\lambda_j(k) & \text{Follower} \end{cases} \tag{18}$$

where μ is the power regulation coefficient, ΔP is the power deviation optimally allocated to the transformer supply zone cluster by the cloud, ΔP_d is the deviation between the control amount allocated by cloud optimization to the transformer supply zone and the actual control amount, $\lambda_j(k)$ is the micro-increase rate of cost of the j th station at the k time, and $\lambda_i(k+1)$ is the micro-increase rate of cost of the i th transformer at the time.

ΔP_d is represented as

$$\Delta P_d = \Delta P - \sum_{i=1}^n \Delta P_i. \tag{19}$$

According to the micro-increase rate of dispatching cost at $k + 1$ time in the i th transformer supply zone, the dispatching power at $k + 1$ time in the i th transformer supply zone is obtained.

$$P_i(k+1) = \begin{cases} P_{i,\min} & , \frac{\lambda_i(k+1) - b_i}{2a_i} \leq P_{i,\min} \\ \frac{\lambda_i(k+1) - b_i}{2a_i} & , P_{i,\min} \leq \frac{\lambda_i(k+1) - b_i}{2a_i} \leq P_{i,\max} \\ P_{i,\max} & , \frac{\lambda_i(k+1) - b_i}{2a_i} \geq P_{i,\max} \end{cases} \tag{20}$$

where $P_i(k+1)$ is the dispatched power of the i th transformer supply zone at $k + 1$ time, and $P_{i,\min}$ and $P_{i,\max}$ are the upper and lower limits of power dispatch in the i th transformer supply zone, respectively.

In the iterative calculation process of the consensus algorithm, ΔP_d is taken as the convergence condition. When $|\Delta P_d| < \varepsilon$, the consistency calculation reaches convergence, and ε is the convergence error.

Iteratively updating λ_i , respectively, until λ_i tends to the same value λ_i^* , the system reaches uniform convergence, and the optimal dispatching cost of each transformer supply zone under this convergence value is obtained. According to the consensus algorithm, the value of the consistency variable of each transformer supply zone is obtained; thus, the optimal value of the active power output of the transformer supply zone under the minimum control cost is

$$P_i = \frac{\lambda_i^* - b_i}{2a_i} \quad (21)$$

3.3 Proof of convergence of consistency algorithm

The proof of the convergence of the consensus algorithm with the micro-increase rate of cost as the consensus variable is shown below.

After repeated iterative calculation using the consistency algorithm, the micro-increase rate of cost of each transformer supply zone can be achieved:

$$\left\{ \begin{array}{l} \frac{\partial C_1(P_1^k)}{\partial P_1} = \frac{\partial C_2(P_2^k)}{\partial P_2} = L = \frac{\partial C_n(P_n^k)}{\partial P_n} \\ P_1^k + P_2^k + L + P_n^k = P_1^{k+1} + P_2^{k+1} + L + P_n^{k+1} \end{array} \right., \quad (22)$$

where k is the number of iterations, $C_i(P_i)$ is the control cost function of transformer supply zone i , and P_i is the control power of transformer supply zone i .

The transformer area dispatching cost function $C_i(P_i)$ is a univariate continuous differentiable convex function; its definition domain is $R = [P_i^{\min}, P_i^{\max}]$ and meets the characteristics of convex function in its definition domain:

$$C_i(P_i^{k+1}) \geq C_i(P_i^k) + \frac{\partial C_i(P_i^k)}{\partial P_i^k} (P_i^{k+1} - P_i^k). \quad (23)$$

A Lyapunov multivariate function about the dispatching power of each transformer supply zone is defined V ; its definition domain is the vector composed of the limit value of dispatch power in each transformer supply zone, and V can be expressed as

$$V(P_i^k) = V(P_1^k, P_2^k, P_3^k, L, P_n^k) = \sum_{i \in v} C_i(P_i^k), \quad (24)$$

where P_i^k represents the dispatching power calculated by the k th iteration of transformer supply zone i .

Assuming that in the k th iteration calculation all transformer supply zones reach the state shown in Eq. 25, the following relationship exists:

$$\begin{aligned} V(P_i^{k+1}) - V(P_i^k) &= \sum_{i \in v} C_i(P_i^{k+1}) - \sum_{i \in v} C_i(P_i^k) \leq \\ &[C_1(P_1^{k+1}) + C_2(P_2^{k+1}) + L C_n(P_n^{k+1})] - \\ &\left[C_1(P_1^k) + \frac{\partial C_1(P_1^k)}{\partial P_1^k} (P_1^k - P_1^{k+1}) \right] - L - \\ &\left[C_n(P_n^k) + \frac{\partial C_n(P_n^k)}{\partial P_n^k} (P_n^k - P_n^{k+1}) \right] = 0 \end{aligned} \quad (25)$$

That is, $V(P_i^{k+1}) - V(P_i^k) \rightarrow 0$; therefore, the cost incremental rate consistency algorithm is convergent.

The solution process of real-time dispatch of transformer supply zone cluster

Flowchart of the power dispatch strategy in edge-side cooperative transformer supply zone based on the consensus algorithm is shown in Figure 2. The specific steps are as follows:

Step 1: The “Leader” transformer supply zone obtains the power deviation allocated after cloud optimization calculation and carries out information interaction with adjacent zones to calculate the consistent state variable value of each transformer supply zone;

Step 2: Obtain Laplace matrix L according to the topology of the transformer supply zone cluster, and then obtain state transition matrix D ;

Step 3: Update the consistency variable of each transformer supply zone cluster according to Eq. 18 and obtain the dispatched power of the transformer supply zone in this state according to Eq. 20;

Step 4: Judge whether the updated dispatch power value meets the constraint conditions. If not, update the network topology again, find the state transition matrix again, and repeat Step 3.

Step 5: Determine whether $|\Delta P_d| < \varepsilon$ is satisfied; if yes, the dispatched power value of the transformer supply zone will be output; if not, the power deviation of the transformer supply zone cluster will be recalculated.

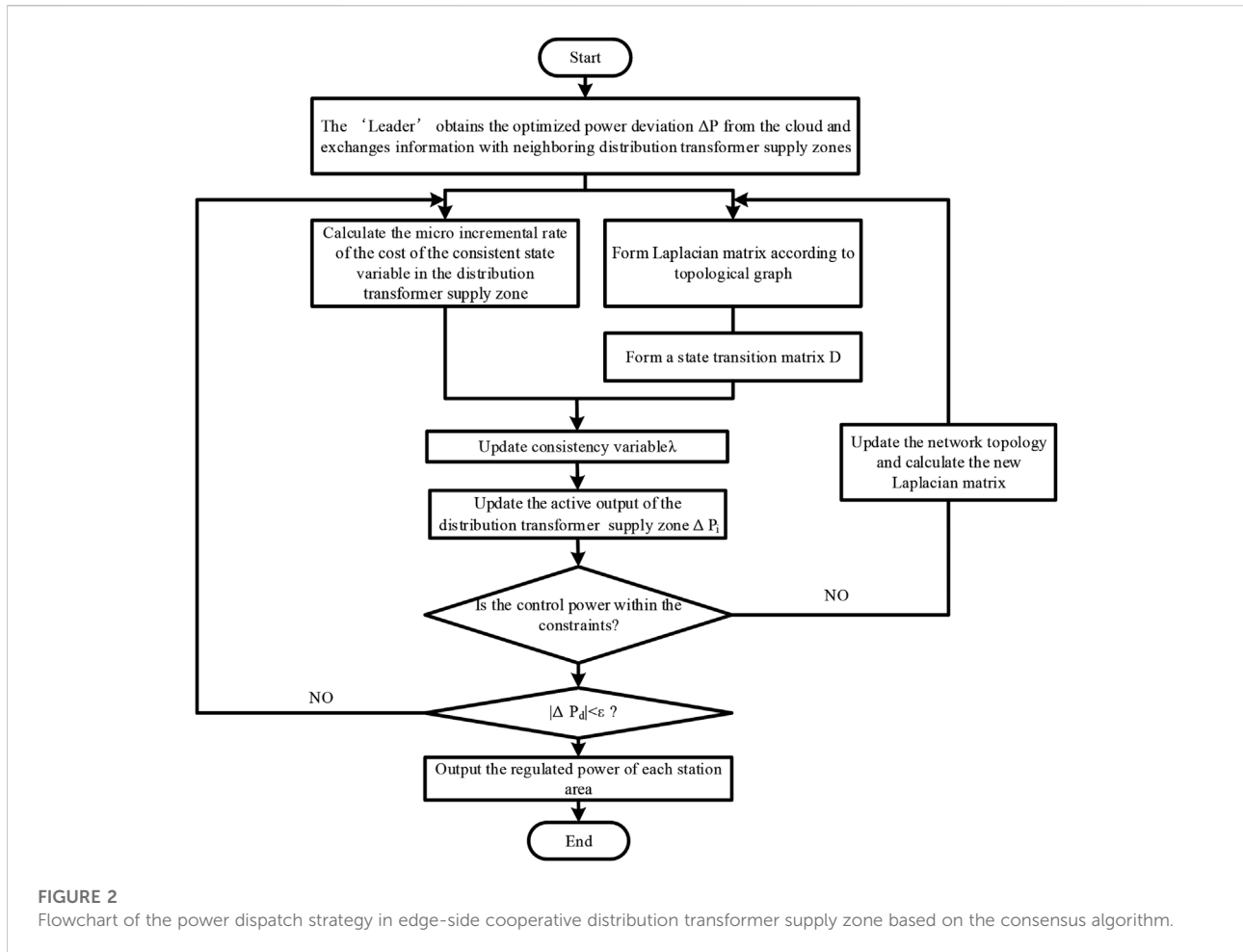
4 Example analysis

4.1 Illustration of the calculation

To verify the effectiveness of the strategy proposed in this article, a typical active distribution network demonstration project in a city is used as an example for calculation and analysis. The network topology of the transformer supply zone cluster is shown in Figure 3. The transformer supply zone cluster consists of six zones, with zone 1 as the “Leader” and zone 2 to zone 6 as the “Followers.” The voltage level of each transformer zone is 10 kV/380 V and the frequency is 50 Hz in the model of the transformer supply zone cluster built in this article.

The categories of constituent units contained in each transformer supply zone cluster are shown in Table 1; zone 1 contains distributed generation resources, energy storage devices, and flexible loads; zone 2 contains distributed generation resources and flexible loads; zone 3 contains energy storage devices and flexible loads; zone 4 contains only distributed generation resources; zone 5 contains only energy storage devices; zone 6 contains only flexible loads.

We have to synthesize the control resources in the transformer supply zone, and perform linear convex combination to obtain the total cost parameters of the transformer supply zone. The parameters for each transformer



supply zone are set as shown in Table 2, which contains the cost coefficient for each transformer supply zone and the upper and lower active output limits.

4.2 Analysis of example results

The real-time power dispatch simulation analysis of the transformer supply zone cluster is carried out with a dispatch period of 15 min, and the total duration is 24 h; then a total of 96 dispatch plans are included. The power dispatching coefficient of the consistency algorithm $\mu = 0.02$, the convergence error $\varepsilon = 0.7$, the deviation of the power allocated by the cloud optimization for this transformer supply zone cluster is $\Delta P = -450$ kW, and the weighting coefficient matrix $Z = [1]$.

The whole-day total power deviation curve is obtained from the predicted value and the actual value of the previous power regulation, as shown in Figure 4, which shows that the power imbalance mainly occurs between 11:00–22:00. The maximum positive power deviation occurs at 14:00, and the power deviation value is 630 kW. The main reason is that due to the large

photovoltaic output at noon, there is excess electric energy. At this time, the generated power shall be reduced, energy storage should be charged, and the load should be increased; the maximum negative power deviation occurs at 18:00 with a power deviation value of -450 kW, which is mainly due to the power shortage caused by the peak load in the evening; at this time, we should increase the power generation, discharge energy, and cut the load.

Based on the analysis of historical data in the region, the controllable active power prediction value of the transformer supply zone on a long-term scale of a typical day in the zone obtained from the distribution network management center is shown in Figure 5.

Applying a cloud-edge collaborative real-time control strategy based on the edge consistency algorithm of the intelligent transformer supply zone cluster to this power transformer supply zones, the simulation results can be obtained as shown in Figures 6, 7.

It can be seen from Figure 6 that the initial value of the micro-increase rate of cost of each transformer zone is different. The value of the micro-increase rate of cost of zone 3 is the highest,

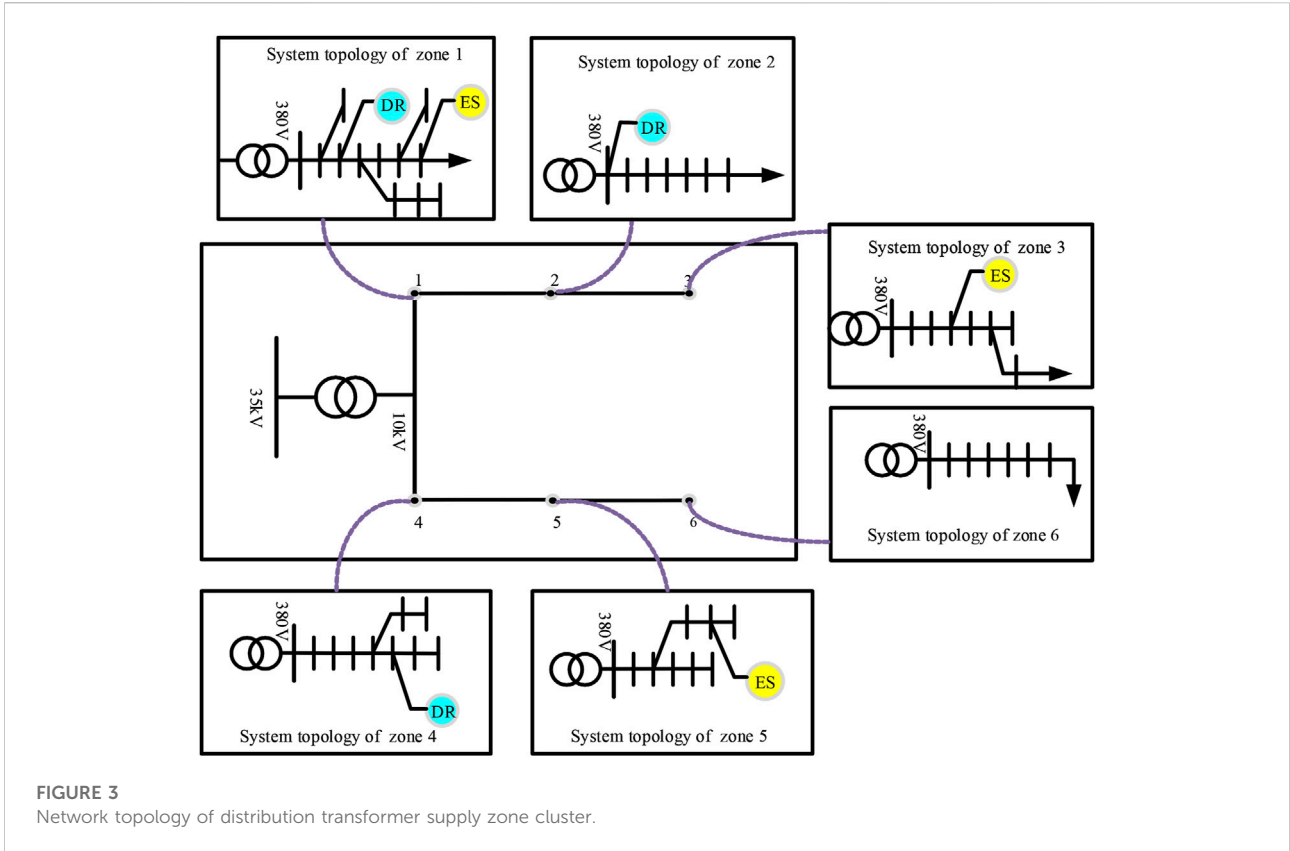


TABLE 1 Components inside the transformer supply zone.

Zone number	Distributed generation resource	Energy storage device	Flexible load
1	√	√	√
2	√	×	√
3	×	√	√
4	√	×	×
5	×	√	×
6	×	×	√

TABLE 2 Cost parameters and generation constraints.

Zone number	a_i	b_i	c_i	$P_{i,min}/kW$	$P_{i,max}/kW$
1	3.2	2.1	0.0085	10	300
2	2.8	1.8	0.0055	10	250
3	2.3	2.0	0	0	200
4	2.5	2.3	0.0073	20	150
5	2.2	0	0	0	80
6	1.8	2.5	0	10	80

the value of the micro-increase rate of cost of zone 6 is the lowest, and its growth rate is the fastest. After the consensus algorithm of the iterative update calculation, the micro-increase rate of cost for zone 1 and zone 2 gradually increases after the first decrease, and the cost incremental rate for zone 3 to zone 6 gradually increases, and when the number of iterations reaches 40, the value of cost incremental rate in all zones tends to be the same, which is 330.57 ¥/kWh.

As can be seen from Figure 7, after the iterative update calculation of the consensus algorithm, in the initial stage, the

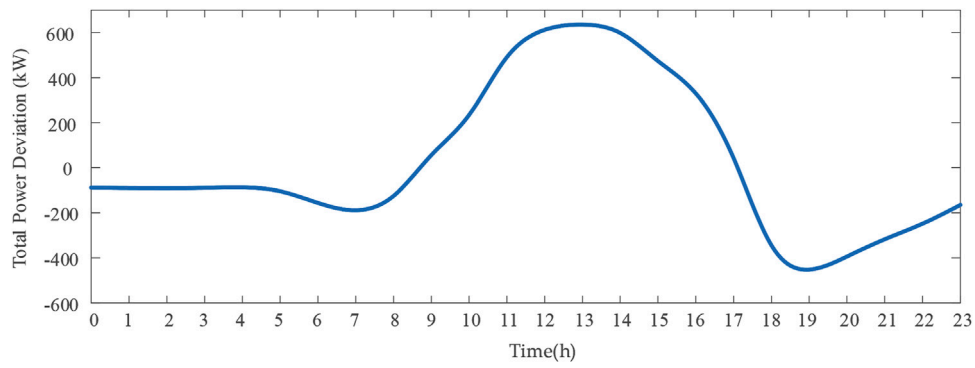


FIGURE 4
All-day power deviation curve.

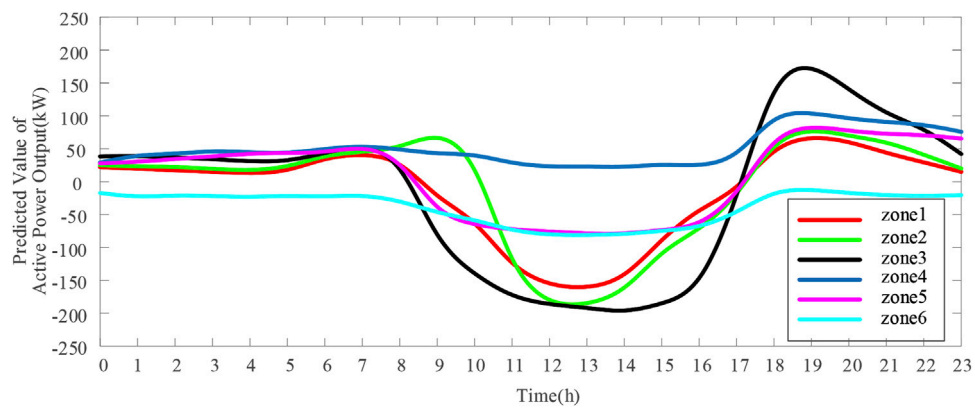


FIGURE 5
Adjustable active power prediction value of each distribution transformer supply zone on a long timescale.

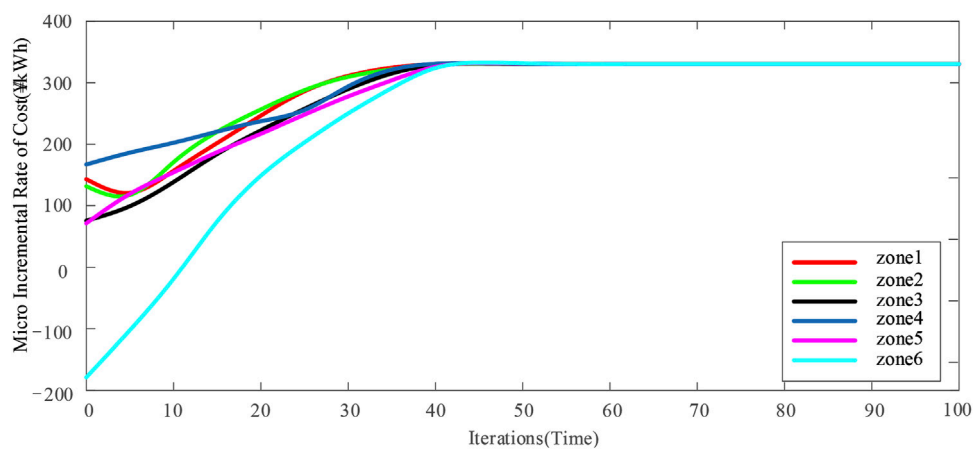
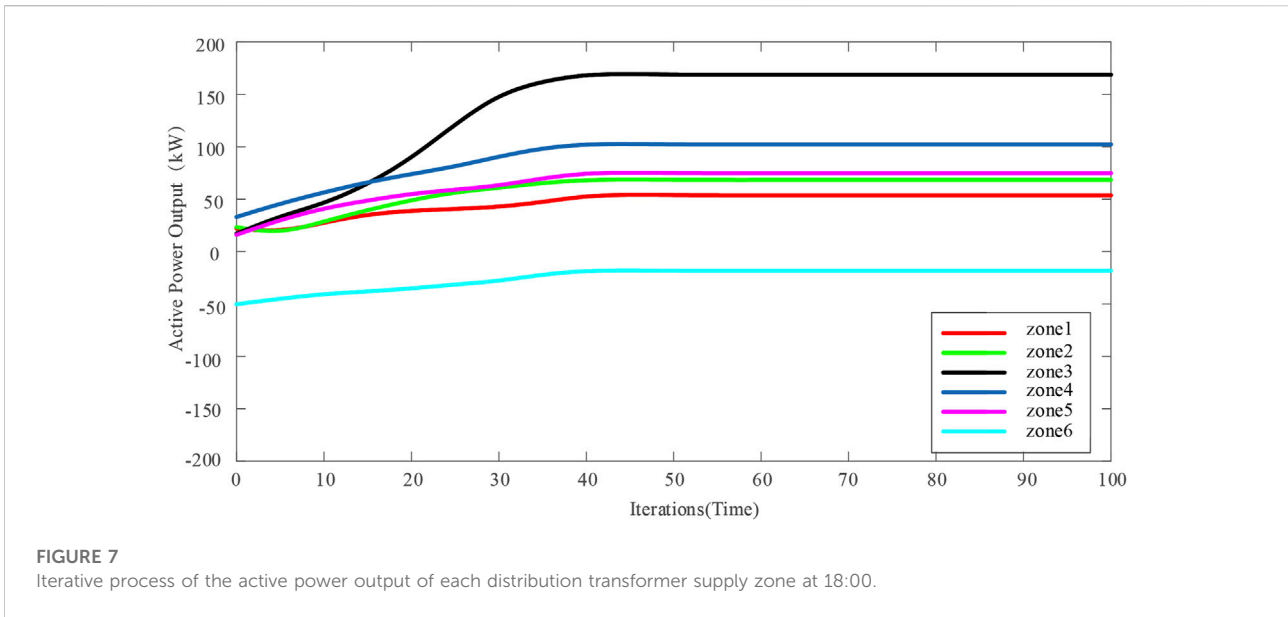


FIGURE 6
Consistent convergence process of the micro-increase rate of cost at 18:00.



active power output of zone 1 and zone 2 first decreases and then gradually increases; the active power output of zone3 to zone 6 gradually increases. At the 40th iteration, the active power output of all zones stabilizes. The active power output from transformer supply zone 1 to transformer supply zone 6 tends to be stable, respectively: $P_1 = 53.75$ kW, $P_2 = 68.45$ kW, $P_3 = 168.85$ kW, $P_4 = 102.31$ kW, $P_5 = 74.89$ kW, and $P_6 = -18.25$ kW, which shows that the active power outputs values of all transformer supply zones are within the operational constraints.

4.3 Comparative analysis of different control methods

In order to verify the effectiveness and economy of the dispatching strategy proposed in this article, the following three control methods are used for the transformer supply zone cluster for comparative analysis.

Mode 1: No information interaction between transformer supply zones; each transformer supply zone operates independently.

Mode 2: Information interaction between transformer supply zones, with each transformer supply zone giving priority to autonomy and taking the initiative to exchange power with the cluster to maintain the cluster's power balance when its own power command differs from the power command of the transformer supply zone cluster.

Mode 3: Information interaction between each transformer supply zone is controlled according to the cloud-edge collaborative fast control strategy based on the intelligent transformer supply zone edge consensus algorithm proposed in this article.

TABLE 3 Dispatching costs of the three control methods.

Zone number	Cost of dispatch/million		
	Mode1	Mode 2	Mode 3
1	1.79	1.19	0.91
2	2.01	1.88	1.65
3	7.24	6.89	6.28
4	3.29	2.76	2.53
5	1.98	1.56	1.20
6	0.26	0.13	0.064
Total	16.57	14.41	12.63

Simulation and analysis of these three control methods were carried out separately, and the total dispatching cost of the transformer supply zone cluster and the dispatching cost of each transformer zone are shown in Table 3.

Table 3 shows that with Mode 3 control, the dispatching cost of each transformer zone is less than those of Mode 1 and Mode 2 control. The total dispatching cost is “Mode 1 > Mode 2 > Mode 3,” and the total dispatching cost of Mode 3 is 23.8% lower than that of Mode 1 and 12.35% lower than that of Mode 2, indicating that the proposed strategy can achieve the optimal economic dispatch of the active output.

In Mode 1, each zone operates independently, and when power deviation occurs, it can only rely on its own internal regulation to make power balance, which will result in more abandoned generation and load shedding; in Mode 2, each transformer zone gives priority to self-governance, and when

TABLE 4 Transmission characteristics of information branch.

Zone number	Cloud computing latency/ms	Edge computing latency/ms
1	158.84	95.23
2	158.84	87.26
3	158.84	85.49
4	158.84	69.25
5	158.84	67.58
6	158.84	65.69

TABLE 5 Comparison of model effects of different control methods.

Different control method	Model size	Transmission delay/ms
Centralized control	22×35	87.56
Distributed control	25×36	88.75
Centralized-distributed control	25×42	182.55

self-governance still cannot make system power balance, then it relies on information interaction with neighboring zones for dispatching; Mode 3 adopts the cloud-edge coordination real-time control strategy based on the intelligent transformer supply zone cluster edge consensus algorithm proposed in this study to control, and for each transformer zone, the active power is allocated based on the micro-increase rate of cost, which can achieve real-time and economic power dispatch.

4.4 Experimental results

In this experiment, RT-Lab is used to physically model the distribution network transformer supply zone cluster in the example, and the semi-physical simulation of the real-time dispatching of the distribution transformer supply zone cluster with cloud-edge coordination is carried out. According to the distribution network structure in the calculation example, a cloud center computing data pool and 6 edge computing groups quantitatively analyze the transmission delay advantage of the centralized-distributed control method in the scheduling process, so as to illustrate the establishment and use of the model in this article, and to verify the rationality and versatility of the model. Table 4 shows the computing delays on the cloud and edge sides. Table 5 shows the comparison of model effects of different control methods.

It can be seen from Table 5 that the computing speed of the centralized-distributed cooperative control method based on cloud-side collaboration is not much different from that of the distributed control method. Compared with the traditional centralized control method, it has a lower communication time. The calculation speed is significantly faster than that of the centralized control method.

5 Conclusion

In order to correct the long-timescale prediction bias in the distribution network, this article proposes a fast cloud-side coordinated dispatching strategy based on the edge consistency algorithm of intelligent transformer areas cluster, in which the cloud makes the first global optimal allocation and the transformer area makes the second coordinated optimal allocation on the edge side. Based on the consensus algorithm, each area uses the micro-increase rate of dispatching cost as a consistent variable and performs consistent iterations to achieve the optimal distribution of the dispatching power in the transformer area. The main advantages of this article are as follows:

- 1) The burden of the cloud is reduced. The cloud is responsible for optimizing the calculation of the cluster power deviation information uploaded by the leaders of each cluster and the dispatching cost, which reduces the calculation amount. The iterative calculation is distributed in each edge transformer area, which reduces the communication delay and ensures the rapid power dispatch of the transformer areas cluster.
- 2) Only the adjacent distribution station areas in the cluster exchange information, which reduces the communication burden of the communication network and improves the reliability of communication.
- 3) The cost micro-increase rate is selected as the consistency variable. When the cost micro-increase rate tends to be consistent, it can ensure that the power distribution transformer supply zone cluster can perform power regulation at a lower cost.

There are still some deficiencies in the work done in this article. This article only considers the cooperative power

interaction between the distribution stations and does not consider the information interaction between groups. This problem will continue to be studied in the next work.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

JIL and JUL contributed to framework establishment and manuscript writing; PL and HF contributed to provide theoretical support; SZ and GY contributed to model solving.

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References

- Bian, X., Sun, M., Zhao, J., Lin, S., Zhou, B., and Li, D. (2021). Distributed coordinative optimal dispatch and control of source and load based on consensus algorithm. *Proc. CSEE* 41 (04), 1334–1347+1540. doi:10.13334/j.0258-8013.pcsee.200416
- Fang, X., Hodge, B.-M., Jiang, H., and Zhang, Y. (2019). Decentralized wind uncertainty management: Alternating direction method of multipliers based distributionally-robust chance constrained optimal power flow. *Appl. Energy* 239, 938–947. doi:10.1016/j.apenergy.2019.01.259
- Gong, G., Luo, A., Chen, Z., Luan, J., An, X., and Wang, X. (2018). Cyber physical system of active distribution network based on edge computing. *Power Syst. Technol.* 42 (10), 3128–3135. doi:10.13335/j.1000-3673.pst.2018.0119
- Huang, C., Wang, C., Zhang, M., Xie, N., and Wang, Y. (2021). A transactive retail market mechanism for active distribution network integrated with large-scale distributed energy resources. *IEEE Trans. Smart Grid* 12 (5), 4225–4237. doi:10.1109/TSG.2021.3087720
- Huang, C., Zhang, M., Wang, C., Xie, N., and Yuan, Z. (2022). An interactive two-stage retail electricity market for microgrids with peer-to-peer flexibility trading. *Appl. Energy* 315, 119085. doi:10.1016/j.apenergy.2022.119085
- Huang, W., Li, N., Tian, Y., and Zhang, Z. (2017). Research on day-ahead and real-time schedule strategy for ADN. *Mod. Electr.* 34 (03), 52–59. doi:10.19725/j.cnki.1007-2322.2017.03.008
- Li, X., Han, X., and Yang, M. (2022). Day-ahead optimal dispatch strategy for active distribution network based on improved deep reinforcement learning. *IEEE Access* 10, 9357–9370. doi:10.1109/ACCESS.2022.3141824
- Li, Y., Dong, P., Liu, M., and Lin, Y. (2018). Distributed coordinated control of DC microgrid based on finite-time consensus algorithm. *Automation Electr. Power Syst.* 42 (16), 96–103. doi:10.7500/AEPS20170907003
- Li, Z., Song, K., Ding, M., Ni, R., Wang, J., Qu, L., et al. (2021). Comparative analysis of three data mining techniques in diagnosis of lung cancer. *Eur. J. Cancer Prev.* 40 (06), 15–20. doi:10.1097/CEJ.0000000000000598
- Liu, H., Li, Z., Cheng, Q., Yao, T., Yang, X., and Hu, Y. (2020). Construction of the evaluation index system of the regional integrated energy system compatible with the hierarchical structure of the energy Internet." in. *IEEE 4th Conference on Energy Internet and Energy System Integration (EI2)*, Wuhan, China, October 30–November 1, 2020, 342–348. doi:10.1109/EI250167.2020.9346665
- Liu, T., Han, D., Wang, Y., and Dong, X. (2021). Strategies of market game behavior of virtual power plants based on Q-learning with augmented Lagrange

Conflict of interest

Authors PL and JL were employed by the company Electric Power Research Institute of State Grid Hebei Electric Power Co, Ltd. Author HF was employed by the company State Grid Hebei Electric Power Co, Ltd. Author GY was employed by the company Handan Power Supply Branch of State Grid Hebei Electric Power Co, Ltd.

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

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function. *Power Syst. Technol.* 45 (10), 4000–4008. doi:10.13335/j.1000-3673.pst.2020.1932

Lv, P., Zhao, J., Su, D., and Chen, G. (2019). Consensus-based distributed dynamic economic dispatching for islanded microgrids. *Automation Electr. Power Syst.* 43 (05), 22–29. doi:10.7500/AEPS20180214001

Peng, C., Liu, Y., Zhou, H., Liu, F., Zhang, K., and Hu, R. (2022). Power ecosystem operation based on cloud-edge collaboration: Theoretical framework. *Proc. CSEE* 42 (09), 3204–3214. doi:10.13334/j.0258-8013.pcsee.202422

Pu, T., Liu, W., Chen, N., Wang, X., and Dong, L. (2017). Distributed optimal dispatching of active distribution network based on consensus algorithm. *Proc. CSEE* 37 (06), 1579–1590. doi:10.13334/j.0258-8013.pcsee.160937

Rahbari-Asr, N., Ojha, U., Zhang, Z., and Chow, M. (2014). Incremental welfare consensus algorithm for cooperative distributed generation/demand response in Smart grid. *IEEE Trans. Smart Grid* 5 (6), 2836–2845. doi:10.1109/TSG.2014.2346511

Ren, J., Yu, G., He, Y., and Li, G. Y. (2019). Collaborative cloud and edge computing for latency minimization. *IEEE Trans. Veh. Technol.* 68 (5), 5031–5044. doi:10.1109/TVT.2019.2904244

Si, Y., Tan, Y., Wang, F., Kang, W., and Liu, S. (2020). Cloud-edge collaborative structure model for power Internet of Things. *Proc. CSEE* 40 (24), 7973–7979+8234. doi:10.13334/j.0258-8013.pcsee.191532

Tofighi-Milani, M., Fattaheian-Dehkordi, S., Fotuhi-Firuzabad, M., and Lehtonen, M. (2022). Decentralized active power management in multi-agent distribution systems considering congestion issue. *IEEE Trans. Smart Grid* 13, 3582–3593. doi:10.1109/TSG.2022.3172757

Yang, Q., Huang, Y., Shi, M., Zhou, J., Chen, X., and Wen, J. (2020). Consensus based distributed control for multiple PV-battery storage units in DC microgrid. *Proc. CSEE* 40 (12), 3919–3928. doi:10.13334/j.0258-8013.pcsee.190444

Yang, X., Xu, C., Zhang, Y., Yao, W., Wen, J., and Cheng, S. (2021). Real-time coordinated scheduling for ADNs with soft open points and charging stations. *IEEE Trans. Power Syst.* 36 (6), 5486–5499. doi:10.1109/TPWRS.2021.3070036

Zeraati, M., Hamedani Golshan, M. E., and Guerrero, J. M. (2019). A consensus-based cooperative control of PEV battery and PV active power curtailment for voltage regulation in distribution networks. *IEEE Trans. Smart Grid* 10 (1), 670–680. doi:10.1109/TSG.2017.2749623

Zhang, B., Wang, J., Liang, D., and Han, X. (2020). Optimization control strategy of distributed energy storage in autonomous microgrid cluster on consensus algorithm. *Power Syst. Technol.* 44 (05), 1705–1713. doi:10.13335/j.1000-3673.pst.2019.1968

Zhang, W., and Wang, D. (2022). Real-time demand response scheduling strategy for electric vehicles based on cloud edge collaboration. *Power Syst. Technol.* 46 (04), 1447–1458. doi:10.13335/j.1000-3673.pst.2021.0581

Zhang, Z., and Chow, M.-Y. (2012). Convergence analysis of the incremental cost consensus algorithm under different communication network topologies in a Smart grid. *IEEE Trans. Power Syst.* 27 (4), 1761–1768. doi:10.1109/TPWRS.2012.2188912

Zhang, Z., and Chow, M.-Y. (2011). “The leader election criterion for decentralized economic dispatch using incremental cost consensus algorithm,”

in *IECON 2011-37th annual conference of the IEEE industrial electronics society* (Raleigh: IEEE), 2730–2735. doi:10.1109/IECON.2011.6119743

Zhao, Y., Wu, Z., Qian, Z., Gu, W., Li, D., and Liu, Y. (2019). Distributed optimal dispatch of active distribution network considering source-load temporal and spatial correlations. *Automation Electr. Power Syst.* 43 (19), 68–76. doi:10.7500/AEPS20190423003

Zheng, J., Wang, J., Sun, Z., and Wu, F. (2022). Improved droop control of optical storage DC microgrid based on consensus algorithm. *Proc. CSUEPSA* 34 (04), 116–125. doi:10.19635/j.cnki.csu-epsa.000859

Zhou, Z., Wang, Z., Liao, H., Wang, Y., and Zhang, H. (2022). 5G cloud-edge-end collaboration framework and resource scheduling method in power Internet of Things. *Power Syst. Technol.* 46 (05), 1641–1651. doi:10.13335/j.1000-3673.pst.2021.2427