A Distributed Optimal Scheduling Method Based on Microgrid Cluster of Plug and Play

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Abstract. This paper proposes a distributed optimization method to solve the problems of centralized optimization and centralized management of a microgrid. Also, the distributed optimization solution method upgrade to a process of distributed iterative solution and optimization, which can solve the distributed optimization problem of a large microgrid cluster. According to iterative calculation, accord the augmented Lagrange function supports the centralized optimization problem divided into corresponding subproblems, and the penalty factors of interconnected variables considered to adjust the consumption of local resources, to make microgrid cluster (MGC) more flexible. In particular, the framework of multi-verse consistency and model predictive control (MPC) can help the global optimization reach the optimal quickly. In this paper, the simulation is solved by Gurobi commercial solver in MATLAB. The results show that the proposed method needs only a few iterations to achieve global optimization, and the effectiveness of plug and play proved.

1. Introduction
The microgrid is an integral part of the smart grid, it effectively solves the problem of a large number of distributed generations into the grid, and allow full play to the economy, environmental protection and flexibility of distributed generation. It also provides high-quality power for power users and meets the requirements of safe and reliable power supply for users [1]. It relies on effective energy management to integrate all kinds of distributed generation, load, and energy storage equipment. At the same time, adjacent microgrids in different regions can be interconnected to form MGC. In particular, MGC includes at least two microgrid units, which are related to each other; they have certain similarity or complementarity.

Moreover, for any microgrid unit in the cluster, there is at least another microgrid unit interconnected with it. MGC can exchange energy with the power grid; it has two operation states: on-grid and off-grid [2]. When the MGC is running in the on-grid state, the island operation and grid-connection operation of the sub microgrid respectively pull out and insert from the MGC, that is, plug and play of the sub microgrid, which has a particular significance in the engineering application.

At present, there are relatively little academic researches on MGC. The literature [3] based on the different objectives pursued by different stakeholders in microgrid scheduling, the Pareto optimal solution set for multi-objective optimal scheduling is proposed from three aspects of the economy, technology, and environment assessment strategy. The literature [4] proposed an optimal dispatch model of the microgrid well-coordinated with the economic development and environmental protection, the multi-objective particle swarm optimization (MOPSO) is used to solve the problem of optimal dispatch
in the microgrid. However, in reality, the MGC problem is a large-scale optimization problem. In the centralized dispatching centre, unified processing will face difficulties in solving, vulnerable to central system failures, and other communication failures. At the same time, due to the different operation subjects between the sub microgrids, with more and more attention to privacy in the era, centralized coordination optimization will become more and more difficult. Distributed optimization will help to solve these problems. Such as, the literature [5] to preserve information privacy and achieve scheduling independence of microgrids, the problem of multi-area economic and environmental dispatch is computed with a distributed algorithm framework.

Moreover, chance-constrained programming (CCP) is added to address the uncertainty factors of renewable energy, cooling, heating, and electrical loads. In the literature [6], consistency algorithm, and primal-dual sub gradient algorithm are used to solve the distributed optimization problem of the smart grid. However, a wholly distributed method requires too many iterations. The literature [7] designed a plug and played hierarchical framework is designed for the flexible topology of MGC. The upper layer is responsible for the distributed solution of the expected exchange power between the microgrid and the large grid, and the lower layer is responsible for the centralized solution of the output of each distributed energy. However, the number of iterations required by the upper layer has reached tens of thousands, and the convergence is not good.

Given the above problems, this paper proposes a distributed optimization method based on multi inverse consistency and model predictive control (MPC) [8] with Lagrange multipliers as iterative variables and consistency variables. Specifically, the method allows the centralized optimization of sub microgrids to deal with discrete variables. The distributed iteration between sub microgrids eliminates the need for centralized dispatching centres in MGC. The Lagrange multipliers corresponding to the interaction variables between interconnected microgrids are equal in value and opposite in sign, and there are several multipliers with different values in MGC, so this paper calls it multi inverse consistency.

2. Description and topology of microgrids clusters

Microgrid refers to a small power generation and distribution system (including energy storage devices when necessary) composed of distributed generation, power load, distribution facilities, monitoring and protection methods. The microgrid divided into grid-connected microgrid and independent microgrid, which can realise self-control and autonomous management. The grid-connected microgrid can not only connect with the external grid, but also can operate independently from the grid; the independent microgrid not connected with the external system, and the electric power and energy balance are self-balanced.

Microgrid cluster is a large-scale integrated system, which is closely connected and coordinated to control each other. Microgrid cluster should have the following characteristics:

- It can be combined with the distribution network or island operation to give full play to the process. For the Regional Cluster Advantage and complementary space-time advantage of new energy, it can also support the safe operation of a distribution network.
- The dynamic characteristics of the microgrid can reflect in the cluster. For example, when it is necessary to support the operation of a microgrid fully, the performance of the microgrid cluster is the characteristic of this microgrid, and other microgrid modules in the microgrid cluster have no economic factors should consider.
- Any microgrid in the cluster has at least one other microgrid connected to it so that it can work in groups.
- Each microgrid cluster should have its resource control system to integrate, optimise and recombine its internal resources.
- The cluster has its economical operation strategy. When it wants to reflect cluster characteristics in a large area, it can directly set the group reaction has its features.
- The cluster needs to have its security system to ensure the safe and stable operation of the group.
The MGC studied in this paper has a high penetration rate of renewable energy, accounting for about 50%, and contains six sub microgrids. Each sub microgrid can communicate with each other through optical fibre, wireless, or power carrier, which are widely used in the distribution network. Therefore, the existing communication lines can be used nearby between each sub microgrid, and there is no need to relay the communication lines.

As shown in Figure 1, each sub microgrid is equipped with an agent, which is responsible for collecting the current energy storage state, running the local optimization program, exchanging the iteration value of the current interaction variable with the neighbor agent, and issuing the optimal control command. Among them, the interactive iteration process between each sub microgrid and the local optimization program run alternately. That is, given the initial value of interactive variables, the sub microgrid takes the minimum local benefit function as the optimization objective to calculate the interaction variables under the current iteration. Then, according to the multi inverse consistency iterative formula, the Lagrange multiplier used in the next iteration is calculated, and the value of the Lagrange multiplier is repeated until the value of the Lagrange multiplier is no longer changed. It is worth noting that each agent only exchanges information with neighbor agents in order to completely eliminate the necessity of a centralized dispatching center.

Also, the whole microgrid cluster interacts with the grid through M6 as the node. As for sub microgrid, for example, M1 has interconnection power between M1 and M2, M5, M6. The interconnection power includes the energy storage charging and discharging power, wind turbine generating power and load power. The red dotted line in the figure represents the communication between each agent through optical fiber or wireless. In contrast, the black dotted line represents the communication between each sub microgrid and the corresponding agent through optical fiber or wireless. The two communication channels are independent and do not interfere with each other.

Figure 1. Topology of microgrid clusters
3. Distributed optimization framework based on multi anti consistency and MPC

3.1. Augmented lagrange formulation

Lagrange function is to solve a class of simple function optimization problems, while the Augmented Lagrange formulation (ALF) is to solve a class of nonsmoothed equality constrained optimization problems with a specific structure (mainly for convex programming). In this paper, considering that the microgrid cluster optimization problem is a nonlinear problem and the problem is not smooth, this paper introduces the ALF. It adds Lagrange term and penalty term to form a dual problem which can solve the maximum and minimum difficulty.

Through the ALF, which can be divided into corresponding subproblems to solve the centralized optimization problem, is described in detail in reference [9]. In the augmented Lagrange function, the local benefit function of each agent includes not only the local cost function but also the interconnection related to interconnection constraints function (1).

\[ F_{\text{inter},ij}(k) = F_{\text{inter},ji}(k) \quad i = 1, 2, \cdots, n_N; j \in N_i \]  

In this formula, \( N_i \) is the neighbor set of subs microgrid \( M_i \); \( n_N \) is the number of subs microgrid, the number of nets is 6 in this paper. For example, above the Figure 1, \( M_1 \) has three neighborhoods which are \( M_2, M_5 \) and \( M_6 \), at present, \( N_i \) is \( N_i = 3 \), and Figure 1 has six sub microgrid, \( n_N = 6 \).

In order to decompose the centralized optimization problem of MGC into local subproblems, interconnection constraints are written into the augmented objective function (1). The expression as follow:

\[ \varphi_{\text{aug}}(X(k), U(k), Y(k), T(k), \Lambda(k)) = \varphi_{\text{local},i}(x_i(k), u_i(k), y_i(k)) + \sum_{i=1}^{n_N} \sum_{j \in N_i} \lambda_{\text{inter},ij}(k)(F_{\text{inter},ij}(k) - F_{\text{inter},ji}(k)) \]  

Above this formula, \( \varphi_{\text{aug}}(X(k), U(k), Y(k), T(k), \Lambda(k)) \) is the objective function of augmented Lagrange formulation, \( X, U, Y, T \) and \( \Lambda \) mean there are five subproblems defined on five variables. \( X(k) = [x_1(k) \ x_2(k) \ \cdots \ x_{n_N}(k)]^T \) is Lagrange term of variable \( X \), the function of \( U, Y, T, \Lambda, \Lambda_i, F_i \) are same as \( X(k) \). \( \varphi_{\text{local},i}(x_i(k), u_i(k), y_i(k)) \) is the local cost function of the sub microgrid \( M_i \), \( \rho \) is the penalty factor which is used to convex the objective function, \( \lambda_{\text{inter},ij} \) is the Lagrange multiplier of the interconnection correlation between the sub microgrid \( M_i \) and the neighboring sub microgrid \( M_j \) (\( j \in N_i \)), \( F_{\text{inter},ij} \) is the Lagrange multiplier of interconnection variable between \( M_i \) and \( M_j \) of the sub microgrid. \( n_N \) means which one sub microgrid, in this paper, \( n_N = 6 \) because there is one microgrid contains six sub microgrids.

According to the dual theory [10], equation (2) can be divided into several subproblems. Each subproblem (local benefit function) can be assigned to the corresponding local agent for execution. For the optimal allocation principle, please refer to reference [11], it proposed an auxiliary problem principle (APP). App method is to linearize the quadratic term of Lagrange function at the current iteration and add a detachable quadratic term. The primary purpose of the added quadratic term is to make the extended Lagrange function linearized by some terms become strictly convex function (Intuitively, the
convex function is the image protruding upward. The reason to distinguish the convex function problem is that the optimal local solution in the convex optimization problem is also the optimal global solution. That is, the local extreme value of convex function must be the extreme global value. If the function is strictly convex, such absolute value must be the minimum value, and the minimum value point is unique, which corresponds to the minimum cost of solving microgrid in this paper.

\[
\varphi_{\text{Agent},i} = \min_{x_i(k), u_i(k), y_i(k)} (\varphi_{\text{local},i}(x_i(k), u_i(k), y_i(k)) + \varphi_{\text{inter},i}(F_i(k)))
\]  

(4)

Above the equation, \(\varphi_{\text{Agent},i}\) is the local benefit function assigned to agent \(i\) (corresponding to sub micro grid \(M_i\)), \(\varphi_{\text{inter},i}(F_i(k))\) is the interconnection function of sub micro grid \(M_i\).

Each subproblem formula (4) executed in an iterative and parallel way. Individually, in each iteration, every agent solves the corresponding subproblem in a centralized and identical way. Then exchanges the solution results (interconnected variables, Lagrange multipliers) under the current iteration steps with the neighboring agents to update the Lagrange multipliers used in the next iteration son.

3.2. Local benefit function based on MPC

Formula (4) gives a pure expression of the local benefit function, which divided into local cost function and interconnection function; the more details shown in formula (5) and formula (6). In particular, this paper considers the penalty factors of interconnected variables to adjust the consumption of local resources.

\[
\sum_{i=1}^{N} \nu_i \left[ \begin{bmatrix} x_i^{(p)}(k + l) \\ u_i^{(p)}(k + l) \\ w_i^{(p)}(k + l) \\ y_i^{(p)}(k + l) \end{bmatrix} - \begin{bmatrix} x_i^{(p)}(k + l) \\ u_i^{(p)}(k + l) \\ w_i^{(p)}(k + l) \\ y_i^{(p)}(k + l) \end{bmatrix} + f_i^T \right] + \varphi_{\text{inter},i}(F_i^{(p)}(k)) = \sum_{i=1}^{N} \sum_{j \in N_i} \lambda_{\text{inter},ij}^{(p)}(F_i^{(p)}(k + l) - F_i^{(p-1)}(k + l)) + \mu_{ij} \frac{\rho}{2} (F_i^{(p)}(k + l) - F_i^{(p-1)}(k + l))^2
\]

(5)

Above the formulas, \(p\) is the current number of iterations, \(N\) is the prediction time domain of MPC, \(\gamma\) is the coefficient of adaptive scheduling, \(0 < \gamma \leq 1\), that is, the farther the prediction time is from the current time, the lower the weight assigned, to reduce the impact of the subsequent time on the results. In this paper, \(\gamma\) is generally took as 1, only when comparing the different values of prediction time-domain \(N\) and different \(\gamma\), the value effects on the optimization result and \(\gamma\) can be changed, \(Q_i\) and \(f_i\) are positive definite weight matrix and vector respectively, only the items related to the large grid, gas turbine, energy storage, and interconnection function of sub micro grid \(M_i\).
set to 0, the $F_{\text{inter},ij}^{(p)}$ and $F_{\text{inter},ji}^{(p)}$ are solved after iteration, remain convergent to 0. At the same time, $\mu_{ji}$ set the of the corresponding term of the sub microgrid $j$ interconnected with the sub microgrid $i$ to a sufficiently large value and set the corresponding interconnection variable to 0. Accordingly, when sub microgrid $i$ am detected to be reinserted into MGC, then the auxiliary aggregation constant $\mu_{ij}$ and $\mu_{ji}$ of the corresponding item are set to 1.

3.3. Distributed iteration based on multi anti consistency

The distributed iteration formula based on multi anti consistency is shown in formula (7) and formula (8).

$$\lambda_{\text{inter},ij}^{(p+1)}(k) = \lambda_{\text{inter},ij}^{(p)}(k) + \omega_{ij} \left( \lambda_{\text{inter},ij}^{(p)}(k) + \lambda_{\text{inter},ij}^{(p)}(k) \right) + \omega_{ij} (F_{\text{inter},ij}^{(p)}(k) - F_{\text{inter},ji}^{(p)}(k)) \quad j \in N_i \quad (7)$$

$$\left| \lambda_{\text{inter},ij}^{(p+1)}(k) - \lambda_{\text{inter},ij}^{(p)}(k) \right| \leq \varepsilon \quad (8)$$

Above the formula, $\omega_{ij}$ is the consistency iteration coefficient, which needs to meet the requirements of $0 \leq \omega_{ij} \leq \left( \max_{i=1,2,\cdots,N} |N_i| \right)^{-1}$ to ensure the polymerization, in this paper, 0.3 is taken for $\omega_{ij}$, $\varepsilon$ is the iteration error limit.

The distributed iteration flow chart is shown in Figure 2, and the specific iteration steps are described as follows.

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**Figure 2.** Flow chart of distributed iteration.

- Collect the current capacity information of the energy storage system.
- Given the initial values of interconnection variables $F_{\text{inter},ij}^{(p-1)}$ and $F_{\text{inter},ji}^{(p-1)}$, and Lagrange's
method $\lambda^{(p)}_{\text{inter},ij}$, the relevant parameters are set.

- Each agent has a centralized solution to equation (4), and obtains the values of interconnected variables $f^{(p)}_{\text{inter},ij}$ under the current iteration.
- Send $f^{(p)}_{\text{inter},ij}$ and $\lambda^{(p)}_{\text{inter},ij}$ to neighbor agent, $f^{(p)}_{\text{inter},ji}$ and $\lambda^{(p)}_{\text{inter},ji}$ collect and of a neighbor agent at the same time.
- Each agent updates $\lambda^{(p)}_{\text{inter},ij}$ required by the next iteration according to formula (7).
- Check whether $p$ has reached the maximum $p_{\text{max}}$, or satisfies the iteration stop condition $|\lambda^{(p+1)}_{\text{inter},ij}(k) - \lambda^{(p)}_{\text{inter},ij}(k)| \leq \varepsilon$. If the maximum value of iteration is reached or the stop condition is met, the iteration is stopped, otherwise, the next iteration is started.
- If the iteration is stopped, the initial value of Lagrange multiplier at the next time is updated according to $\lambda^{(p)}_{\text{inter},ij}(k+1) = \lambda^{(p)}_{\text{inter},ij}(k)$ or $\lambda^{(p)}_{\text{inter},ij}(k+1) = \lambda^{p_{\text{max}}}_{\text{inter},ij}(k)$ to update the initial value of Lagrange multiplier at the next time, that is, hot start, to accelerate the convergence rate at the next time. Where $P_t$ is the number of iterations obtained by stopping condition equation (8).
- Start the optimization process at the next moment. In this paper, $\rho = \omega_{ij} = 0.3$. On the one hand, the literature [11] was made the minimum value of global optimal parameter $\rho$ ($\rho \geq \omega_{ij}$) and the given empirical value $\rho = 2\omega_{ij}$, on the other hand, many simulation experiments are done and compared with the centralized quadratic programming method.

Among them, the optimal value $\varphi_{\text{Agent},i}$ of each sub microgrid is based on satisfying the power balance constraint (MPC framework with power balance constraint). Interconnection power constraint and coordination between sub microgrid (consistency algorithm equation (7)), not in the independent sense, and is related to the coordination formula (7) between sub microgrid and the joint benefit function formula (6) contains the optimal global aggregation constant $\rho$. According to reference [12], when the objective function is convex and the constraint is affine, the solution of the subproblem obtained by parallel and iterative method is optimal, which is the same as that of the centralized optimization problem. Because the local benefit function formula (4) and centralized optimization problem formula (2) of sub microgrid $i$ satisfy convex assumption, interconnection constraint formula (1), subsequent battery constraint, and both MPC frame constraints and unit ramp rate constraints are affine. When the value of $\rho$ meets the minimum value requirement and is small enough, the global optimization can be achieved quickly by optimizing the local benefit function formula (4) of each sub microgrid. And the coordination between sub microgrids, which is the same as the solution of MGC centralized optimization problem equation (2).

4. Simulations

4.1. Polymerization

This paper used the software of MATLAB to finished the simulations. Gurobi commercial solver solves the example in MATLAB (Gurobi is a new generation of large-scale mathematical programming optimizer developed by American Gurobi company, and it has a convenient interface with MATLAB.), and the method refers to reference [13]. Above the Figure 3, each agent executes equation (4) at an interval of 1 hour, the equation (4) used App method to solve minimum cost of every agent (for details, please refer to chapter 3.1.), and finally obtains the optimization result of 24 steps. Within the error limit $\varepsilon=0.001$, the required number of iterations at each time, and the optimization error are obtained, as shown in figure 3. At the time of midnight, the number of iterations reached the maximum value about 75. The optimization error reached the minimum value about 0.00005, that means the more Lagrange iterations, the lower the optimization error at midnight in a whole day. At this time we can maximize the local benefits and minimize the power consumption of each sub microgrid in the whole microgrid through augmented Lagrange function, target decomposition, and app distributed decomposition.
calculation. Also, from figure 3, the MGC can achieve aggregation in a few iterations at each optimization time.

![Graph showing optimization error and iteration times](image)

**Figure 3.** Optimization error and iteration times

4.2. plug and play

Figure 4 shows the aggregation process of sub microgrid actual cost at k=1, sub microgrid 5 pulled out before iteration at k = 1, pulled out before iteration and recovered at 100 iterations, pulled out at 70 iterations and recovered at 150 iterations respectively, the actual cost is of active power, and the unit is MW. Comparing the results of figure 4 (a) and figure 4 (b), it can be seen when the sub microgrid five is not pulled out, it no output basically, and the necessary power is provided by the sub microgrid 6. After the sub microgrid five is pulled out, its internal power is provided by itself, and the cost increases. In contrast, the cost of the corresponding sub microgrid six is reduced. Similarly, it can be seen from figure 4 (c) that after 100 iterations, the internal cost of sub microgrid five is rapidly reduced to 0, the cost of corresponding sub microgrid six increases rapidly, and MGC reaches a new balance again. The continuous pull-out and insertion process of sub microgrid five is shown in figure 4 (d). After 70 iterations of sub microgrid five are pulled out, and 150 iterations of sub microgrid five are reinserted, MGC can respond quickly. Each change process achieves a new balance in a short time, which proves the effectiveness of the proposed method for MGC plug and play.
(a) Sub microgrid 5 is not pull out

(b) Sub microgrid 5 is pulled out before iteration
Figure 4. Convergences of Sub microgrid 5 in different situations

As to why the cost of sub microgrid changes before and after iteration, it can be seen from the comparison between figure 4(a) and figure 4(b) that whether the sub microgrid pulled out or not before iteration, the cost remains unchanged, that is, the power provided by itself to the microgrid remains unchanged. However, after the iterative calculation of the augmented Lagrange function in the section three, it can be found that before the sub microgrid, five is pulled out and inserted. After that, the cost
will change. Through the iterative aggregation solution, the power of other sub microgrid provided to supplement, which makes the cost of the whole MGC reach a new balance.

4.3. Prediction time domain

The figure 5 shows the influence of different prediction time domains on the results with and without adaptive scheduling, the unit of actual cost is the same as section 4.2. It can be seen when there is no adaptive scheduling, the change of prediction time domain has a high impact on the results. The general trend is that the smaller the prediction time-domain N, the higher actual cost of MGC, otherwise, it will be lower. When there is adaptive scheduling, the impact of the change in the prediction time domain on the results is not visible, which is due to the reduction of the impact of the subsequent time by the adaptive scheduling. The effectiveness of the proposed MPC method is further proved by figure 5.

![Figure 5](image_url)

**Figure 5.** Effects of different horizons with and without adaptive scheduling
4.4. Penalty factor

Figure 6 shows the change curve of energy storage capacity at different penalty factors and different optimization times. It can be seen when the penalty factor is small (0.5); the changing trend of energy storage capacity is the same. When the penalty factor is increased to 1.5, the energy storage capacity of microgrid 1, 3, 4, 5 changes greatly, that is, the charge-discharge is deeper, which is caused by the higher penalty factor makes more energy consumed or absorbed in the local microgrid. When the penalty factor is higher, it is 4.5, the power flow between the sub microgrid is further reduced, and the energy storage is charged and discharged according to its capacity configuration and local energy configuration.

(a) Energy storage capacity when penalty factor is 0.5

(b) Energy storage capacity when penalty factor is 1.5
Figure 6. Optimization error and iteration time

Figure 7 taking E_1 as an example, the seventh figure shows the change of penalty factor at 0.5, 1.5, and 4.5, respectively. It can see from the picture that with the increase of penalty factor, the energy storage capacity will change more, corresponding to the higher penalty factor mentioned above, which makes the local microgrid consume more energy. Also, E_3, E_4 and E_5 is similar to E_1. The higher the penalty factor, the greater the energy storage capacity.

Figure 7. The change of energy storage capacity under different penalty factors of E_1

Figure 8 shows the MGC operating costs under different penalty factors. It can be seen that the higher penalty factor, the higher MGC cost. The lower penalty factor, the free flow of power between the sub microgrid, MGC preferentially chooses the energy with low generation cost, so the cost is significantly
reduced. It can be seen in figure 5 and figure 6 that the proposed method dramatically enhances the flexibility of MGC.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{graph.png}
\caption{Optimization error and iteration time}
\end{figure}

5. Conclusions
In this paper, through the establishment of MGC topology, taking the interconnection of six sub microgrid as an example, a microgrid cluster is formed. Through the MATLAB model and Gurobi commercial solver, the augmented Lagrange function introduced to verify the multi anti consistency assumption. Taking sub microgrid five as an example, the effectiveness of MGC plug and play proved. After changing the penalty factor, it found that the lower the penalty factor, the better MGC chooses the energy with the most economical cost, which enhances the flexibility of MGC.

This paper presents a distributed optimization algorithm of plug and play MGC based on multi anti consistency and MPC. Through the distributed algorithm, MGC with large-scale and complex structures can manage energy quickly by local centralized optimization and global distributed iteration. This hybrid optimization method dramatically enhances the flexibility of MGC and protects the privacy information of local microgrid. It not only can let MGC be flexible, but plug and play settings of MGC also realized quickly. As an optimal control method, MPC considers the possible state of the scheduled time and corrects the related variables which will affect the scheduled time in order to form the closed-loop control of the related variables and enhance the robustness of the system. Therefore, the distributed iteration method combined with MPC can not only remove the centralized dispatching center but also enhance the anti-jamming performance of the system. Finally, by adjusting the penalty factor, the local microgrid can choose whether to participate in the cluster operation or weaken the cluster operation, thus giving users more choice rights.

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