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Peak Shaving Methods of Distributed Generation Clusters Using Dynamic Evaluation and Self-Renewal Mechanism

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Abstract: As one of the power auxiliary services, peak shaving is the key problem to be solved in the power grid. With the rapid development of DGs, the traditional peak shaving scheduling method for centralized adjustable energy is no longer applicable. Thus, this paper proposes two-layer optimization methods of allocating the peak shaving task for DGs. Layer 1 mainly proposes four evaluation indexes and the peak shaving priority sequence can be obtained with modified TOPSIS, then the DG cluster's task is allocated to the corresponding DGs. On the basis of dynamic evaluation and the self-renewal mechanism, layer 2 proposes a peak shaving optimization model with dynamic constraints which assigns peak shaving instructions to each cluster. Finally, the effectiveness of the method is verified by using the real DGs data of a regional power grid in China based on the MATLAB simulation platform. The results demonstrate that the proposed methods can simply the calculation complexity by ranking the DGs in the peak shaving task and update the reliable aggregate adjustable power of each cluster in time to allocate more reasonably.

Keywords: dynamic evaluation; peak shaving; distributed generation cluster; self-renewal mechanism; optimal dispatching

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1. Introduction

As an important part of the modern energy system, distributed generations are characterized by nearby utilization, low carbon, multi-interaction, flexibility, and high efficiency [1], etc. In recent years, DGs have developed rapidly. Take the distributed PV as an example, the total cumulative installed capacity for PV at the end of 2021 reached at least 942 GW throughout the world [2], and in China, the capacity of distributed PV reached 107.5 GW, accounting for 35% of the total installed capacity. In order to maintain the balance of active power and the stability of system frequency, peak shaving is considered as one of the auxiliary services for the power system and it is also the key problem and common challenge [3,4] to be solved which has great significance to ensure safe, stable, and economic operation of the power system [5]. The traditional peak shaving methods are mainly based on thermal power [6,7]. Yet, this way is easy to cause environmental pollution; also, the peak shaving capacity of thermal power units becomes seriously insufficient with a growing number of the renewable energy connected to the grid. Thus, in recent years, DGs are explored to provide the services for the peak shaving to release the pressure of the thermal power units.

At present, most of the research focuses on peak shaving methods of utilizing the resources at the generation side, especially renewable energy. In terms of battery energy storage peak shaving, from an economic point of view, the potential of battery energy storage in peak shaving is verified in [8]. The authors in [9] analyze the impact of peak shaving characteristics on regional power grid peak shaving and propose a coordinated peak shaving control strategy between energy storage and thermal power units based on the multi-scale signal decomposition theory. In [10], a Bayesian analysis model is applied to realize a simple and effective peak shaving method considering equipment constraints. The authors in [11] propose an intra-day coordinated peak shaving and frequency regulation optimization strategy of energy storage to improve the economic benefits. In terms of PV or wind power peak shaving. The authors in [12] propose an optimal peak shaving control strategy for the PV system with energy storages which are based on the dynamic requirements and feed-in restrictions. In [13], an Isolated Microgrid (IMG) model was developed to ensure the optimal use of the PV generation system and can serve the peak shaving service effectively. The authors in [14–16] analyze the output characteristics of wind power and PV, and establish a peak shaving optimization operation model in the wind–solar–storage hybrid power generation system. The authors in [17] propose a mathematical model of peak shaving strategy, and the pumped storage power stations combined with wind power and PV are utilized.

However, as summarized in Table 1, the peak shaving optimization scheduling models in the above research are usually and mainly established for centralized and utility-scale PV, energy storage, and wind power, and there are few research studies focusing on the DGs in peak shaving. Moreover, due to the small capacity, large number, random location of DGs, applying the above method in scheduling for each DG participating in peak shaving directly will lead to problems, such as difficulty in solving, explosion of variable dimensions, and hard in convergence of the solution results [18].Clustering partition provides a new way to deal with a large number of scattered DGs [19,20], and the cluster algorithm is one of the commonly used methods, such as K-means, self-organizing mappings, fuzzy C-means, and agglomerative hierarchical clustering [21–23]. Through the cluster methods, the corresponding aggregation model can be obtained, so that the roughly adjustable capacity of each cluster can be estimated, and this value is often fixed. Thus, this paper proposes to allocate the peak shaving task to each cluster, preferentially consulting the reliable regulation capacity based on the partitioned distributed generation clusters. Additionally, the cluster's task is further allocated to some appropriate DGs according to the peak shaving priority sequence of DGs in each cluster.

Table 1. Comparison of related work with proposed work.

Reference	Power Type	Peak Shaving Method	Applicable Conditions
[12]	centralized	optimal control model	small quantity
[14–16]	centralized	optimization operation model	small quantity
[17]	centralized	mathematical model	small quantity
this paper	decentralized	two-layer methods	large quantity

In addition, this paper evaluates the specific peak shaving performance of each DG from multiple aspects and at different timescales shown in Figure 1, which is respectively used to update the peak shaving priority sequence of each DG and the peak shaving capacity of each cluster, so as to measure the peak shaving ability of each DG and cluster more accurately, as well as allocate peak shaving tasks more reasonably. The authors in [24] integrate four peak shaving indexes, including peak and off-peak capacity indexes, rapid response index, and fluctuation smoothing index, and implement them in the peak shaving generation scheduling of a hydropower plant. The authors in [25] classify the factors about competitive development abilities of distributed PV generations into six dimensions and for examining the availability of the evaluation index system, the TOPSIS method is adopted based on the combination weighting. The research above is mainly for the evaluation of a single type of source, and it is more accurate and targeted. However, for DGs, each cluster may contain more than one type. The authors in [11] consider economic benefits to establish the evaluation system for different types of DGs. The authors in [26] apply the MCDM technique employing Fuzzy TOPSIS to ranking DG systems and the criteria includes cost, minimum starting time, noise, emission level, and continuity. Although the evaluation indexes above are diverse and comprehensive, their correlation with peak shaving capacity is poor to some extent and need to be further screened and refined. So, this paper proposes some general and multi-dimensional evaluation indexes to measure the peak shaving performance, and the evaluation for DGs is conducted regularly.

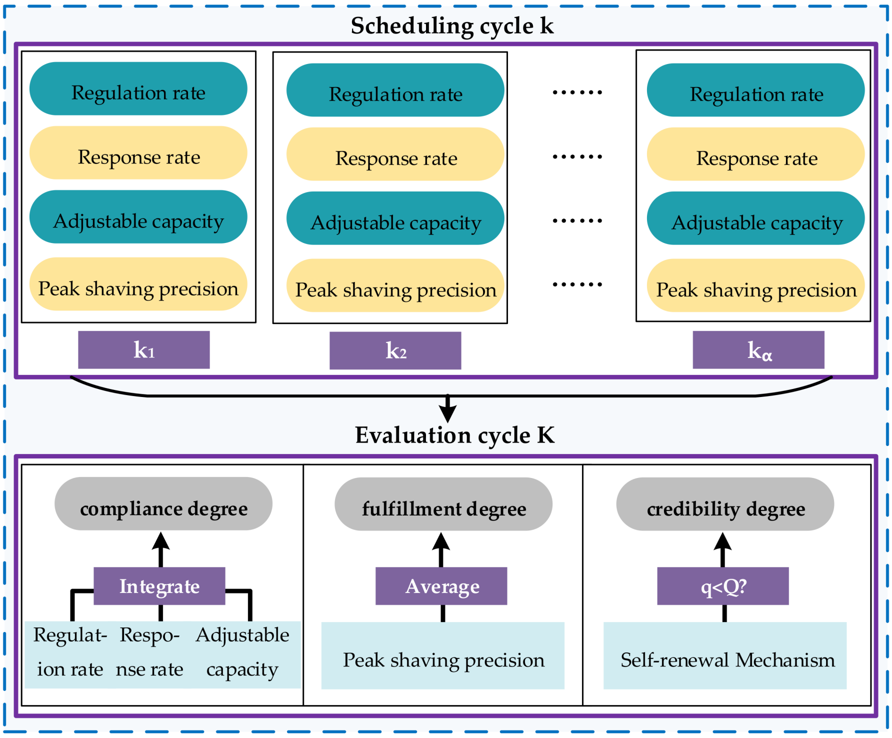

Figure 1. Indexes of DGs for each scheduling and evaluation cycle.

This novel cast: on the one hand, it helps greatly reduce the computational complexity and variable dimensions by establishing a two-layer peak shaving task allocation model. On the other hand, the proposed evaluation and self-renewal mechanism is the key improving the peak shaving precision problem by updating the dynamic constrains in layer 2. The organization of the paper is as follows. Section 2 proposes the method of peak shaving task allocation from the cluster to every DG unit based on the modified TOPSIS. Subsequently, according to the three-dimensional dynamic evaluation and self-renewal mechanism, Section 3 introduces the optimization method of peak shaving task allocation between clusters. Section 4 presents the implementation details of the proposed two-layer optimization method and discusses simulation results. Finally, the paper is concluded in Section 5.

2. Peak Shaving Priority Sequencing of Distributed Generations

In this section, the multidimensional evaluation indexes based on the peak shaving performance of DG units are proposed firstly, then combination weighting is adopted to determine the weight of each index, and finally the DGs within each cluster are arranged according to the peak shaving priority sequence based on the modified TOPSIS [27].

2.1. Multi-Index Evaluation for Peak Shaving Performance

(1) Regulation rate: The index of the regulation rate is firstly introduced to measure the speed of each DG that responds to the peak shaving instructions, and it can be calculated as follows:

$$v_{i,k} = \frac{p_{e,i,k} - p_{s,i,k}}{\Delta t_k} \tag{1}$$

where: $v_{i,k}$ represents the actual regulation speed of DG i during the scheduling cycle k. Δt_k is the duration of k. $p_{s,i,k}$ and $p_{e,i,k}$ are the output power of the DG at the starting and ending time of the scheduling cycle k.

Then, the regulation rate γ_1 can be formulated as:

$$\gamma_1 = \begin{cases} \dfrac{v_{i,k}}{v_{i,N}}, & \dfrac{v_{i,k}}{v_{i,N}} < \gamma_{1,\max} \\ \gamma_{1,\max}, & \dfrac{v_{i,k}}{v_{i,N}} \geq \gamma_{1,\max} \end{cases} \tag{2}$$

where: $v_{i,N}$ represents the standard regulation speed of the DG, so the rate γ_1 indicates the degree to which the actual regulation speed is compared with the standard speed.

In addition, considering the stability of the power system and the service life and safety of the DG, the upper limit $\gamma_{1,\max}$ is applied to this index. Concretely, the significance of setting this upper limit is that the evaluations of peak shaving performance of DGs need to consider multiple aspects and to be comprehensive, rather than just considering one aspect of the performance. In the process of peak shaving, the regulation rate, stability, sustainability, and other factors of a DG unit are coupled and would interact with each other. Excessive pursuit of improving the regulation rate unilaterally may not only have an adverse impact on the power system, but also increase the burden and failure probability of DGs, which also affect its service life and the performance of peak shaving. Therefore, considering the overall performance of the whole distributed generation cluster and referring to the performance standards of peak shaving in different regions, this paper proposes to set a reasonable regulation speed range for each DG, and this can effectively avoid other adverse results and excessive investment caused by the excessive pursuit of this index.

(2) Response rate: The following index of the response rate is also introduced, which refers to the time taken to reliably step out of the adjustment dead zone, consistent with the adjustment direction after the peak shaving instruction was issued.

Besides, in order to skip the matrix forward in TOPSIS, this index is converted into a benefit index, and it can be formulated as:

$$\gamma_2 = 2 - \frac{\Delta t_{ac,i,k}}{\Delta t_{i,N}} \tag{3}$$

where: $\Delta t_{ac,i,k}$ represents the actual response time of DG i in the cycle k. $\Delta t_{i,N}$ is the standard time. Similarity, the index γ_2 shows the degree to which the actual response time is compared with the standard time, and the lower limit is also designed. In order to avoid the long response time of some DG units causing the calculated value of this index to become negative and avoid too much impact on the subsequent calculation of compliance degree, it is necessary to set a reasonable lower limit of γ_2.

(3) Adjustable capacity: The index of adjustable capacity is introduced to represent the maximum adjustable power of each DG based on its original output power at the time of receiving the peak shaving instruction. The larger the adjustable power is, the less DG units need to be regulated with the same peak shaving task, which is conducive to improving the overall peak shaving efficiency. It can be formulated as:

$$\gamma_3 = \frac{\Delta p_{i,k}}{\Delta p_{\max,k}} = \frac{\Delta p_{i,k}}{\max(\Delta p_{1,k}, \Delta p_{2,k}, \cdots, \Delta p_{n,k})} \tag{4}$$

where: $\Delta p_{i,k}$ is the adjustable power of DG i. $\Delta p_{\max,k}$ is the maximum of $\Delta p_{i,k}$ among the DGs in a distributed generation cluster in the cycle k. n is the number of DGs which are allowed to participate in peak shaving in this cluster. Consequently, the index γ_3 indicates the proportion of maximum adjustable power of each DG within a cluster to their maximum $\Delta p_{\max,k}$.

The solutions of $\Delta p_{i,k}$, $i = 1, 2, \cdots, n$ can be considered as an optimization problem, and the objective function is formulated as:

$$\Delta P_{\max,ag} = \max(\Delta p_{1,k} + \Delta p_{2,k} + \cdots + \Delta p_{n,k}) \tag{5}$$

Additionally, (5) is also constrained by the following:

a. Based on the max operational ratings $p_{\max,i}$, the limits of output power $p_{i,k}$:

$$p_{i,k} \leq p_{\max,i} \tag{6}$$

b. The min/max current and voltage limits within the power system in the cycle k:

$$\begin{cases} I_{\min} \leq I_k \leq I_{\max} \\ U_{\min} \leq U_k \leq U_{\max} \end{cases} \tag{7}$$

c. The limit of max power conversion of DG i, $\Delta p_{con,i}^{\max}$:

$$p_{i,k}(t_e) - p_{i,k}(t_s) \leq \Delta p_{con,i}^{\max} \tag{8}$$

where: t_s and t_e are the starting and ending time of the scheduling cycle k.

(4) Peak shaving precision: The index γ_4 is defined to measure the peak shaving reliability and accuracy of each DG, and it can be formulated as:

$$\gamma_4 = \frac{\Delta p_{ac,i,k}}{\Delta p_{ob,i,k}} \tag{9}$$

where: $\Delta p_{ob,i,k}$ $\Delta p_{ac,i,k}$ represents the adjustment objective of the output power. Then, $\Delta p_{ac,i,k}$ is the actual power regulation during a peak shaving cycle.

2.2. Priority Sequencing by Objective and Subjective Synthetic Approach and TOPSIS

2.2.1. Combination Weighting of Multidimensional Indexes

This paper adopts the objective and subjective synthetic approach to assign the weights of proposed evaluation indexes. Specifically, the weights are calculated, integrating the objective weights employed by the EWM [28] with the subjective ones determined by the AHP [29].

The subjective weights calculation steps based on AHP are as follows, and firstly make the pairwise comparison between the four indexes, including regulation rate, response rate, adjustable capacity, and peak shaving precision through the 1–9 scale method. The evaluation matrix Y can be obtained:

$$Y = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{14} \\ Y_{21} & Y_{22} & \cdots & Y_{24} \\ \vdots & \vdots & \ddots & \vdots \\ Y_{41} & Y_{42} & \cdots & Y_{44} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 4 & 1/3 \\ 1 & 1 & 4 & 1/3 \\ 1/4 & 1/4 & 1 & 1/3 \\ 3 & 3 & 3 & 1 \end{bmatrix} \tag{10}$$

The value of random consistency index RI is 0.89, and the consistency ratio CR is calculated as:

$$CR = \frac{CI}{RI} = \frac{\lambda_{\max} - 4}{3 \times 0.89} = 0.093343 \tag{11}$$

Thus, the value of CR is less than 0.1, which means the evaluation matrix Y passes the consistency examination in AHP, and is also reasonable. After that, this paper considers the average of three kinds of subjective weights as the final subjective weights, calculated separately by arithmetic average method, geometric average method, and eigenvalue method, so as to avoid the deviation caused by using just a single method, and to make the weights more comprehensive and effective.

Then, the vector of subjective weights w_{1J} is equal to [0.2207 0.2207 0.0827 0.4758], it can be seen that the peak shaving precision γ_4 is the most important, the rates of regulation and response γ_1, γ_2 come second, and the index of adjustable capacity γ_3 is the least from the subjective perspective.

Thus, as shown in formula (12), the comprehensive weight vector w_J of the four evaluation indexes is calculated as follows:

$$w_J = \left(w_j\right)_{4\times 1} = \left(s_1 w_{1j} + s_2 w_{2j}\right)_{4\times 1} \tag{12}$$

where: w_{2j} is the objective weight vector determined by the EWM, s_1 and s_2 are the pro portion modulus of the two types of weights.

2.2.2. Priority Sequencing Based on the Modified TOPSIS

Based on the comprehensive weights, this paper carries out multidimensional evaluation and priority sequencing of each DG in the distributed generation cluster using the modified TOPSIS method, thereby obtaining the suitable peak shaving allocation scheme during every scheduling cycle.

(1) Step1: construction and normalization of the decision matrix

In this paper, the DGs in one cluster are the objects $A = \{A_1, A_2, \cdots, A_n\}$ of assessment and sequencing based on the proposed evaluation indexes $\gamma = \{\gamma_1, \gamma_2, \gamma_3, \gamma_4\}$. Additionally, the performance rating for each object against each index can be formed in the decision matrix R:

$$R = (r_{ij})_{n\times 4} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{14} \\ r_{21} & r_{22} & \cdots & r_{24} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{n4} \end{bmatrix} \tag{13}$$

where: r_{ij} represents the performance rating for object A_i against index γ_j.

It is unnecessary to handle the indexes positively because all of them are designed as benefit indexes in this paper, so it is only required to normalize the decision matrix R to eliminate different influences of dimension. The normalized rating b_{ij} is calculated via formula (14) applying the vector normalization, and it can be displayed as the matrix B:

$$B = \left(b_{ij}\right)_{n\times 4} = \left(r_{ij} \middle/ \sqrt{\sum_{i=1}^{n} r_{ij}^2}\right)_{n\times 4} \tag{14}$$

(2) Step2: identification of the ideal solution

The positive and negative ideal solutions B^+, B^- are defined, respectively, as:

$$\begin{cases} B^+ = ({b_1}^+, {b_2}^+, {b_3}^+, {b_4}^+) = (\max(b_{11}, b_{21}, \ldots, b_{n1}), \ldots, \max(b_{14}, b_{24}, \ldots, b_{n4})) \\ B^- = ({b_1}^-, {b_2}^-, {b_3}^-, {b_4}^-) = (\min(b_{11}, b_{21}, \ldots, b_{n1}), \ldots, \min(b_{14}, b_{24}, \ldots, b_{n4})) \end{cases} \tag{15}$$

where: b_j^+ is the maximum of vector $\left(b_{ij}\right)_{n\times 1}$, and the b_j^- is the minimum of the vector because the indexes this paper proposed all belong to benefit attribute.

(3) Step3: calculation of the weighted Euclidean distance

Subsequently, the weighted Euclidean distances from the positive and negative ideal solutions ${D_i}^+$, ${D_i}^-$ for the A_i are calculated as:

$$\begin{cases} {D_i}^+ = \sqrt{\sum\limits_{j=1}^{4} w_j (\mathrm{b}_{ij} - b_j^+)^2} \\ {D_i}^- = \sqrt{\sum\limits_{j=1}^{4} w_j (b_{ij} - b_j^-)^2} \end{cases} \tag{16}$$

(4) Step4: calculation of the overall performance score

At last, the overall score for A_i is obtained as:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{17}$$

where: the performance score C_i is utilized to rank the competing objects.

Therefore, the flow chart of this modified TOPSIS method is shown in Figure 2. The overall performance score C_i ranges from 0 to 1 and a higher score means a better performance and evaluation, especially when A_i happens to be the positive ideal solution, the score C_i = 1, or the score C_i = 0 when it happens to be the negative one. In other words, the priority sequence can be obtained by comparing the scores of each DG in the distributed generation cluster.

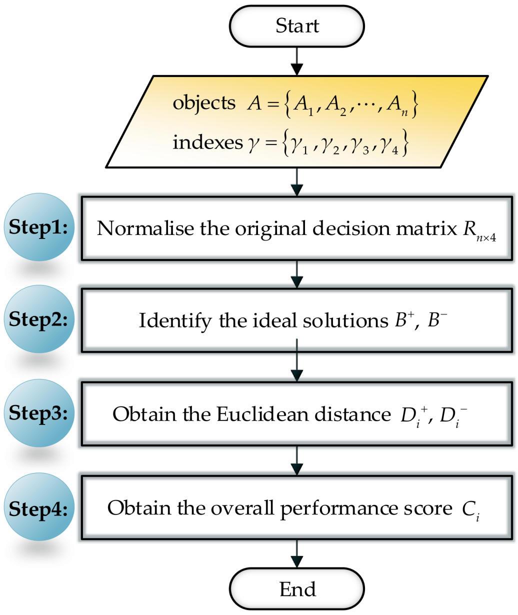

Figure 2. Flow chart of modified TOPSIS method.

3. Peak Shaving Method with Dynamic Evaluation and Self-Renewal Mechanism

From the macroscopic level, this paper proposes a two-layer optimization method of peak shaving task allocation. The three-dimensional system is used to make dynamic evaluation of DGs in the distributed generation cluster. Then, according to the evaluation results, the DGs of each cluster are selected or eliminated in time through the self-renewal mechanism. Besides, the mechanism corresponds to the principle of "survival of the fittest" and also is instrumental in openness and constancy development of clusters. Finally, the constraints of the allocation model in layer 1 dynamically change for promoting rational allocation of peak shaving tasks, mainly by the three-dimensional evaluation of DGs, as well as the self-renewal mechanism.

3.1. Three-Dimensional Dynamic Evaluation

Within one evaluation cycle K, this paper considers three dimensions: compliance degree, fulfillment degree, and credibility degree to evaluate the peak shaving effect of each DG comprehensively, so as to determine whether they can continue to participate in the auxiliary service of peak shaving, which has significance to allocate the regulation task from one cluster to internal DGs.

(1) The first dimension—compliance degree Γ_i: It reflects the matching degree between the regulation ability of DG i and the peak shaving task from the power dispatching center, so this dimension is mainly designed to measure and quantify the peak shaving ability of DGs.

Therefore, according to the specific indexes proposed in Section 2, the indexes of regulation rate γ_1, response rate γ_2, and adjustable capacity γ_3 should be included by the first dimension of compliance. By integrating and averaging these three indexes, the peak shaving performance of DGs can be measured in more depth. So as shown in formula (18), the value of the compliance degree can be calculated:

$$\Gamma_i = \left(\sum_{l=1}^{\alpha} \gamma_{1,i,l} \Big/ \alpha \right) * \left(\sum_{l=1}^{\alpha} \gamma_{2,i,l} \Big/ \alpha \right) * \left(\sum_{l=1}^{\alpha} \gamma_{3,i,l} \Big/ \alpha \right) \tag{18}$$

where: $\gamma_{1,i,l}$, $\gamma_{2,i,l}$, and $\gamma_{3,i,l}$ represent the index values of DG i in the scheduling cycle l of the evaluation cycle, and $l = 1, 2, \cdots, \alpha$.

Additionally, the evaluation cycle K is defined as follows:

$$K = \alpha k \tag{19}$$

where: α is the multiple of the evaluation cycle and a scheduling cycle k, and attention should be paid to the value selection of α. If the value of α is over-large, it will lead to evaluate and update untimely and will further affect allocation of the task unreasonably. Conversely, if it is over-small, it will lead to too frequent evaluation and update with little difference of results between each evaluation cycle, which will also waste the computing resources to some extent.

(2) The second dimension—fulfillment degree Ψ_i: This dimension represents the average peak shaving accuracy of DGs during an evaluation cycle, and is applied to measure the reliability and precision of regulation. So, the index of peak shaving precision γ_4 is used in the calculation of the fulfillment degree, which is as follows:

$$\Psi_i = \sum_{l=1}^{\alpha} \gamma_{4,i,l} \Big/ \alpha \tag{20}$$

(3) The third dimension—credibility degree Φ_g: This dimension is proposed to judge whether the DGs should be permissioned to continue participating in the auxiliary service of peak shaving. This judgment is mainly made by counting the historical records where a DG unit is temporarily prohibited from participating in peak shaving, that is, the times of revoking its peak shaving permit. The degree of credibility Φ_g is defined as:

$$\Phi_g = \begin{cases} 1, q < Q \\ 0, q \geq Q \end{cases} \tag{21}$$

where: $g = 1, 2, \cdots, G$ and G is the total number of DGs in one cluster, including all DGs allowed and not allowed for peak shaving. Specifically, a maximum record of revoking the permit is firstly preset as Q. Only the times q that it has been revoked less than Q, the credibility degree can be eligible and equal to 1, otherwise $\Phi_g = 0$ and the peak shaving permit will be permanently revoked.

3.2. Self-Renewal Mechanism of Clusters

Consequently, according to the designed three-dimensional evaluation system, this paper further proposes a self-renewal mechanism for distributed generation clusters, which is shown in Figure 3.

In an evaluation cycle, if any one of the compliance degrees and fulfillment degrees fail to meet the corresponding eligibility criteria, the DG will get to enter the prohibition period until expiration. During the prohibition period, the DG is deemed an uncontrollable unit and its permit will also be revoked for a while. Moreover, the DG prohibited is also not qualified to participate in the peak shaving, as well as the prioritization and dynamic evaluation.

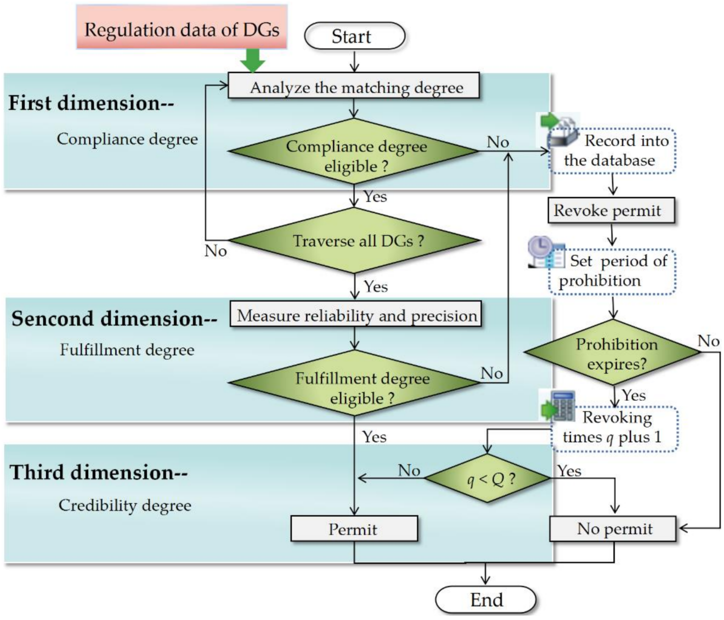

Figure 3. Self-renewal mechanism process.

After the prohibition period expires, it will be endowed with the average multi-index and three-dimensional evaluation of the other DGs and return to the cluster to participate in peak shaving in the next scheduling cycle. Until the records of permit revoked reach the maximum Q, its ascription within one distributed generation cluster will be canceled permanently. It should also be noted that whether the peak shaving permits of DGs in a cluster is temporarily or permanently revoked, the aggregate adjustable power $\Delta P_{\max,ag}$ of this cluster needs to be recalculated and updated accordingly for the peak shaving task allocation between clusters in the new scheduling cycle.

3.3. Two-Layer Optimization Method of Peak Shaving Task Allocation

The two-layer peak shaving methods are shown in Figure 4. For layer 1, Section 2 proposes the method for the peak shaving task allocation from the cluster to each DG unit. The four indexes are firstly designed, then they calculate the peak shaving priority sequence of DGs based on the combination weighting and modified TOPSIS. According to the priority sequence of each cluster, the DGs are regulated in turn to complete the corresponding peak shaving task.

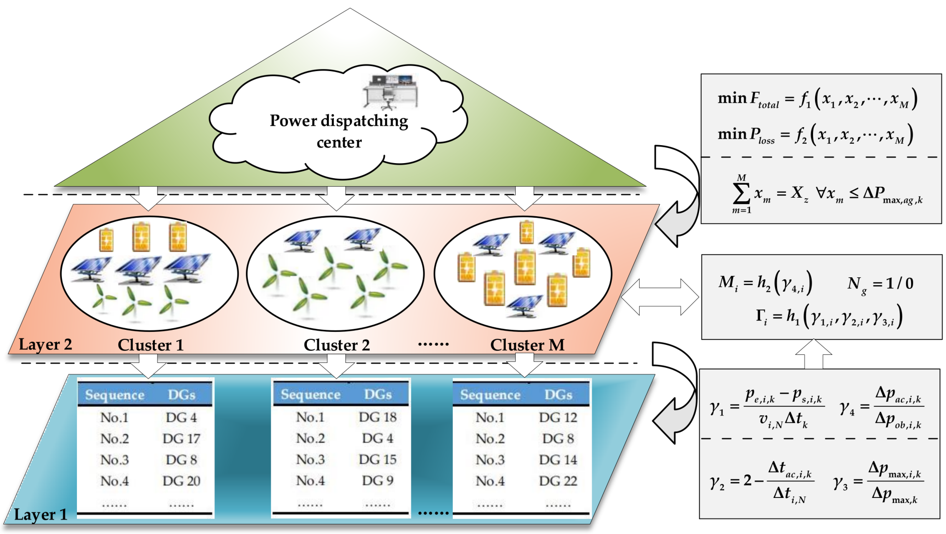

Figure 4. Two-layer peak shaving methods.

Layer 2 assigns peak shaving instructions to each cluster, and in order to determine the peak shaving task of each cluster, the multi-objective optimization model is formulated. Considering the economic indicators of peak shaving cost F_{total} and active power transmission losses P_{loss}, the objective functions are shown in Equations (22) and (23):

$$\min F_{total} = \sum_{m=1}^{M} F_m = \sum_{m=1}^{M} \xi_m x_m = f_1(x_1, x_2, \cdots, x_M) \tag{22}$$

$$\min P_{loss} = \sum_{e=1}^{S} \sum_{z=1}^{S} [\alpha_{ez}(P_e P_z + Q_e Q_z) + \beta_{ez}(Q_e P_z - P_e Q_z)] = f_2(x_1, x_2, \cdots, x_M) \tag{23}$$

where: ξ_m represents the peak shaving cost per kW of cluster m. M is the number of clusters. F_m is the peak shaving cost of completing peak shaving task x_m. P_e and Q_e are the injected active and reactive power at bus e.

The calculation formulas of α_{ez} and β_{ez} are as follows:

$$\alpha_{ez} = \frac{r_{ez}}{U_e U_z} \cos \delta_{ez} \tag{24}$$

$$\beta_{ez} = \frac{r_{ez}}{U_e U_z} \sin \delta_{ez} \tag{25}$$

where: U_e, U_z are the voltages of bus e and z. δ_{ez} is the phase difference of voltages. r_{ez} is the phase difference and resistance of the line between bus e and z.

Since the constraints such as the min/max allowable current and voltage in the power system, the max output power and the max power conversion of each DG have been considered when calculating the aggregate adjustable power of each cluster $\Delta P_{\max,ag}$ in Section 2. So, there is no need to repeatedly consider the above constraints in this optimization allocation model between distributed generation clusters, and only the range of adjustable power of each cluster needs to be considered. Therefore, the constraints are as follows:

$$\sum_{m=1}^{M} x_m = X_N \tag{26}$$

$$\forall x_m \leq \Delta P_{\max,ag,m} \tag{27}$$

where: X_N is the peak shaving instruction issued from the power dispatching center. $\Delta P_{\max,ag,m}$ is the aggregate adjustable power of cluster m.

In particular, the DGs will be screened according to the proposed dynamic evaluation system and self-renewal mechanism. Therefore, this paper proposes that when the DG enters the prohibition period or returns back to the cluster when the prohibition period expires, the aggregate adjustable power of this cluster is dynamically updated accordingly, which is equivalent to obtaining the reliable adjustable power of each distributed generation cluster, and then readjusts the constraints in formula (27) of the optimization problem during each evaluation cycle.

According to the peak shaving performance of each DG in each scheduling cycle, for DG with poor performance, such as slower response, larger error margin, and lower reliability, through three-dimensional evaluation and survival of the fittest, this DG can be temporarily removed from the cluster in time. The reliable adjustable power of each cluster in each evaluation cycle can be obtained, and the constraints can also be updated, so that peak shaving tasks can be reasonably and appropriately allocated to each cluster and avoid the problem that peak shaving tasks are assigned to DGs with poor reliability to regulate, which is helpful to improve the overall peak shaving effect, such as peak shaving precision and reliability.

4. Case Study and Discussion

The experiments are conducted on a regional power system in China, and on the basis of the theories and methods correlated to cluster partition, it is divided into three distributed generation clusters in this case. The number of DG units and the aggregate adjustable power of each cluster $\Delta P_{\max,ag}$ are shown in Table 2.

Table 2. Settings of distributed generation clusters.

Distributed Generation Clusters	Number of DG Units	Aggregate Adjustable Power
cluster 1	28	24.86 MW
cluster 2	58	51.32 MW
cluster 3	42	37.75 MW

According to the regulation process of peak shaving, every 15 min is regarded as a scheduling cycle k, and there are 96 scheduling cycles during one dispatching day. Take the 49th, 50th, 51st, and 52nd scheduling cycles as examples, their peak shaving tasks are shown in Table 3.

Table 3. Peak shaving tasks for distributed generation clusters.

Distributed Generation Clusters	k = 49	k = 50	k = 51	k = 52
cluster 1	0 MW	24.86 MW	24.86 MW	24.86 MW
cluster 2	29 MW	15.14 MW	15.14 MW	51.32 MW
cluster 3	0 MW	0 MW	0 MW	13.82 MW

Firstly, based on the objective and subjective synthetic approach, the weights of the four indexes including: regulation rate, response rate, adjustable capacity, and peak shaving precision are assigned. The subjective, objective, and comprehensive weights of each index for DGs in cluster 1, cluster 2, and cluster 3 during the 48th, 49th, 50th, and 51st scheduling cycles are shown as in Figures 5–7.

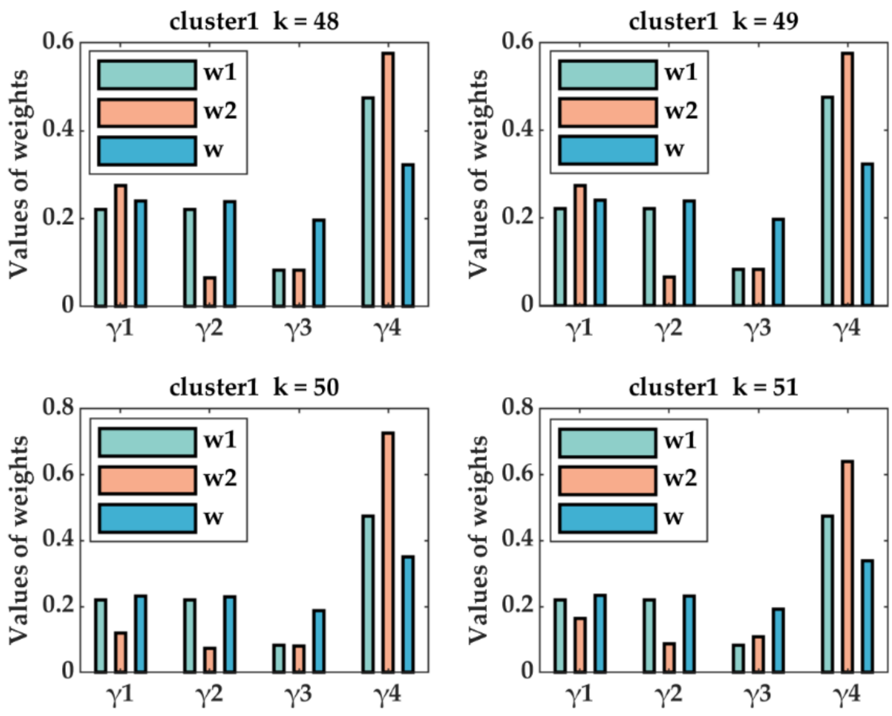

Figure 5. Weights of each index for DGs in cluster 1.

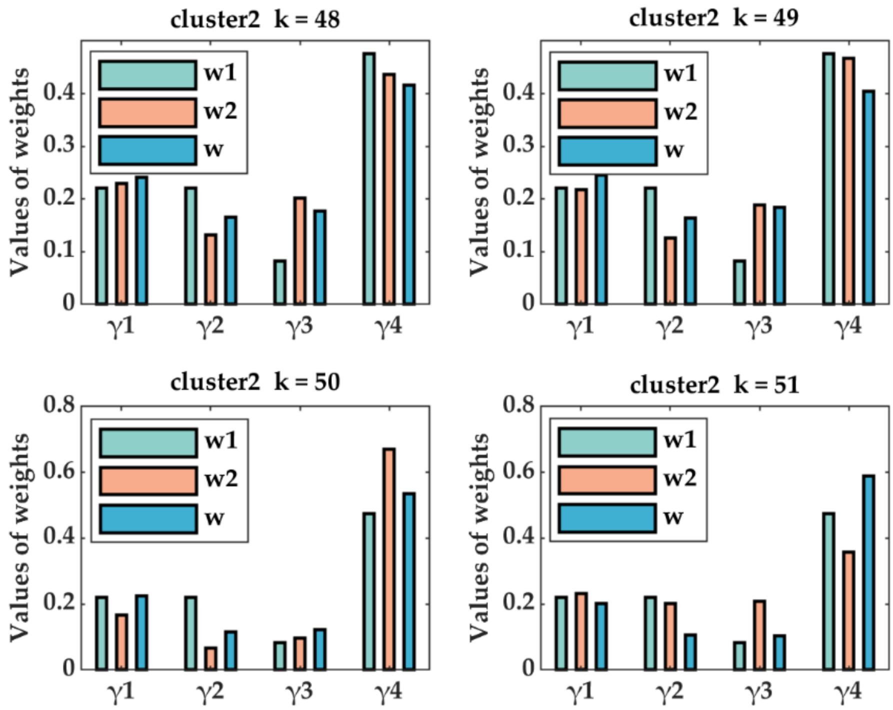

Figure 6. Weights of each index for DGs in cluster 2.

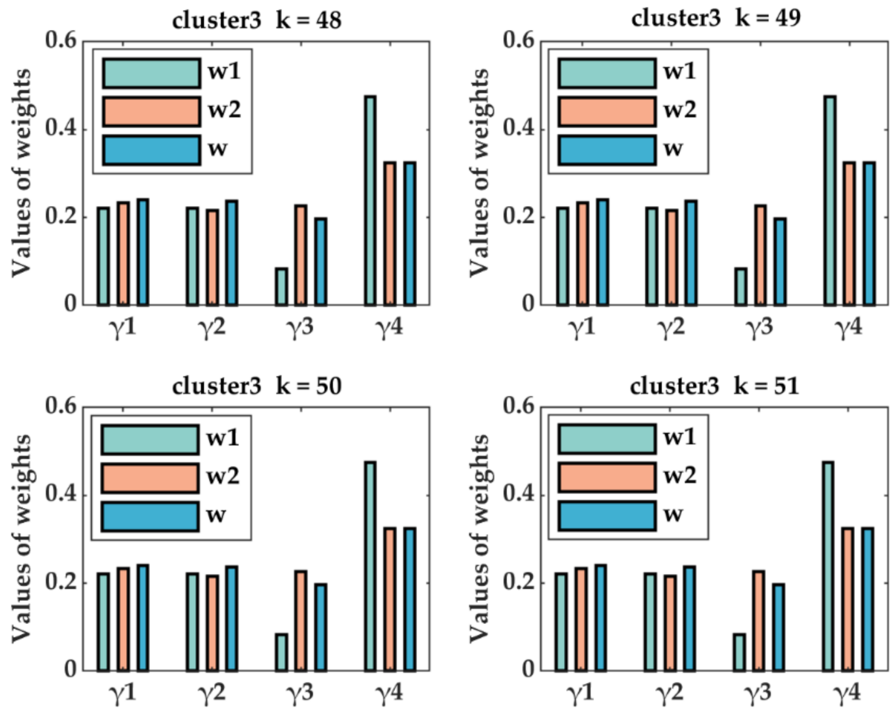

Figure 7. Weights of each index for DGs in cluster 3.

Next, the values of four indexes are calculated after the corresponding scheduling cycle ends. Particularly, for DGs that do not participate in power grid peak shaving, this paper continues to maintain the evaluation results of their last participation in peak shaving. The modified TOPSIS method is used to determine the priority sequences of peak shaving in the 49th, 50th, 51st, and 52nd scheduling cycles. Take cluster 1 as an example, the sequences are shown in Table 4.

Table 4. Sequence of DGs in cluster 1.

Sequence	Modified TOPSIS Sequence			
	k = 49	k = 50	k = 51	k = 52
1	8	8	2	20
2	10	10	7	26
3	15	15	23	16
4	25	25	26	8
5	4	4	8	18
6	22	22	22	15
7	27	27	10	7
8	17	17	19	21
9	14	14	28	12
10	21	21	13	28
11	28	28	14	19
12	16	16	21	27
13	13	13	6	4
14	6	6	1	9
15	12	12	5	2
16	5	5	18	6
17	2	2	3	22
18	9	9	17	10
19	19	19	4	3
20	1	1	25	23
21	23	23	11	14
22	7	7	9	24
23	20	20	12	5
24	18	18	24	25
25	24	24	27	11
26	26	26	15	17
27	11	11	16	13
28	3	3	20	1

It can be seen from Table 2 that the peak shaving instruction is only completed by cluster 2 in the 49th scheduling cycle, and cluster 1 is not assigned the peak shaving task. As a result, the values of four indexes for each DG in cluster 1 are maintained, and the priority sequence in the 50th scheduling cycle is also spontaneously the same as that in the 49th scheduling cycle.

In this case, α is taken as 4 through repeated experiments and comparisons. After the peak shaving instruction in the 52nd scheduling cycle is completed, it is not only necessary to update the priority sequence for the task allocation in the next cycle, but also the three-dimensional evaluation of peak shaving performance is carried out. The calculated compliance degree and fulfillment degree of each DG are shown in Figures 8–10, where the eligibility criteria for the compliance degree and fulfillment degree are both set to 0.5 according to the ancillary service level agreement.

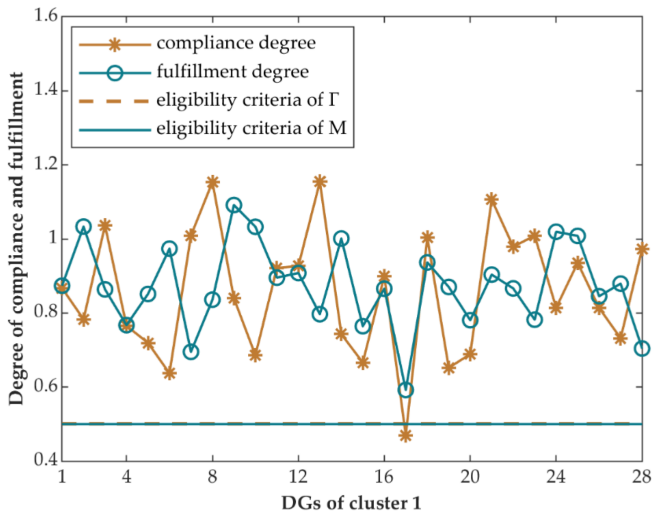

Figure 8. Degree of compliance and fulfillment in cluster 1.

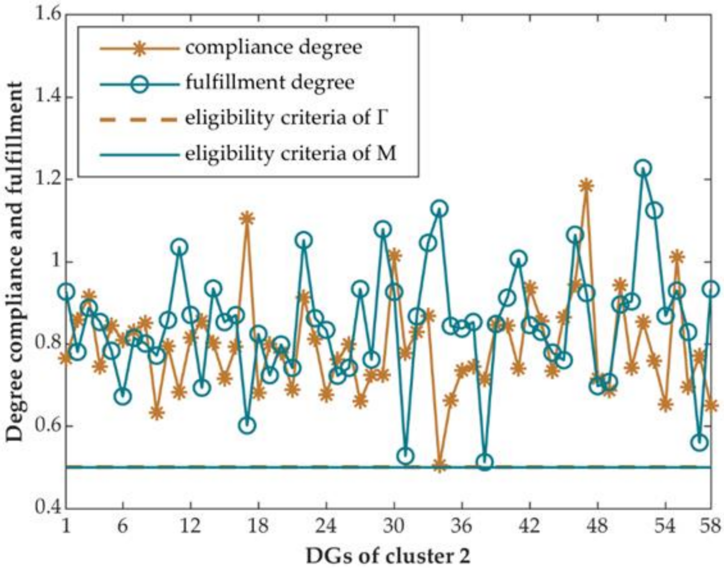

Figure 9. Degree of compliance and fulfillment in cluster 2.

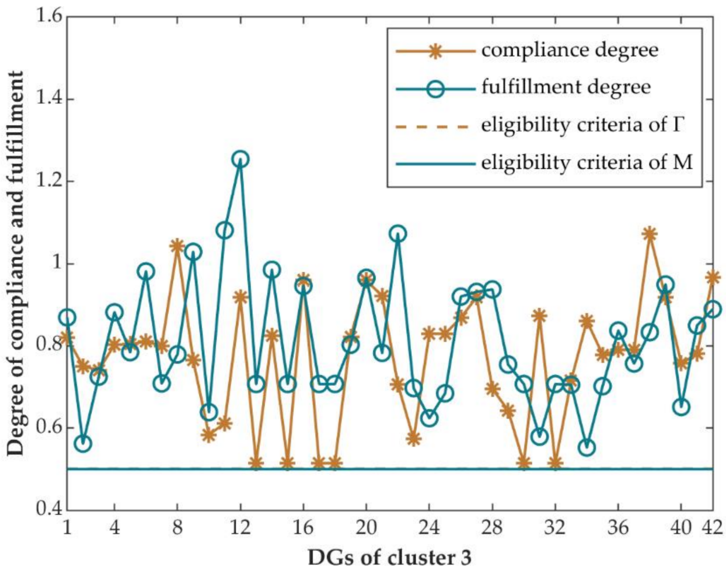

Figure 10. Degree of compliance and fulfillment in cluster 3.

Particularly, as shown in Figure 8, the fulfillment degree of DG whose serial number is 17 in cluster 1 is 0.47, less than the eligibility criteria 0.5. So, the peak shaving permit of this DG is revoked temporarily and converted to enter the prohibition period with the historical times of prohibition plus 1. In this case, the prohibition period is taken as twice the evaluation cycle, which means 8 times the scheduling cycle. Therefore, the DG No.17 in cluster 1 is forbidden to participate in peak shaving from the 53rd to the 60th scheduling cycle.

Then, this paper proposes that if the DGs in one cluster are eliminated to enter the prohibition period, the aggregate adjustable power of this cluster requires to be recalculated and updated, as well as the allocation of peak shaving instructions. Since the adjustable power of the DG unit eliminated from cluster 1 is 0.84 MW, the aggregate adjustable power of cluster 1 should change from 24.86 MW to 24.02 MW and the reallocation of peak shaving instructions during the 53rd to the 60th scheduling cycle are shown in Table 5.

Table 5. Comparison of peak shaving tasks allocation.

Cycle	Peak Shaving Instructions	No Self-Renewal Mechanism			Self-Renewal Mechanism		
		Cluster 1	Cluster 2	Cluster 3	Cluster 1	Cluster 2	Cluster 3
$k = 53$	40 MW	24.86 MW	15.14 MW	0 MW	24.02 MW	15.98 MW	0 MW
$k = 54$	90 MW	24.86 MW	51.32 MW	13.82 MW	24.02 MW	51.32 MW	14.66 MW
$k = 55$	70 MW	18.68 MW	51.32 MW	0 MW	18.68 MW	51.32 MW	0 MW
$k = 56$	100 MW	24.86 MW	51.32 MW	23.82 MW	24.02 MW	51.32 MW	24.66 MW
$k = 57$	70 MW	18.68 MW	51.32 MW	0 MW	18.68 MW	51.32 MW	0 MW
$k = 58$	60 MW	8.68 MW	51.32 MW	0 MW	8.68 MW	51.32 MW	0 MW
$k = 59$	0 MW	/	/	/	/	/	/
$k = 60$	0 MW	/	/	/	/	/	/

According to the allocation in Table 5, each cluster conducts their designative peak shaving tasks separately, the overall peak shaving precision which is defined as the ratio of the sum of all the cluster regulated power to the peak shaving instruction. The precisions of every cycle are compared and shown in Figure 11.

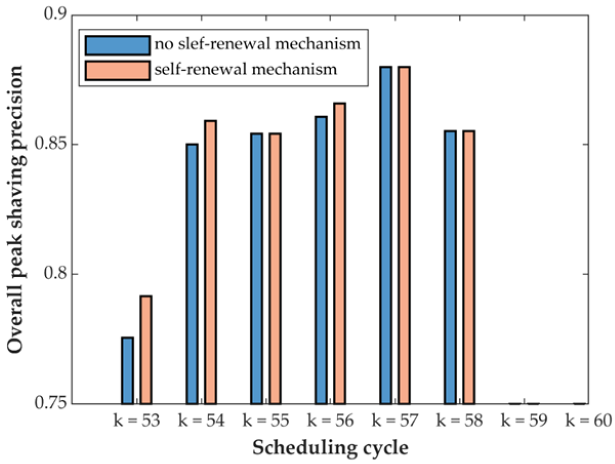

Figure 11. Overall precision based on the self-renewal mechanism.

In this case, the DG No.17 of cluster 1 is eliminated due to the unqualified fulfillment degree, so the impact of the self-renewal mechanism proposed on the overall peak shaving precision is mainly measured through comparative simulations. As shown in Figure 11, the self-renewal mechanism can manage the distributed generation well and effectively improve the regulation accuracy of peak shaving for aggregated clusters. The peak shaving effect of 96 scheduling cycles is shown in Figure 12.

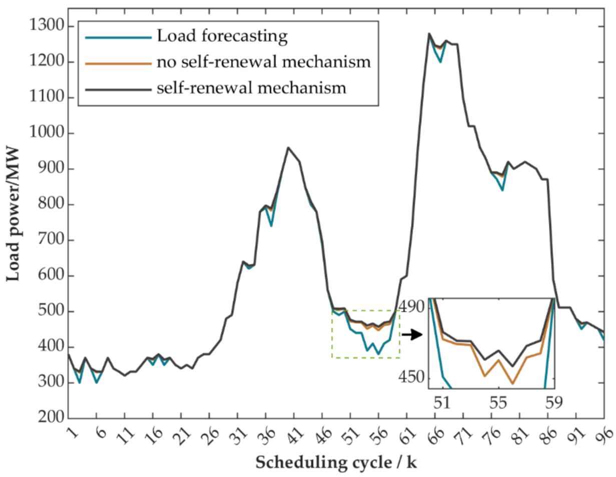

Figure 12. Comparison of peak shaving effect of 96 scheduling cycles.

5. Conclusions

This paper mainly proposes the task allocation and optimization method of DG clusters in peak shaving. Firstly, layer 1 proposes four indexes including: regulation rate, response rate, adjustable capacity, and peak shaving precision. Additionally, the priority sequencing of each DG is obtained and will be updated in every scheduling cycle. Then, this paper proposes a dynamic evaluation system to measure the peak shaving performance of each DG including: compliance, fulfillment, and credibility degree. The self-renewal mechanism is designed to update the aggregate adjustable power of the cluster, thus the constraints of the optimization model can also be changed. Experiments are conducted and simulation results validate the proposed two-layer peak shaving methods. The DG with poor peak shaving performance where the compliance degree or fulfillment degree is ineligible can be forbidden to participate in peak shaving in the next scheduling cycles temporarily based on the three-dimensional evaluation and the self-renewal mechanism. Further, the peak shaving precision can be promoted, the peak and valley difference can be also improved. The results indicate the evaluation of peak shaving performance is realistic and the mechanism is effective in avoiding overestimating or underestimating the peak shaving ability of each cluster. The dynamic change of aggregate adjustable power constraints of layer 2 can result in a more reasonable peak shaving task allocation. Especially when the peak shaving is so large that all DGs in the cluster need to participate in, together with the layer 1, it can avoid making the DGs with poor peak shaving performance participate in peak shaving as far as possible to improve the overall peak shaving effect. Further work will be carried out in the following aspects: simplifying the computation of sequencing in layer 1, breaking the quantity limit of clusters in layer 2, and so on.

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Abbreviations

AHP	analytic hierarchy process
DGs	distributed generations
EWM	entropy weight method
MCDM	Multi-Criteria Decision Making
PV	photovoltaic
TOPSIS	techniques for order preference by similarity to an ideal solution

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