Quantitative evaluation method of load side flexibility for industrial park

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Abstract. In view of the researches on the quantitative evaluation methods systems for load side flexibility, the evaluation methods using matter-element extension and setting pair analysis usually qualitative analysis the flexibility of load only. At present, they do not quantify the flexibility of each load. Thus, firstly, according to the factors affecting the load flexibility of industrial parks, this paper selects 10 indicators from four aspects to form an index system to evaluate the load flexibility of industrial parks. Secondly, considering the correlation between indicators, the grey correlation matrix is proposed to improve the entropy weight method for the first time. Thirdly, in order to eliminate the influence of human subjective factors, the coupling method of analytic hierarchy process and improved entropy weight method is used to determine the weight of indicators. Finally, in order to overcome the shortcomings of the traditional TOPSIS method, an improved set pair analysis (SPA) based on grey entropy and TOPSIS coupling method is proposed to quantify the load flexibility of industrial parks.

1. Introduction

With the large-scale access of random clean energy such as wind power and photovoltaic to the power grid, the flexibility of traditional generation scheduling is limited. And load regulation has gradually become an important means to alleviate the shortage of electricity. Through load regulation, the original power consumption mode is changed to improve the terminal power consumption efficiency and the safety and reliability of the power system. In this context, it is of great significance to accurately quantify the flexibility of load and formulate corresponding strategies, especially for the industrial load that ranks first in the composition of national economic development.

For load flexibility index system and quantitative evaluation model, reference[1] proposed a consumption capacity evaluation method based on the operation data of regional wind power projects. Reference[2] established an evaluation system from the two dimensions of effect evaluation index and economic evaluation index, and established a demand response evaluation model based on grey comprehensive evaluation method. Reference[3] constructs the index system from the five dimensions of user load, user energy consumption, user energy reliability, user energy consumption and user energy consumption habit, establishes the matter-element extension method, establishes the demand response evaluation model. Reference[4] proposed an evaluation method of demand side user response potential based on fuzzy optimization set pair analysis theory. Reference [5] established an evaluation index system from five aspects: socio-economic level, energy consumption structure, environmental protection constraints, economy and supporting support, and proposed a regional power substitution.
potential evaluation method based on TOPSIS (technology for order preference by similarity to and ideal solution) method. Reference[6] proposed a quantitative method of load regulation potential based on improved grey target prospect theory.

This paper constructs the evaluation index system of load flexibility of industrial parks, and puts forward a quantitative evaluation method of Industrial Park flexibility based on the coupling of SPA and TOPSIS.

2. Evaluation index system of load flexibility in industrial parks

When evaluating the flexibility of different loads in industrial parks, the same load reduction rate may correspond to different load reduction due to the different power consumption of loads in different industrial parks. In order to make up for the deficiency of the evaluation index of load reduction rate, this paper proposes the adjustable depth as the evaluation index to make the quantitative evaluation of industrial load flexibility more accurate. At the same time, due to the different information receiving efficiency of each load, there are requirements for timeliness and accuracy in the process of participating in power grid regulation. Therefore, this paper proposes to take the information receiving efficiency as the index to evaluate the load flexibility of industrial parks. The meaning of each sub index value is as follows:

1) Adjustable depth $C_1$: The maximum value of the i-th load power change in the load regulation process of the industrial park is mathematically expressed as:

$$C_i = \max |Q'_{bi} - Q'_{ai}|$$

where, $Q'_{bi}$ refers to the power consumption at t time before the i-th load regulation in the process of load regulation in the industrial park, $Q'_{ai}$ refers to the power consumption of the industrial park at time t after the i-th load regulation in the regulation process.

2) Response deviation rate $C_2$: During the load regulation process of the industrial park, the amount of response required by the ith load is only different from the actual response. The ratio of the difference to the amount of response required is mathematically expressed as:

$$C_2 = \frac{\int_{t_{on,i}}^{t_{off,i}} (P_{ı,need} - P_{i,off}) \, dt}{\int_{t_{off,i}}^{t_{on,i}} P_{ı,need} \, dt}$$

where, $P_{ı,need}$ is the response amount required for the ith load in the regulation process of Industrial Park load, $P_{i,off}$ is the actual response of the ith load in the regulation process of Industrial Park load.

3) Maximum adjustable rate $C_3$: The maximum value of power regulation per unit time of the ith load in the regulation process of Industrial Park load reflects the speed of power regulation per unit time.

4) Maximum adjustable time $C_4$: The maximum value of Industrial Park load in the ith load regulation time in the regulation process describes the maximum duration of Industrial Park load regulation, and its expression is:

$$C_4 = t_{off,i} - t_{on,i} = \max(t_{off,i} - t_{on,i})$$

where, $t_{off,i}$ is the time after the ith load regulation, $t_{on,i}$ is the time before the ith load regulation.

5) Number of participation in scheduling $C_5$: The number of times the Industrial Park load receives the assigned task in the i-th load week during the regulation process.

6) Energy consumption violation record $C_6$: The number of violations of the i-th load in a week during the regulation of the load in the industrial park[7].
7) Completion times $C_7$: The number of times that the Industrial Park load receives and completes the power grid dispatching task in the $i$-th load in a week during the regulation process.

8) Information receiving efficiency $C_8$: After the power grid issues the dispatching command, the speed and accuracy of the $i$-th load receiving the dispatching command information in the regulation process of the Industrial Park:

$$S_{i,j}(t,k) = e^{-k_{i,j}}$$

where, $S_{i,j}(t,k) \in (0,1]$ task assigned for the $i$-th load after receiving the power grid $w_j$ information receiving efficiency at time $t$, $k_{i,j}$ is the information forgetting rate of the $i$-th load after receiving the task issued by the power grid.

9) Compensation for response $C_9$: The compensation given by the power grid for the $i$-th load participating in the response during the load regulation process of the industrial park consists of the incentive compensation brought by participating in the demand response project and the punishment for the arrival of the unfinished demand response project.

10) Proportion of energy income $C_{10}$: The ratio of economic income and energy consumption cost generated by power consumption per unit time of the $i$-th load in the regulation process of Industrial Park.

3. Load flexibility evaluation determine weight of Industrial Park

According to the flexibility evaluation index, the evaluation matrix is established. And the weight determined by analytic hierarchy process is used $\omega_j$, and Weight determined by entropy weight method $\omega_j$, and integrate with each other to determine the comprehensive weight of each flexibility index $W_j$. It makes up for the defects of the two methods when used alone, improves the entropy weight method on the basis of considering the correlation of indicators, and applies the obtained index weight to the quantitative model based on SPA and TOPSIS coupling method, so that the flexibility of quantification is closer to reality. The specific steps are as follows:

1) Establish evaluation matrix:

Assuming that the evaluation matrix contains $n$ evaluation objects and $M$ evaluation indexes, the initial evaluation matrix $X$ is obtained according to the sample observation data:

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nn} \end{bmatrix}$$

(5)

where, $x_{ij}$ is the $m$-th evaluation index of the $n$th industrial load.

2) Positive and standardized indicators

In order to eliminate the influence of different dimensions or index dimensions, dimensionless processing is required. The evaluation matrix $X$ is standardized according to the following equation to obtain the standardized matrix $B = [b_{ij}]$:

$$b_{ij} = \frac{x_{ij} - \min\{x_{1j}, x_{2j}, \ldots, x_{nj}\}}{\max\{x_{1j}, x_{2j}, \ldots, x_{nj}\} - \min\{x_{1j}, x_{2j}, \ldots, x_{nj}\}}$$

(6)

3) Select reference matrix

$$B_0 = (\max(b_{11}, b_{21}, \ldots, b_{m1}), \ldots, \max(b_{1n}, b_{2n}, \ldots, b_{mn}))$$

(7)

4) The grey correlation coefficient is calculated to obtain the grey correlation matrix $C$:

$$C_{ij} = \frac{\min_{i,j} |B_{0i} - b_{ij}| + \rho \max_{i,j} |B_{0i} - b_{ij}|}{|B_{0i} - b_{ij}| + \rho \max_{i,j} |B_{0i} - b_{ij}|}$$

(8)

where, $\rho = 0.5[24]$. 

3
(5) Standardize the grey incidence matrix $C$ to obtain the standardized matrix $Z$:

$$Z_j = \frac{C_j - \min\{C_{ij}, C_{2j}, \ldots, C_{nj}\}}{\max\{C_{ij}, C_{2j}, \ldots, C_{nj}\} - \min\{C_{ij}, C_{2j}, \ldots, C_{nj}\}} \quad (9)$$

(6) Calculate the proportion of the $i$-th sample under the $j$-th index, regard it as the probability used in the calculation of relative entropy, and calculate the probability matrix $P$:

$$p_j = \frac{z_j}{\sum z_j} \quad (10)$$

(7) Calculate the entropy of each index:

$$e_j = -k \sum_{i=1}^{n} p_{ij} \ln(p_{ij}), \ j = 1 \ldots m \quad (11)$$

where, $k=1/\ln(n)>0$.

4. Simulation verification analysis

(1) Establishment of index system

The analysis of the load flexibility of the industrial park is the prerequisite for realizing load dispatching. Through the processing and mining of the original data of the park load, the initial values of the indicators in this paper can be obtained, and the initial values of the indicators of the load users in the park are shown in Table 1.

| User   | $C_1$/kW | $C_2$ | $C_3$/kW/h | $C_4$/h | $C_5$ | $C_6$ | $C_7$ | $C_8$ | $C_9$ | $C_{10}$ |
|--------|----------|-------|------------|---------|-------|-------|-------|-------|-------|----------|
| Load1  | 4840     | 15.1  | 82.63      | 13      | 2     | 5     | 2     | 83.9  | 89    | 4.5      |
| Load2  | 7008     | 14.6  | 116.8      | 8       | 3     | 4     | 3     | 84.9  | 59    | 3.0      |
| Load3  | 971.2    | 10.5  | 16.19      | 1       | 4     | 2     | 3     | 85.3  | 48    | 3.5      |
| Load4  | 241.2    | 9.4   | 4.02       | 1       | 1     | 1     | 1     | 85.8  | 94    | 4.0      |
| Load5  | 11931    | 5.6   | 198.8      | 13      | 3     | 0     | 3     | 85.9  | 80    | 2.5      |
| Load6  | 1536     | 6     | 25.6       | 1       | 2     | 0     | 2     | 87.3  | 42    | 5.0      |
| Load7  | 916      | 11.5  | 15.22      | 16      | 0     | 3     | 0     | 88    | 75    | 4.2      |
| Load8  | 1373     | 12.1  | 22.89      | 7       | 0     | 3     | 0     | 84.1  | 41    | 5.0      |
| Load9  | 1128     | 9.9   | 18.81      | 4       | 0     | 1     | 0     | 87.4  | 69    | 3.0      |
| Load10 | 3946     | 12.2  | 66.27      | 9       | 1     | 3     | 1     | 90    | 87    | 2.6      |

(2) Combination weighting determines the weight of indicators:
Figure 1 Comparison of three weights

The weight of each index is shown in figure 1. According to the weight calculation results in figure 1, the evaluation index that has the greatest impact on the load flexibility of the industrial park is $C_1$, which is 0.35199. The size of these three indicators has a significant impact on the flexibility of adjustable load in industrial parks. The weights of other indicators are different.

Figure 1 show the comparison of weights obtained by analytic hierarchy process, improved entropy weight method and combined weight method. It can be seen from the figure that the combined weighting method improves the weights of adjustable depth and maximum adjustable rate by 52.85% and 60.158% respectively on the basis of the original analytic hierarchy process and the improved entropy weight method.

5. Conclusion
Through the example simulation, the following conclusions are obtained:

1) Due to different loads and power consumption in different industrial parks, the corresponding load reduction rate index can not better reflect the defect of load flexibility in different parks. The indexes of adjustable depth and information receiving efficiency proposed in this paper make the established system more in line with the reality of Industrial Park load.

2) The simulation results show that the improved combined weighting method improves the weights of adjustable depth and maximum adjustable rate by 52.85% and 60.158% respectively on the basis of the original analytic hierarchy process and the improved entropy weight method, which can more accurately and objectively evaluate the weights of various load indicators.

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