The Evaluation of the Comprehensive Contribution of Digital Twin Virtual Power Plant Participation in the Electricity Market

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Abstract. A comprehensive contribution index assessment system of internal resources of virtual power plants is established to accurately and thoroughly evaluate the role that internal resources play in digital twin virtual power plants, as well as to explore their potential, encourage their internal aggregated resources, and fully take into account their impact on the efficiency of power grids, the balance of power and electricity, the use of new energy, etc. In addition, a comprehensive contribution assessment method for virtual power plants is constructed. Finally, we analyze the comprehensive contribution of different types of distributed energy resources to the digital twin virtual power plant through calculation examples.

Keywords: Digital twin · Virtual power plant · Electricity market · Comprehensive contribution

1 Introduction

With the continuous development of digitalization, the concept of digital twin virtual power plants has attracted attention as a novel approach to meet demand-side load requirements in the electricity market, whose reform is gradually deepening. Some scholars have noted that as virtual power plants gradually develop to participate in regional market-oriented transactions, their economics will be more fully reflected [1, 2], necessitating urgent attention to the problem of new energy consumption within virtual power plants in order to reflect their high economic value.

Under the background of the new power system, Yan Qin [3] proposed a demand response optimization scheme for electric vehicle PV charging stations considering risk assessment. In the economic dimension, Xu Jiamin [4] took the comprehensive economic benefit of virtual power plants as an economic index and constructed a comprehensive evaluation index system for the active scheduling of virtual power plants. Li Ran [5] fully considered the choice of different investors under different risk orientations and proposed a capacity allocation model for multi-investor virtual power plants based on cost-benefit analysis. Mao Tian [6] evaluated the economic benefits of virtual power plants from three perspectives: cost evaluation, investment benefit, and investment evaluation, and constructed a virtual power plant benefit evaluation index system.

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Given the current contribution from virtual power plants in the electricity market, this paper proposes the construction of a comprehensive contribution evaluation index system taking the internal resources of virtual power plants into account, and aims to establish a comprehensive contribution evaluation model, which will serve as a theoretical basis for advancing the feasibility of digital twin virtual power plants participating in the electricity market.

2 Index System

The comprehensive contribution index evaluation system of virtual power plants evaluates the comprehensive contribution of digital twin virtual power plants to participate in the electricity market from three aspects: safety, reliability, and economy, as shown in Table 1. It considers factors like safe grid operation, power and energy balance, and new energy consumption.

(1) Security

To comprehensively evaluate the impact of internal resources, such as distributed generation and energy storage on the stable operation and dynamic control of the power grid in virtual power plants, this paper focuses on three security indexes, namely, the voltage qualification rate, the reliability rate of power supply, and the contract completion rate, to gain a more thorough understanding of the security of power generation and consumption of internal resources of virtual power plants.

(2) Reliability

This paper evaluates the stable power supply capacity and demand response level of various resources for the power and energy balance of the aggregated resources within the virtual power plant after the new energy is connected to the system in three indexes, namely, the timely response rate, average power outage duration, and the number of 24 h power outages, to reflect their impact on the overall reliability of the virtual power plant.

Table 1. Index evaluation system of virtual power plants

First grade index	Second grade indexes	Third grade indexes
Comprehensive contribution evaluation value	Security	Voltage qualification rate
		Reliability rate of power supply
		Contract completion rate
	Reliability	Timely response rate
		Average power outage duration
		Number of 24 h power outages
	Economy	Average electricity price
		Controllable capacity
		Average contribution of electricity

(3) Economy

To assess the economic benefits generated by the aggregation of internal resources, such as distributed power and energy storage to the virtual power plant as a whole, as well as to investigate the economic impact of the internal resource allocation of the virtual power plant on its new energy consumption, this paper selects three evaluation indexes in the economic dimension: average electricity price, controllable capacity, and the average contribution of electricity.

3 Evaluation Model

(1) Establishment of a set of risk factors and risk assessment sets related to the research object

All risk factors of the evaluated object are aggregated into a collection, which constitutes the set of risk factors. The identification of these risk factors involves a two-layer classification, consisting of the criterion layer and the index layer. The former layer encompasses various types of influencing factors, which contribute to the overall target influencing factor set W = $\{W_1, W_2, W_3, \ldots, W_a\}$.

Each factor within the set of goal-influencing factors has a second level of factors influencing it. Assuming there are b second level factors influencing a factor, this set of factors is denoted as W_1 $(W_2, W_3, \ldots, W_a) = \{W_{11}, W_{12}, W_{13}, \ldots, W_{1b}\}$. Subsequently, the set of evaluations is also created, and assuming there are c evaluations, this set is denoted as Y = $\{Y_1, Y_2, Y_3, \ldots, Y_c\}$.

(2) Construction of the judgment matrix of each risk factor

We can improve the accuracy and objectivity of the results and simplify the analysis by comparing the factors in pairs and minimizing the interference of other components. The judgment matrix is constructed to compare the relative importance of the factors under a factor in the first layer.

In order to ensure the rationality and objectivity of the constructed judgment matrix, a consistency verification process is implemented before using this matrix. The specific method for this process is outlined as follows:

1) To test the consistency of the two comparison scores, when the number of factors is less than three, the consistency index CI of the judgment matrix is calculated. Ideally, the CI obtained should be less than 0.10, and its calculation is as follows:

$$CI = \frac{\lambda_{\max} - n}{n - 1}, \tag{1}$$

where the maximum characteristic root $\lambda_{\max}$ in Eq. (1) can be obtained from Eq. (2):

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{W\omega_i}{n\omega_i}. \tag{2}$$

The n in the equation is the order of the judgment matrix, and $W\omega_i$ is the ith element of the matrix obtained by multiplying the judgment matrix W and the eigenvector ω; ω_i is the ith element of the eigenvector of the judgment matrix.

2) To verify the consistency of the two comparison scores, the random consistency index CR is calculated when the number of factors ranges from 3 to 9, and the desired CR < 0.10 is obtained with the following equation:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}. \tag{3}$$

(3) Construction of the risk fuzzy evaluation matrix

In order to gather data on the degree of risk factors, as well as to score and evaluate the comprehensive importance of each risk factor, a questionnaire is designed and distributed to industry experts. The collected data is then used to calculate the importance interval of the risk factors, and the affiliation of the ith risk factor to the jth evaluation level is obtained through Eq. (4).

$$\mathrm{r}_{ij} = \frac{\sum_{k=1}^{n} x_{ij}^{(k)}}{N}, \tag{4}$$

where N in the equation represents the total number of participants in the questionnaire; $\sum_{\mathrm{k}=1}^{n} x_{ij}^{(k)}$ represents the number of votes received by x_{ij} at the kth evaluation level. The affiliation of each risk factor to the provided evaluation level (generally chosen from 1–5 importance evaluation levels) obtained by the above method leads to the following evaluation matrix of Eq. (5).

$$\mathrm{R}_i = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix}. \tag{5}$$

The evaluation matrix multiplied by the weight vector ω_i is the evaluation result Bi of the hierarchical risk factor set Wi. Then the evaluation matrix of the total objective is the combination of the evaluation result Bi obtained by each factor set and the corresponding weight vector, i.e., the matrix is shown as follows:

$$R = \begin{bmatrix} B_1 \\ B_2 \\ \cdots \\ B_m \end{bmatrix} = \begin{bmatrix} \omega_1.R_1 \\ \omega_2.R_2 \\ \cdots \\ \omega_m.R_m \end{bmatrix}. \tag{6}$$

After the evaluation matrix R of the total objective is obtained and multiplied with the corresponding weight vector ω, the evaluation result of the final total objective W can be obtained as follow:

$$B = \omega.R. \tag{7}$$

(4) Application of the EWM method to modify index weights

Given the subjectivity of the FAHP method, this paper employs the EWM objective weighting method to fully consider the variability of aggregated resource data, and the indexes with small data variability will be given smaller weights, thus making the evaluation model more targeted. The main steps include data standardization, information entropy calculation, and the final determination of index weights.

1) Data standardization

The data are standardized according to Eq. (8), and the weight pij of the jth index value of the ith evaluation object is calculated.

$$p_{ij} = y_{ij} \Big/ \sum_{i=1}^{m} y_{ij}. \tag{8}$$

2) Calculation of the information entropy

The entropy value of the jth index is calculated according to Eq. (9), where k = 1/l nm and m is the number of evaluation objects.

$$e_j = -k \sum_{i=1}^{m} \left(p_{ij} * \ln p_{ij}\right) \tag{9}$$

3) Determination of the index weights

The entropy weight wij of the jth index is calculated according to Eq. (10) to determine the index weights.

$$w_{ij} = \frac{1 - e_j}{\sum \left(1 - e_j\right)}. \tag{10}$$

where n is the number of evaluation indexes, and the vector WEMW is used as the weights obtained by the EWM method.

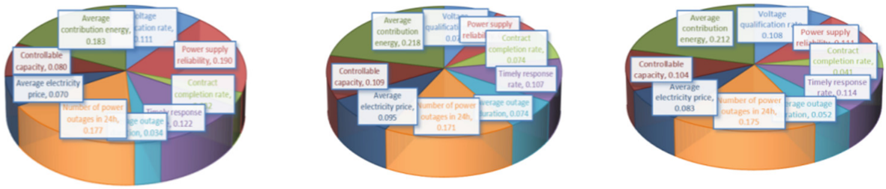
4) Correction of index weights.

The FAHP method has certain subjective limitations and ignores the actual data information, while the EWM method has certain objective limitations and ignores the subjective bias. To address these issues, it is necessary to combine subjective and objective assessment methods to assign weights. The final weight after correction is set to W.

$$W = \frac{W_{FAHP} * W_{EMW}}{\sum_{j=1}^{n} \left(W_{FAHP} * W_{EMW}\right)} \tag{11}$$

4 Example Analysis

(1) Determination of the evaluation object factor set and comment set



FAHP EWM FAHP-EWM

Fig. 1. Contribution evaluation results

The measured data are input into the comprehensive contribution index system, and the index set U = {voltage qualification rate, reliability rate of power supply,…, average contribution of electricity} = {u_1, u_2, …, u_9}. The set of comments is divided into 5 levels according to the expert ratings and the set of comments V = {good, good, fair, poor, poor} = {v_1, v_2, …, v_5}.

(2) Establishment of the judgment matrix and subjective weighting

To establish the expert scoring judgment matrix, the widely used 1–9 scale method is adopted. Based on the FAHP subjective weight method, the weight vector WFAHP of each index in the internal resource comprehensive contribution assessment system of the virtual power plant is calculated as WFAHP = (0.111, 0.190, 0.032, 0.122, 0.034, 0.177, 0.070, 0.080, 0.183)T.

(3) Weight correction of the assessment system based on the FAHP-EWM method
 1) Objective weighting based on the EWM method

According to Eqs. (8) and (10), the objective weights WEMW of the index in the assessment system of the internal resources of the virtual power plant based on the EMW objective weighting method are calculated as WEMW = (0.078, 0.074, 0.074, 0. 107, 0.074, 0. 171, 0.095, 0. 109, 0.217)T.

2) Results of the correction of the subjective and objective weight values of the comprehensive contribution degree

The final weights of the EWM method modified for the FAHP method are calculated using Eq. (11). The results of the comprehensive contribution degree assessment model of the aggregated resources within the virtual power plant based on the FAHP-EWM method are shown in Fig. 1.

5 Conclusion

The example results demonstrate that factors like the average contribution of electricity and the reliability rate of a power supply contribute more by building a comprehensive contribution index system and an evaluation model for virtual power plant participation in the electricity market. Energy storage in virtual power plants has the best effect on contributing electricity in real production. Therefore, it is recommended that priority be given to the configuration of energy storage devices in virtual power plants to meet the consumption needs of distributed new energy in virtual power plants and to improve the reliability and economy of virtual power plant participation in the electricity market.

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