Comprehensive Evaluation of the Modes of Investment and Operation of Multi-station Integration

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Abstract. With the reform of energy and the promotion of the digital economy, multi-station integration is being implemented. In order to promote the investment and operation of multi-station integration smoothly, it is necessary to study the comprehensive evaluation of the modes of investment and operation of multi-station integration. Firstly, five modes of investment and operation of multi-station integration are proposed. Secondly, the comprehensive evaluation model of the modes of investment and operation of multi-station integration based on the AHP-cloud model-TOPSIS is built up. The index system of the comprehensive evaluation of the modes of investment and operation of multi-station integration covering project characteristics, integration effect, project risk, economic benefit, and social benefit is constructed, and then considering the randomness and fuzziness of semantic information, the cloud model is used to improve AHP and TOPSIS respectively. The best scheme can be got by final order. Finally, through case analysis and comparative analysis, it can be concluded that the comprehensive evaluation model has high accuracy and feasibility, and it can better provide a decision-making basis and method for investment and operation of multi-station integration.

Keywords: Multi-Station Integration · Energy Internet · Modes of Investment and Operation · Comprehensive Evaluation · Cloud Model

1 Introduction

As an important application of Energy Internet, multi-station integration brings together resources such as transformer substation, data center station, and energy storage station, which is in the primary stage of implementation [6]. At present, there are still problems of uncertain modes of investment and operation at the level of investment and operation

N. Radojević et al. (Eds.): ICAID 2022, AHIS 7, pp. 931–941, 2023.
https://doi.org/10.2991/978-94-6463-010-7_93

of multi-station integration, [8]. It is urgent to propose and comprehensively evaluate the modes of investment and operation of multi-station integration, and select the best mode of investment and operation of multi-station integration to ensure the progress of investment and operation of multi-station integration smoothly.

At present, the research on multi-station integration mostly focuses on the technical aspects of operation and capacity allocation, and there is little research on the comprehensive evaluation of the modes of investment and operation of multi-station integration. The comprehensive evaluation of the modes of investment and operation of multi-station integration need to comprehensively consider the influence of multiple factors. Therefore, the comprehensive evaluation of the modes of investment and operation of multi-station integration is a multi-attribute decision-making problem. Considering the balance between economy and security of distribution network, reference [14] advanced a comprehensive evaluation model of a distribution network based on improved AHP-TOPSIS; Considering the characteristics of photovoltaic power generation, reference [1] used grey correlation degree and TOPSIS method to evaluate the risk of photovoltaic power generation projects; Considering the risk preference of decision-makers, reference [15] advanced a comprehensive evaluation method combining prospect theory and TOPSIS method; Considering the importance of materials, reference [9] advanced a candidate evaluation model of spare parts in power enterprises based on AHP and Delphi method. However, the evaluation process of the above references is affected by the subjectivity of the rater, which could not better overcome the randomness and fuzziness of semantic evaluation information, which was easy to lead to the roughness and one-sidedness of the evaluation results.

Firstly, this paper proposes five modes of investment and operation of multi-station integration. Secondly, this paper builds up a comprehensive evaluation model of the modes of investment and operation of multi-station integration based on the AHP-cloud model-TOPSIS. Firstly, it constructs a comprehensive evaluation index system of the modes of investment and operation of multi-station integration with project characteristics, integration effect, project risk, economic benefit, and social benefit as the criterion layer including 25 indexes. Then the cloud model is used to fully describe the randomness and fuzziness of semantic information in the evaluation process. Firstly, the index weight is determined to belong to the cloud based on the AHP-cloud model, and then the best scheme of five modes of investment and operation of multi-station integration is determined based on the ranking of the cloud model-TOPSIS decision-making method, in order to provide reliable decision-making basis and method for investment and operation of multi-station integration.

2 Proposal of the Modes of Investment and Operation of Multi-station Integration

At present, the common modes of investment and operation of engineering projects mainly include: 1. Boo mode, i.e. construction ownership operation mode, refers to the mode of investment and operation of who builds and who operates. 2. TOT model, i.e. handover operation handover, refers to that the owner transfers the operation right of its built project to other enterprises for a certain period. Other enterprises can share reasonable profits during the operation period and return the project to the owner at the expiration of the operation period. 3. PPP mode, i.e. public-private cooperation mode or joint-stock cooperation mode, refers to the state-owned capital attracting social capital to participate in the investment and operation of engineering projects in the form of equity participation.

Based on the above, five modes of investment and operation of multi-station integration are proposed: the mode of power grid enterprise's construction-joint operation (A_1), the mode of power grid enterprise's construction-joint operation-transfer (A_2), the mode of other enterprise's construction-joint operation (A_3), the mode of other enterprise's construction-joint operation-transfer (A_4), the mode of joint-stock cooperation (A_5).

2.1 The Mode of Power Grid Enterprise's Construction-Joint Operation

The mode of Power grid enterprise's construction-joint operation refers to the multi-station integration project is invested by power grid enterprises in full and operated jointly with other enterprises [3].

2.2 The Mode of Grid Enterprise's Construction-Joint Operation-Transfer Mode

The mode of power grid enterprise's construction-joint operation-transfer refers to that the power grid enterprise fully contributes to the construction and signs a franchise agreement with other enterprises. During the franchise period, other enterprises are allowed to participate in the operation of multi-station integration, and the multi-station integration will be transferred to the power grid enterprise free of charge [3].

2.3 The Mode of Other Enterprise's Construction-Joint Operation

The mode of other enterprise's construction-joint operation refers to the multi-station integration project invested by other enterprises in full and operated jointly with power grid enterprises. This mode of investment operation is relatively rare at present.

2.4 The Mode of Other Enterprise's Construction-Joint Operation-Transfer

The mode of other enterprise's construction-joint operation-transfer refers to that the power grid enterprises mainly invest in the construction, other enterprises participate in the construction and operate together with the power grid enterprises during the concession period, and transfer the multi-station integration project to the power grid enterprises free of charge at the expiration of the period [3].

2.5 The Mode of Joint-Stock Cooperation

The mode of joint-stock cooperation refers to that power grid enterprises take shares with substation resources or some funds to attract social capital to jointly form joint-stock companies, and rely on joint-stock companies to carry out investment and operation of multi-station integration [2]. This mode of investment operation is common at present.

3 Comprehensive Evaluation of the Modes of Investment and Operation of Multi-station Integration

3.1 Comprehensive Evaluation Index System of the Modes of Investment and Operation of Multi-station Integration

Based on the analysis of five modes of investment and operation of multi-station integration, this paper preliminarily selects 35 indexes from five aspects: project features, integration effects, project risks, economic benefits, and social benefits. To reduce the correlation between similar indexes, the appropriate number of classification is determined according to the actual needs, and 35 indexes are clustered by criterion layer by European square method; Then, through grey correlation analysis, it solves the grey correlation degree of similar indicators after clustering, screens out various indicators with high internal correlation degree, eliminates various indicators with low internal correlation degree [2], and finally determines the index system of the comprehensive evaluation of the modes of investment and operation multi-station integration including 25 indexes, as shown in Fig. 1.

3.2 Comprehensive Evaluation and Decision-Making Method of the Modes of Investment and Operation of Multi-station Integration Based on the AHP-Cloud Model-TOPSIS

3.2.1 Calculation Method of Index Weight Based on the AHP-Cloud Model

Analytic hierarchy process (AHP) is a method to determine the index weight according to the subjective evaluation of experts. By judging each factor, it divides each factor into different layers, compares two factors in each layer, and establishes a judgment matrix to further obtain the index weight [13].

The cloud model can realize qualitative and quantitative transformation. Adding subordinate cloud to the evaluation scale represents the fuzziness and randomness of the evaluation language, which can improve the subjectivity of the AHP method to a certain extent [4].

According to the respective characteristics of the AHP method and cloud model, the hierarchical weight represented by the subordinate cloud is used to calculate the index weight. The calculation steps of index weight based on the AHP cloud model are as follows:

Step 1: Invite n experts in the research field of multi-station integration in the form of questionnaire surveys to score each index of the index system of the comprehensive evaluation of investment and operation mode of multi-station integration. The evaluation scale is 1–9 scale method [7], and finally, get the single ranking judgment matrix of each level $A = \left(a_{ij}^{(k)}\right), k = 1, 2, ...n$.

Step 2: Calculate the expectation *Ex*, entropy *En* and super entropy *He* of each level single ranking judgment matrix $a_{ij}^{(k)}$ through the reverse membership cloud generator [11]. When calculating expectations, to effectively reflect the expectations of multiple experts, the scale of 1–9 can be replaced with the scale of - 8–8, specifically 9 corresponds

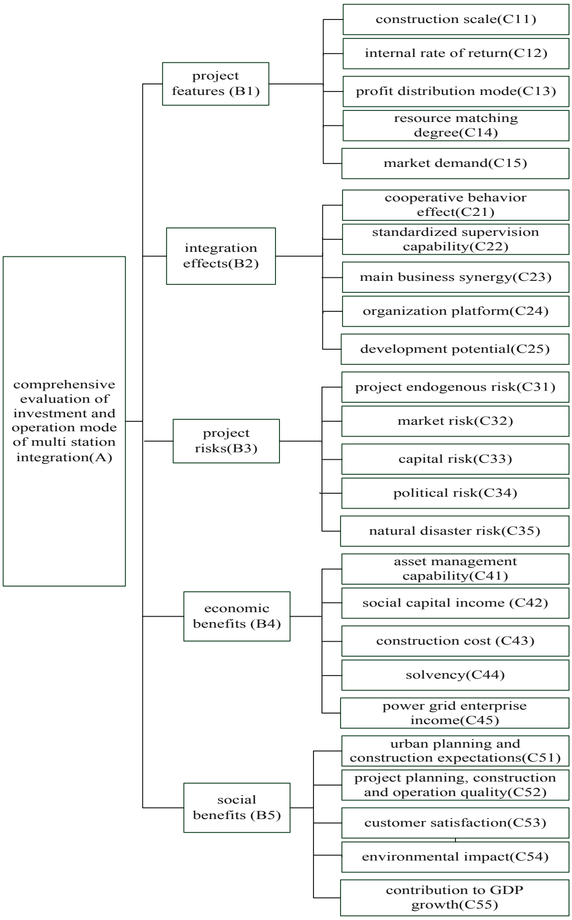

Fig. 1. Comparison of relative closeness between the two methods

to 8, 8 corresponds to 7,…, 1 corresponds to 0, −1 corresponds to 1/2, −2 corresponds to 1/3,…, and −8 corresponds to 1/9 [11].

Based on the above, the judgment matrix $a_{ij}^{(k)}$ will be transformed into $b_{ij}^{(k)}$. $b_{ij}^{(k)}$ is averaged to get $\frac{1}{n}\sum_{k=1}^{n} b_{ij}^{(k)}$. $\frac{1}{n}\sum_{k=1}^{n} b_{ij}^{(k)}$ will be rounded to $\left[\frac{1}{n}\sum_{k=1}^{n} b_{ij}^{(k)}\right]$ and then transformed into a 1–9 scale:

$$Ex = \begin{cases} [\frac{1}{n}\sum_{k=1}^{n} {b_{ij}}^{(k)}]+1, [\frac{1}{n}\sum_{k=1}^{n} {b_{ij}}^{(k)}] \geq 0 \\ \frac{1}{1-[\frac{1}{n}\sum_{k=1}^{n} {b_{ij}}^{(k)}]}, [\frac{1}{n}\sum_{k=1}^{n} {b_{ij}}^{(k)}] \leq 0 \end{cases} \tag{1}$$

$$En = \sqrt{\frac{\pi}{2}} \times \frac{1}{n}\sum\nolimits_{k=1}^{n} \left| b_{ij}^{(k)} - Ex \right| \tag{2}$$

$$He = \sqrt{S^2 - En^2}$$
$$(S^2 = \frac{1}{n-1}\sum\nolimits_{k=1}^{n}(b_{ij}^{(k)} - \overline{X})^2) \tag{3}$$

Step 3: Sort the hierarchical list and check the consistency. Based on Eqs. (1), (2) and (3), the original judgment matrix $a_{ij}^{(k)}$ is transformed into the subordinate cloud judgment matrix:

$$a_{ij}^{(k)} = \begin{pmatrix} a_{11}^{k} & \ldots & a_{1n}^{k} \\ \vdots & & \vdots \\ a_{n1}^{k} & \cdots & a_{nn}^{k} \end{pmatrix} = \begin{pmatrix} (Ex_{11}, En_{11}, He_{11}) & \ldots & (Ex_{1n}, En_{1n}, He_{1n}) \\ \vdots & & \vdots \\ (Ex_{n1}, En_{n1}, He_{n1}) & \cdots & (Ex_{nn}, En_{nn}, He_{nn}) \end{pmatrix}$$

The membership cloud judgment matrix is regarded as three matrices: expectation Ex, entropy En and super entropy He. The three matrices are ranked in a single hierarchy, and the consistency test of the expectation matrix is carried out according to Eqs. (4), (5) (the consistency test is not required for the judgment matrix of entropy and super entropy [13], the consistency index of the judgment matrix is calculated [13]:

$$C.I. = (\lambda_{\max} - n)/(-1) \tag{4}$$

To measure the random consistency of different scales, the consistency ratio is calculated [13]:

$$C.R. = C.I./R.I. \tag{5}$$

When $C.R. < 0.1$, the matrix has satisfactory consistency, including random consistency index $R.I.$

Step 4: Sort the hierarchy. According to the multiplication operation method [12] of the digital characteristics of the cloud model, the total hierarchy is sorted from high level to low level, and finally, the weight of the index layer relative to the target layer belongs to the cloud.

3.2.2 Decision-Making Method Based on Cloud Model-TOPSIS Combined with Weight

Step 1: The first step is to invite experts to score and use the reverse cloud generator for processing. Based on the five modes of investment and operation of multi-station integration in Sect. 2, experts are invited to score the indexes of the five modes of investment and operation of multi-station integration, and the decision-making subordinate cloud is obtained by using the reverse cloud generator. In order to ensure the stability and accuracy of the reverse cloud algorithm, it reduces the calculation error and avoids the situation that the calculated super entropy He is an imaginary number. The multi-step restoration reverse cloud algorithm, the MBCT-SR algorithm [13], is used to process the data. The MBCT-SR algorithm is stable and convergent. Based on the MBCT-SR algorithm, with executing T = N times, it takes entropy En and super entropy He as the mean value of the estimated value, and calculates the indexes of the evaluation of five modes of investment and operation of multi-station integration.

Step 2: Construct a weighted decision membership cloud. According to the multiplication regulation based on the digital characteristics of cloud model [4], the index weight subordinate cloud and the index evaluation value subordinate cloud are aggregated to obtain the weighted decision subordinate cloud matrix $Z = (z_{ij})_{m\times n}$(i represents the scheme ranking, i = 1, 2, 3, 4, 5; j represents the index ranking, j = 1, 2,…, 25). Let the characteristic value of the weighted subordinate cloud be $\omega_j = (Ex_j, En_j, He_j)$, and let the decision subordinate cloud matrix be $B = (b_{ij})_{m\times n}$ $(b_{ij} = (Ex_{ij}, En_{ij}, He_{ij}))$. The weighted decision subordinate cloud is:

$$\begin{aligned} z_{ij} &= \omega_j b_{ij} \\ &= (Ex_j, En_j, He_j)(Ex_{ij}, En_{ij}, He_{ij}) \end{aligned} \tag{6}$$

(i represents the scheme ranking, $i = 1, 2, 3, 4, 5. j$ represents the index ranking, $j = 1, 2, ..., 25$).

Step 3: Construct the cloud of the positive ideal solution and negative ideal solution. The benefit-effective indexes indicate that the larger the attribute value is, the better it is. The cost-effective indexes indicate that the smaller the attribute value is, the better it is. Therefore, in the index system of evaluation, the project risk level indexes {C31, C32, C33, C34, C35} are cost-effective indexes, other indexes are benefit indexes. The benefit-effective indexes are set up T_1, and cost-effective indexes are set up T_2.

Then the subordinate cloud of the positive ideal solution is:

$$\begin{cases} z_{ij}^{*+} = (\max_i Ex_{ij}^*, \min_i En_{ij}^*, \min_i He_{ij}^*),\ j \in T_1 \\ z_{ij}^{*+} = (\min_i Ex_{ij}^*, \min_i En_{ij}^*, \min_i He_{ij}^*),\ j \in T_2 \end{cases} \tag{7}$$

The subordinate cloud of the negative ideal solution is:

$$\begin{cases} z_{ij}^{*-} = (\min_i Ex_{ij}^*, \max_i En_{ij}^*, \max_i He_{ij}^*),\ j \in T_1 \\ z_{ij}^{*-} = (\max_i Ex_{ij}^*, \max_i En_{ij}^*, \max_i He_{ij}^*),\ j \in T_2 \end{cases} \tag{8}$$

The weighted-decision subordinate cloud and the subordinate cloud of the positive ideal solution and negative ideal solution are obtained from Eqs. (6), (7), and (8) in steps 2 and 3.

Step 4: Calculate the distance between the weighted-decision subordinate cloud of each index of the five modes of investment and operation of multi-station integration and the subordinate cloud of positive ideal solution and negative ideal solution. The similarity measure concept of the cloud model is used to calculate the distance between the weighted-decision subordinate cloud of five schemes and the subordinate cloud of positive ideal solutions and negative ideal solutions [11, 12].

To objectively reflect the similarity between subordinate clouds, the vector 1-norm is used to define the distance between any two subordinate cloud vectors $a_i(Ex_i, En_i, He_i)$ and $a_j(Ex_j, En_j, He_j)$ which are all zero when their digital features are different [10]:

$$\begin{aligned} d(a_i, a_j) &= \frac{\left\| a_i - a_j \right\|}{\|a_i\| + \left\| a_j \right\|} \\ &= \frac{\left|Ex_i - Ex_j\right| + \left|En_i - En_j\right| + \left|He_i - He_j\right|}{|Ex_i| + |En_i| + |He_i| + \left|Ex_j\right| + \left|En_j\right| + \left|He_j\right|} \end{aligned} \tag{9}$$

From the weighted-decision subordinate cloud and the sum of subordinate clouds of positive ideal solution and negative ideal solution from Eq. (9), the distance between the weighted-decision subordinate cloud, and the subordinate cloud of positive ideal solution and negative ideal solution of the modes of the investment operation of multi-station integration can be obtained.

Step 5: Calculate the Euclidean distance between the five modes of investment and operation of multi-station integration and the subordinate cloud of positive ideal solutions and negative ideal solutions, as well as the relative closeness of the five schemes.

The Euclidean distance between the scheme and the subordinate cloud of the positive ideal solution [13]:

$$D_i^+ = \sqrt{\sum_j^n (d_j^+)^2} \tag{10}$$

The Euclidean distance between the scheme and the subordinate cloud of negative ideal solution [13]:

$$D_i^- = \sqrt{\sum_j^n (d_j^-)^2} \tag{11}$$

The relative closeness of the scheme A_i [13]:

$$C_i^+ = \frac{D_i^-}{D_i^- + D_i^+} \tag{12}$$

Through (10), (11), (12), the Euclidean distance and relative closeness between the five modes of investment operation of multi-station integration can be got. The bigger the relative closeness is, the better the scheme is. By comparing the calculation results of the relative closeness, the best mode of investment and operation of multi-station integration can be got.

4 Results and Discussion

4.1 Case Analysis

This paper selects the first pilot of multi-station integration in Jiangsu – 220 kV Hongqi substation as an example. The pilot of multi-station integration integrates the construction of EV charging station, data center station, 5G base station, and Beidou base station based on the transformer substation.

Firstly, 25 experts from different fields of power system, economy, engineering, society, and environment are invited to give weight to each index based on the interaction relationship of each index. According to the index weight calculation method based on the AHP - cloud model, the data is processed, and the index weight of the comprehensive evaluation of the modes of investment and operation of multi-station integration belongs to the cloud. Then, 25 experts are invited to continue to evaluate and score the index

Table 1. Relative Closeness between the Five Schemes

B_0	A_1	A_2	A_3	A_4	A_5
C_i^+	0.5017	0.5356	0.4636	0.5355	0.5567

Table 2. Relative Closeness between the Five Schemes

B_0	A_1	A_2	A_3	A_4	A_5
C_i^+	0.4037	0.5746	0.3335	0.3915	0.6072

attributes under the five modes of investment and operation of multi-station integration. According to the decision-making method based on the cloud model - TOPSIS combined with the weight, the data are processed. Finally, the relative closeness C_i^+ of the five schemes is obtained, and the calculation results are shown in the Table 1.

(B_0: the modes of investment and operation of multi-station integration)

According to the calculation results of relative closeness $C_5^+ > C_2^+ > C_4^+ > C_1^+ > C_3^+$, the five schemes can be ranked. The scheme with bigger relative closeness is better, that is, the modes of investment and operation of multi-station integration are ranked as $A_5 > A_2 > A_4 > A_1 > A_3$.

Therefore, the best scheme is A_5, and the best scheme is the mode of joint-stock cooperation.

4.2 Comparative Analysis

In reference [5], the normal fuzzy-TOPSIS method calculates the example and the relative closeness of each scheme is obtained. The calculation results are shown in Table 2.

(B_0: the modes of investment and operation of multi-station integration)

According to the calculation results of relative closeness, the ranking result of the schemes is $A_5 > A_2 > A_1 > A_4 > A_3$ (Fig. 2).

Combined with the results of the two decision-making methods, it can be seen that the two methods can get the same scheme, but the difference lies in the order of A_1 and A_4. The main reason is that the cloud model and normal membership function should obey the law of normal distribution, but the cloud model also should consider the randomness of subordinate degree, which can better solve the problem of information distortion to a certain extent. Therefore, the AHP-cloud model-TOPSIS method will be more credible than the normal fuzzy-TOPSIS method.

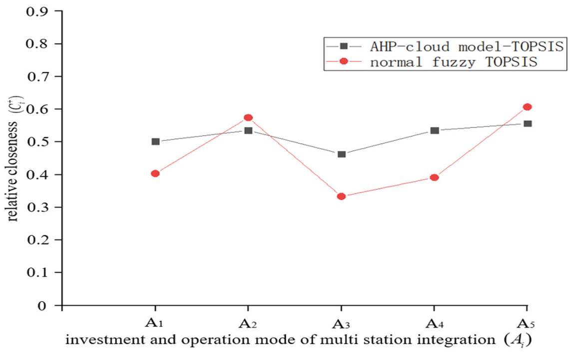

Fig. 2. Comparison of relative closeness between the two methods

5 Conclusion

This paper firstly proposes five modes of investment and operation of multi-station integration, and then constructs a comprehensive evaluation of the modes of investment and operation of multi-station integration. The AHP-cloud model-TOPSIS method is adopted to study the comprehensive evaluation of the modes of investment and operation of multi-station integration.

The main conclusions can be summarized as follows: (1) The best scheme of the modes of investment and operation of multi-station integration is the mode of joint-stock cooperation. (2) The comprehensive evaluation model based on AHP-cloud model-TOPSIS can better provide decision-making basis and method for investment and operation of multi-station integration.

At present, multi-station integration is still in the early stage of implementation, and the data of quantitative indexes are difficult to obtain, which can only be obtained in the form of expert scoring. When more multi-station integration will enter the stage of investment and operation in the future, the comprehensive evaluation of the modes of investment and operation of multi-station integration can be further improved through the actual data.

Acknowledgments. This study is supported by Science & Technology Project of SGCC (1400-202057226A-0-0-00).

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