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Multi-level Fuzzy Statistics and Maximum Entropy Rule Based Comprehensive Evaluation Strategy for Development Level of Global Energy Interconnection

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Abstract. Global energy interconnection is the next development stage of future power grid. In order to evaluate its development level and identify the weakness spot in the developing process, a comprehensive evaluation strategy for development level of global energy interconnection is proposed in this paper. This strategy is proposed based on the fuzzy statistics method and maximum entropy rule. The effectiveness of this evaluation strategy is illustrated through calculation examples. The calculation results show that the development degree of global energy interconnection in China, United States and Germany has reached a very good level.

1. Introduction

With the rapid increase of renewable energy installed capacity, it is necessary to build a world's platform to achieve the unified development, allocation and accommodation of renewable energy. Therefore, the concept of global energy interconnection [1] is put forward. Global energy interconnection is a global energy allocation platform on the base of ultra-high voltage power grid and smart grid. The main task of global energy interconnection is to transmit renewable energy on a global scale. Global energy interconnection is the next development stage of future power grid, which conforms to the development trend of world energy and power grid.

The basic theoretical system of global energy interconnection has been established, including concepts, layout frame, development stage and main features. However, in order to identify the weakness spot in the construction process of global energy interconnection, the comprehensive evaluation method of its development level still needs further study.

Lots of work has been done focusing on the development level evaluation of smart grid. A maturity model for smart grid has been proposed by IBM [2]. The United States department of energy has developed a smart grid development evaluation index system, which summarizes six characteristics of smart grid's development level [3]. A revenue assessment system has been put forward by European Union, which summarizes the driving factors of smart grid development into three aspects: market, security and power quality, environment. The above research results have provided good foundation for the development level evaluation for global energy interconnection. However, global energy interconnection is a grand goal which involves complex and numerous influence factors. Therefore, current research results for smart grid cannot be used directly.



A comprehensive evaluation strategy for development level of global energy interconnection is proposed in this paper. Firstly, the hierarchical evaluation structure of index system is proposed. Then, a qualitative index's quantified method based on fuzzy statistics and expert evaluation is put forward. Afterwards, a weighting method for indexes based on maximum entropy rule is analyzed. Finally, the effectiveness of this comprehensive evaluation strategy is illustrated through calculation examples.

2. Technological Process Chart of Comprehensive Evaluation Strategy

The technological process chart of comprehensive evaluation strategy is proposed first in fig.1, in which the core methods are multilevel fuzzy statistics and maximum entropy criterion based weight design.

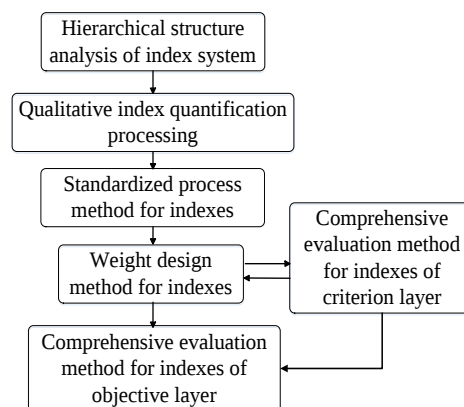


Figure 1.Technological process chart of comprehensive evaluation strategy.

Firstly, the hierarchical structure of index system is analyzed. Based on this, the value of comprehensive evaluation index is obtained using analytic hierarchy process. In this work, the index system is divided into three layers: objective layer, criterion layer and index layer. Secondly, the qualitative indexes are quantified using fuzzy statistics and expert evaluation method. The indexes are normalized using range transformation method. Afterwards, the weights of indexes are obtained using maximum entropy criterion based optimal design method. Finally, the values of comprehensive evaluation index for objective layer is calculated.

3. Hierarchical Structure Analysis of Index System

There are lots of influence factor and indexes of development level for global energy interconnection. It will be very complicated if all the indexes are calculated directly. Therefore the hierarchical structure for indexes is proposed in table1.

There are three layers in this hierarchical index system. Objective layer is the ultimate goal of evaluation and it is development level for global energy interconnection in this paper. Criterion layer is the detail description and extension of objective layer, which is divided into nine classes according the main influence factor. Index layer is the further detail decomposition for each influence factor in Criterion layer. The subordinate relation of each influence factor is determined based on the hierarchical structure. The essence of this development level evaluation is a multilevel and multi-factor comprehensive evaluation problem considering the influence of uncertainty.

Table 1. Hierarchical Structure of Indexes System

Objective layer	Criterion layer	Index layer	Index attribute
Development level for global energy interconnection	Concept promotion	Energy structure adjustment target	qualitative
		Electrification target	qualitative
		Emission reduction target	qualitative
		Interconnectivity target	qualitative

		Education degree	qualitative
		Domestic political stability	qualitative
	Technical level	Voltage level of main power grid	quantitative
		Technology level of ultra-high voltage(UHV)	qualitative
		Technology level of power forecasting for renewable energy	qualitative
		Technology level of renewable integration	qualitative
	Engineering construction	Number of interregional transmission lines	quantitative
		Capacity of interregional transmission lines	quantitative
		Presence of UHV engineering construction	quantitative
		Per capita transmission line length	quantitative
		Per capita installed capacity	quantitative
		Development level of renewable energy	qualitative
	Market operation	Power demand growth level	quantitative
		Opening degree of international market	qualitative
		Investment risk for electric power project	qualitative
	Extensive interconnection	Power grid covering range	quantitative
		Complementary capability	qualitative
		Import and export activity	quantitative
	Reliability and security	N-1 pass rate of transmission rate	quantitative
		Regulation capability	quantitative
		Power outage time	quantitative
		Line loss rate	quantitative
	Economy and efficiency	Wind power curtailment rate	quantitative
		Photovoltaic power curtailment rate	quantitative
		Generation cost for renewable energy	quantitative
	Emission reduce	Development plan for renewable energy	quantitative
		Investment for renewable energy	quantitative
		Per capita renewable energy installed capacity	quantitative
		Generation hours for renewable energy	quantitative
		Carbon emission for unit power generation	quantitative
		Per capita electric vehicle ownership	quantitative
		Per capita electric vehicle charging infrastructure	quantitative
	Smartness and interaction	Flexible pricing mechanism	quantitative
		Investment for smart grid	quantitative
		Demand response participation	quantitative
		Installed rate for smart meters	quantitative
		Interactive technology level	quantitative

4. Qualitative Index Quantification Method Based on Fuzzy Statistics

It is difficult to quantify the qualitative indexes in table1, which brings great difficulty to the comprehensive evaluation method. Therefore, a fuzzy statistical^[4-6] based method is proposed here to quantify the qualitative indexes, considering the fuzzy linear transformation and subordinate degree synthesis principle.

The membership degree for each element is obtained using fuzzy test in fuzzy statistical method. There are four basic elements for fuzzy test: (1) Theory of domain U, which is the scope of researched problem. (2) A certain element u in U. (3) A fuzzy set A^* related to a common set of random motion A. (4) Condition S, which is linked to the objective or psychological factors of segmentation process for fuzzy concept.

There are three main steps for fuzzy statistical method. Firstly, the theory of domain U and influence factor set should be determined. Secondly, the test participants should vote for whether a certain point in U belongs to each element of influence factor set. Finally, analyzing the vote results, the membership frequency can be calculated using equation (1). As the increase of n , the membership frequency will become stable, which converge to the membership degree of u belonging to A^* .

$$f_n(u) = \frac{\theta(u)}{n} \quad (1)$$

Where $f_n(u)$ is the membership frequency of u belonging to A_* , $\theta(u)$ is the number of A_* covering u , n is the number of total test.

The score set can be divided into five grades first, which are “very good”, “good”, “common”, “poor” and “very poor”, respectively. Then, the membership degree of a qualitative index belongs to each score grade is obtained using fuzzy statistical method. The membership degree matrix of index system can also be obtained, shown in equation (2).

$$\begin{bmatrix} R_1 \\ R_2 \\ \dots \\ R_g \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{15} \\ r_{21} & r_{22} & \dots & r_{25} \\ M & M & \dots & M \\ r_{g1} & r_{g2} & \dots & r_{g5} \end{bmatrix} \quad (2)$$

Where R_g is the g -th qualitative index, r_{gm} is the membership degree of index g belongs to score grade m .

The membership degree matrix should be quantified to obtain the comprehensive score corresponding to each index. Firstly, each score grade is given a certain score value. Then, the comprehensive score is obtained through the multiplex operation between score vector and membership degree matrix, as in shown in equation (3).

$$\begin{bmatrix} F_1 \\ F_2 \\ \dots \\ F_g \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{15} \\ r_{21} & r_{22} & \dots & r_{25} \\ M & M & \dots & M \\ r_{g1} & r_{g2} & \dots & r_{g5} \end{bmatrix} \cdot \begin{bmatrix} c_1 \\ c_2 \\ \dots \\ c_5 \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^5 r_{1i}c_i \\ \sum_{i=1}^5 r_{2i}c_i \\ M \\ \sum_{i=1}^5 r_{gi}c_i \end{bmatrix} \quad (3)$$

Where $c_1 \sim c_5$ is the score value of each score grade, respectively. For the small value prefer indexes, such as investment risk, it is considered that a smaller index value corresponds to a higher score value. For the larger value prefer index, such as economic benefit, it is considered that a larger index value corresponds to a higher score value.

5. Index Normalization Processing Method Based on Range Transformation Method

In order to calculate and analyze the indexes with different dimension, all the indexes should be normalized. A range transformation method [7] is introduced here to normalize the indexes. For a positive index r_{ij} prefers high value, it can be normalized using equation (4). For a negative index r_{ij} prefers low value, it can be normalized using equation (5).

$$y_{ij} = \frac{x_{ij} - \min_{1 \leq t \leq n} x_{it}}{\max_{1 \leq t \leq n} x_{it} - \min_{1 \leq t \leq n} x_{it}} (1 \leq i \leq m, 1 \leq j \leq n) \quad (4)$$

$$y_{ij} = \frac{x_{ij} - \min_{1 \leq t \leq n} x_{it}}{\max_{1 \leq t \leq n} x_{it} - \min_{1 \leq t \leq n} x_{it}} (1 \leq i \leq m, 1 \leq j \leq n) \quad (5)$$

All the indexes normalized by this method satisfy the range of $0 \leq y_{ij} \leq 1$. In addition, no matter negative or positive index, the optimal value is 1 and the worst value is 0.

6. Optimal Design of Index Weights Based on Maximum Entropy Criterion

The main factor affects the rationality the multiple indexes' comprehensive evaluation is the weight of each index. Index weight is the quantitative distribution of importance for evaluation object from different aspects. Through the reasonable setting of index weight, the real contribution degree of each index for evaluation object can be obtained. Comparing to the subjective weighting method, the

weighting method based on entropy has higher reliability. In addition, the computational complexity of weighting method based on entropy is lower comparing to most of objective weighting method.

A maximum entropy rule [8-9] based index weighting method is used here to determine the weights of indexes in index layer relative to the corresponding indexes in criterion layer, and the weights of indexes in criterion layer relative to the objective index. Based on the maximum entropy mathematical model and optimization method, the optimal weights can be obtained in equation (6).

$$w_j = \frac{\exp\left(-\left[1 + \delta \sum_{i=1}^n (1-r_{ij})^2 / (1-\delta)\right]\right)}{\sum_{j=1}^m \exp\left(-\left[1 + \delta \sum_{i=1}^n (1-r_{ij})^2 / (1-\delta)\right]\right)}, j=1,2,L,m \quad (6)$$

Where n is the number of calculation sample, r_{ij} is the normalized index value of i -th index in calculation sample j . δ is a parameter that can be assigned of any value in the range $0 \leq \delta \leq 1$.

7. Calculation Examples

10 countries are considered as research objective in the calculation examples here, which are United States, Australia, Thailand, China, Russia, Brazil, Pakistan, Germany, Ethiopia and Saudi Arabia, respectively. The current development level of global energy interconnection construction in 2015 of each country is calculated using the method proposed above. The values of quantitative index are obtained using public data from internet.

7.1. Weights Analysis of Index Layer Relative to Criterion Layer

The weights of indexes in the index layer relative to corresponding index in the criterion layer are analyzed here using maximum entropy rule based method. Taking technical level and engineering construction for example, the weighting results are shown in fig.2 and fig. 3.

From fig.2, it is shown that the technology level of renewable integration has the most obvious influence on technical level index, while the voltage level of main power gird has the minimum influence. From fig. 3, it can be seen that the development level of renewable energy has the most obvious influence on engineering construction index, while the capacity of interregional transmission lines has the minimum influence.

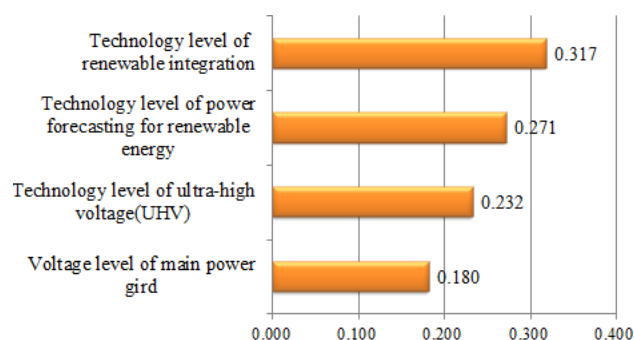


Figure 2. Weights of indexes relative to technical level.

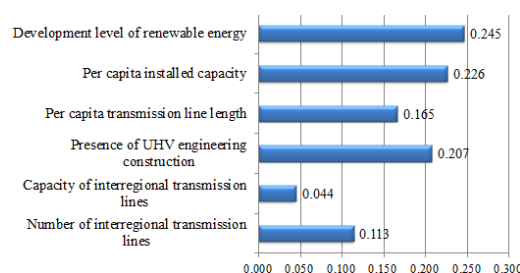
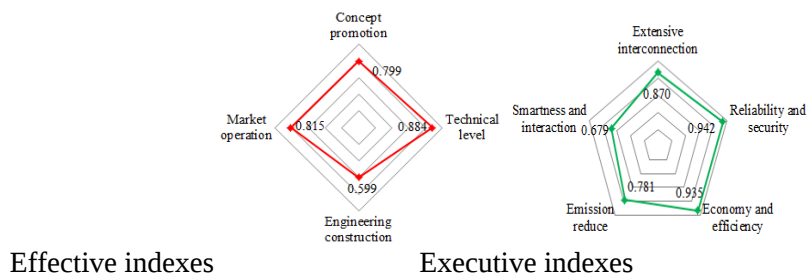
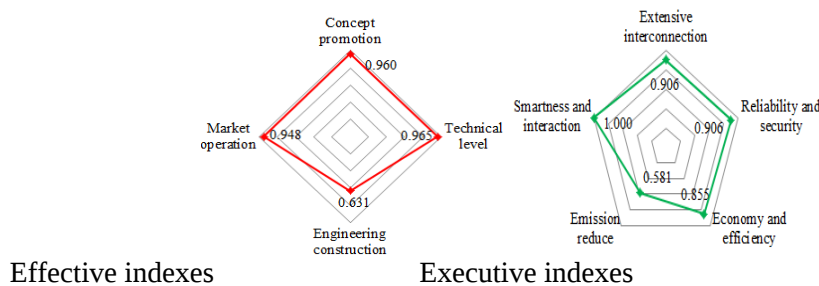
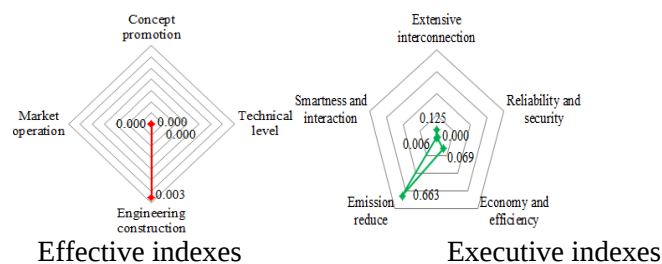


Figure 3. Weights of indexes relative to engineering construction.

7.2. Comprehensive Evaluation Value of Indexes in Criterion Layer

The comprehensive evaluation values of indexes in criterion layer for each country are calculated here. The results of United States, China, Ethiopia are given in fig. 4~5. From fig. 4 and fig. 5, it can be seen that the nine criterion indexes of United States and China have reached a relatively high level, which reflects a relatively good development level of global energy interconnection in this country. However, from fig. 6, we can see that the nine criterion indexes of Ethiopia is very low, which reflects a very poor development level of global energy interconnection limited by poor domestic political and economic environment.

**Figure 4.** Value of indexes in criterion layer for United States.**Figure 5.** Value of indexes in criterion layer for China.**Figure 6.** Value of indexes in criterion layer for Ethiopia.

7.3. Analysis of Effective Index and Executive Index

The comprehensive evaluation values of effective index and executive index for each country are shown in fig. 7, of which effective indexes including concept promotion, technical level, engineering construction and market operation, while executive indexes including extensive interconnection, reliability and security, economy and efficiency, emission reduce, smartness and interaction.

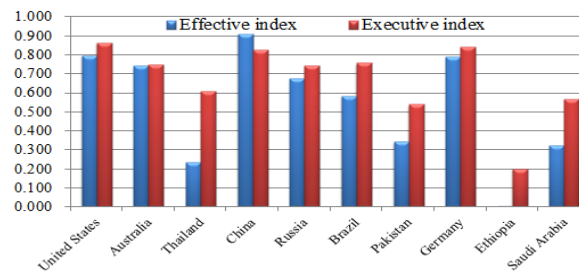


Figure 7. Effective and executive indexes for each country.

From the results in fig.7, it can be seen that both of the effective and executive indexes for United States, China and Germany have reached a relatively high level, which reflects that these countries have invested a lot in the construction process of global energy interconnection and these investments have achieved good effect.

The values of executive indexes for Thailand, Pakistan, Saudi Arabia and Brazil are higher than the effective indexes obviously, which shows that some investment of these countries in the construction process of global energy interconnection has not fully achieved benefit yet.

7.4. Developmet Level Evaluation Value of Global Energy Interconnection

The comprehensive development level evaluation values of global energy interconnection for ten countries are shown in fig.8. From the results we can see that the development level of global energy interconnection in China lies in the first place while Ethiopic lies in the last place. The development of these ten countries can divide into four classes: China, United States and Germany are in the first class with a very good development level. Australia, Russia and Brazil are in the second class with a good development level. Saudi Arabia, Thailand and Pakistan are divided in the third class with a common development level. While the development level of Ethiopia is very poor.

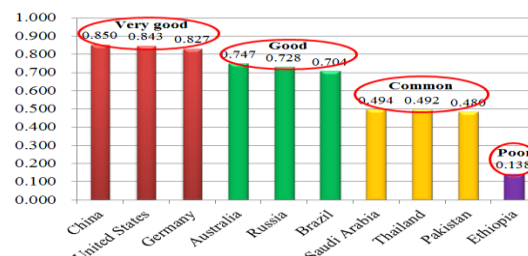


Figure 8. Developmet level evaluation value of global energy interconnection for each country.

8. Conclusion

Global energy interconnection is the next development stage of future power grid on the base of smart grid. The construction of global energy interconnection conforms to the development trend of world energy and power grid.

In order to identify the weakness in the development process of different countries, the development level global energy interconnection should be quantified. Therefore, a multi-level fuzzy statistics and maximum entropy rule based comprehensive evaluation strategy for development Level of global energy interconnection is proposed in this paper. The calculation examples for development level evaluation of ten typical countries illustrate the effectiveness of this strategy. From the results, the main factors that influence development level in terms of different aspects are identified through the weights analysis of index layer. The final evaluation values show that the development degree of global energy interconnection in China, United States and Germany has reached a very good level.

9. References

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