Research on Improved Fuzzy Evaluation Model for Power System Development Diagnosis

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Abstract. With the increase of clean-green energy connected to the power system, the development of power system becomes increasingly complicated. There are many internal and external factors that affect the planning and development of power system. Thus, it is important to evaluate and analysis the development state of the power system. This paper proposed an improved fuzzy evaluation model for power system development diagnosis which can determine the development stages and situation of the power system.

Keywords: Power system development diagnosis; Dynamic assessment; Fuzzy evaluation model.

1. Introduction
With the maturity of new technologies such as artificial intelligence and the increase of clean energy connecting to the power system, the characteristics of the power system have become more complex. It is critical to determine the development status of the power system through evaluation methods and guide the future development. Use relevant data to complete the scientific evaluation of the development state of power system can not only grasp the macro development law of power system but also put forward targeted diagnosis suggestions for a better development of power system.

There are many researches about the diagnosis of power system development. Erchao [1] constructs a diagnostic index system of regional power system development level with the technology and operation index, and the comparative analysis method is used for diagnostic evaluation. Research Zhengyang [2] and Kaiqiang [3] construct the development level evaluation system using power system operation, economic, social and environmental aspects respectively. Research Yifan et al. [4] establish a more detailed internal index division, including coordination and scheduling, power generation level, power consumption level, and even puts forward the power development potential from the perspective of company operation, and constructs a three-level evaluation system of the power system development. It is not difficult to see that the comprehensive evaluation index system is the key point to diagnose the power system development [5][6].

For the evaluation methods, loads of work is already done in the power system area [7]. Fengzhan et al. [8] and Pengpeng et al. [9] use Delphi and improvement G1 method to define the main and objective weights of index of different system evaluation scenarios. Bo et al. [10] use hierarchical analysis method to assessment the efficiency of new-clean energy access to provincial power system. Yanlong et al. [11] use gray correlation method in post-evaluation of safety for power system project.

It can be seen that the index system of power system development diagnosis and evaluation method will influence and restrict each other. As for the evaluation system, the existing research has considered its comprehensive characteristics, but the index of power system dynamic development is...
insufficient. Hence, this paper continues the research framework of traditional comprehensive evaluation and studies the diagnosis of power system development.

2. Improved Fuzzy Evaluation Model for Power System Development Diagnosis

2.1. Dynamic Index System for Development Diagnosis in the Power System

Power system evaluation index system is used to evaluate the stability, quality, performance of the power system. The index system can help the researchers to understand the main process of historical development and the status of power system. It also can find out the problem of the system and sum up the experience of developing, so that a developing trend and strategy can be provided to guide the power system planning.

In the latest Power System Development Diagnostic and Analysis Index System (2021 edition) and Power System Development Diagnostic and Analysis Outline released by China State Grid Economic and Technological Research Institute, the development status of power system is described in 6 aspects of power system development coordination, safety, quality, efficiency, operation and policy. This system has a detailed index construction model and a wide radiation surface. It clarifies the close coupling relationship between power system development and the other influencing factors which can be applicable to the index construction basis of power system development diagnosis. The comprehensive evaluation of power system development diagnosis involves a large number of indicators. In order to eliminate the impact of different scales between multiple types of indicators, the tertiary index set should be standardized at first. With the development of various technologies of the power system, the number of three indicators at each static moment, and the number of indicators that should participate in the power system rating and diagnosis will increase dynamically. The index type needs to be analyzed before the standardization, and treated with a suitable standardized formula.

For extremely large indicators, such as the growth rate of generators and loads, the greater the index value, the better the development effect. These indicators should be handled according to formula (1).

$$x_{ij}^1 = \frac{(x_{ij}^0 - \min x_{ij}^0)}{(\max x_{ij}^0 - \min x_{ij}^0)}$$

For the other indicators such as line loss rate, environmental carbon emissions, sulfur emissions and distribution cost, they are extremely small indicators, its physical significance is the opposite, should be handled according to formula (2).

$$x_{ij}^1 = \frac{(\max x_{ij}^0 - x_{ij}^0)}{(\max x_{ij}^0 - \min x_{ij}^0)}$$

For qualified indicators, such as major accidents and other safety risk indicators, it is more reasonable to standardize them based on whether to exceed the prescribed limit. Therefore, this paper introduces the type 0-1 treatment as formula (3).

$$\begin{align*}
x_{ij}^1 &= 1 & x_{ij}^0 > \zeta \\
x_{ij}^1 &= 0 & x_{ij}^0 < \zeta
\end{align*}$$

$x_{ij}^0$ represents the index elements before standardization and $x_{ij}^1$ represents the index elements after standardization. Because the index type exists in each evaluation time section, $x_{ij}^1(\epsilon)$ is used to express the index elements in different time scale. $\zeta$ is the safety threshold. The set of indicators is presented in space as a time-by-time temporal-stereoscopic data table.

Dynamic comprehensive evaluation aims to quantify the dynamic growth of evaluation objectives. However, the present study is a weighted gathering of multiple static comprehensive evaluation results, and the evaluation system remains unchanged at any time. The development problem of power system studied in this paper will consider the increase or decrease of basic indicators caused with the development of power system, which needs to break the fixed structure of the traditional evaluation system and correspondingly influence the weight determination of static indicators. In this paper, the principal component analysis method (PCA) is introduced to integrate the three-level indicators with different quantities on different time cross sections [12], so the evaluation system can be converted...
into a unified quantitative secondary index. It can avoid the influence of the overall evaluation results while retaining the key information reflected by the basic index.

2.2. Improved Comprehensive Fuzzy Evaluation Model

2.2.1. Comprehensive fuzzy evaluation model. Comprehensive fuzzy evaluation method is an important way to carry out the diagnostic research work of power system development. The key point is to describe the multiple restricted factors of the evaluation objectives through the membership theory of fuzzy mathematics. According to the three-level index system established in this paper, the integrated power system development secondary index will participate in the model calculation of this section. The specific mathematical ideas will be summarized as follows:

1) Use fuzzy function to map a secondary indicators \( P = \{ x_j^2 | j = 1,2, ..., Q \} \) into a state set \( S = \{ s_1, s_2, ..., s_k \} \). \( x_j^2 \) is the secondary index with the fusion processing;

2) Use method of endowed with weight to evaluate the fuzzy weight vector of the objective in this scenario \( A = \{ a_1, a_2, ..., a_n \} \);

3) Use some reasonable operator way to gather the \( S \) and \( A \), then obtain the final membership vector \( \text{Mark} = \{ m_1, m_2, ..., m_k \} \);

4) Rank the evaluation objectives according to the principle of maximum membership and comprehensive scoring to obtain the final evaluation results.

2.2.2. Characteristic analysis of the membership matrix. Membership function incorporates the characteristics of the fuzzy concept and the uncertainty quantification, which can be used as a bridge to realize the corresponding mathematical operation and processing between the power system evaluation index and the rating calculation. The choice of the function is closely related to establishing the description accuracy of evaluating the ambiguity of the objective. This paper conducts diagnostic rating for the dynamic development of power system, and it is hoped that the membership degree of each index value is obvious among different grades, so the ridge function is selected as the membership function between each grade, as shown in Figure 1.

**Figure 1.** The fuzzy distribution of ridge function.

Through the above research analysis, the parameter of membership function can be determined, and then the membership vector of the secondary indicator of the power system development diagnosis can be determined as \( \text{Mark} = (m_{n1}, m_{n2}, ..., m_{nk}), n = 1, 2, ..., J \). In this formula \( m_{nk} \) indicates the degree value of the indicator belonging to each state and \( J \) represents the number of secondary indicators under the evaluation time section. The membership matrix analysis can further explore the dynamic law of power system development. At the same time, the clustering results further characterize the correlation of the secondary metrics and the comprehensive rating results. The idea of subspace clustering for clustering analysis can be also used in the analysis of membership vector paradigm to minimize the sum of squares within the group, the equation is shown as below.

\[
\min E = \sum_{i=1}^{\mathcal{C}} \sum_{m \in \mathcal{C}_i} \left\| \mathcal{M}_n - 1/|\mathcal{C}_i| \sum_{m \in \mathcal{C}_i} m \right\|^2
\]

\( \mathcal{C}_i \) is the centre of the various type observation value. According to the above work, the membership matrix characteristics of the power system development will be obtained, and the overall state reflected by different indicators at each moment by the hidden Markov model can be explored.
2.2.3. A hidden Markov-based evaluation model. The Hidden Markov model can derive the relations in non-stationary time series and make predictions in a probabilistic statistical manner. It has been widely used in power system such as fault detection, power system prediction [13] [14]. The hidden Markov theory can dig out the deep meaning behind the indicators which is similar to the comprehensive evaluation structure. Therefore, if the process of index evaluation is inferred by the probability model and replaces the mathematical statistical method relying on weight assembly, the uncertainty ignored in the traditional evaluation process can be better retained and the evaluation results will be more realistic.

The comprehensive rating process for an improved fuzzy evaluation model based on a hidden Markov model can be described by the following details:

1. Initializes the parameters of the model $A_0, B_0, \pi_0 \rightarrow \lambda_0$.
2. Use iterative approach to renew the HMM parameters with equation 5 and 6.
3. Iterative calculation $P(O|S)$, when the conditions are satisfied, output $A_{\text{iter}}, B_{\text{iter}}, \pi_{\text{iter}}$, complete the hidden Markov model construction.
4. Use the dynamic planning method to obtain the sequence of power system development diagnosis grade reflected in the secondary index membership matrix.

$$\begin{align*}
\alpha_{i,j} &= \sum_{t=1}^{T-1} \zeta_t(i,j) / \sum_{t=1}^{T-1} y_t(i) \\
\beta_j(k) &= \sum_{t=1, \alpha_t=v_k}^T y_t(i) / \sum_{t=1}^{T} y_t(j) \\
\pi_i &= y_t(i) \\
\zeta_t(i,j) &= \alpha_t(i) \beta_t(j) / \sum_{i=1}^{N} \alpha_t(i) \beta_t(j) \\
\gamma_t(i) &= \sum_{i=1}^{N} \alpha_t(i) \beta_t(j) / \sum_{t=1}^{T-1} \sum_{j=1}^{N} \alpha_t(i) \beta_t(j)
\end{align*}$$

3. Case Analysis

3.1. Sorting the Index

Referring to the index system proposed in this paper, the tertiary indicators are subordinate to four secondary indicators: power system development speed (A), safety and stability condition of power system (B), power system development efficiency (C) and operation state (D). The actual indicators participating in the calculation examples are shown in Table 1 below, showing the annual growth trend of the total indicators of each year. Through the above analysis, the original indicators are first standardized to eliminate the different dimensions between indicators and unify the types of multiple indexes. Use multiple principal components to integrate the secondary index values at each moment. Through the fusion of tertiary indexes, the evaluation information contained in the data can be maximum and reflected into the secondary index. At the same time, the evaluation system turns from dynamic to static.

| Index/Year | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|------------|------|------|------|------|------|------|------|------|
| A          | 8    | 8    | 8    | 8    | 8    | 12   | 17   | 18   |
| B          | 15   | 15   | 15   | 15   | 15   | 15   | 19   | 19   |
| C          | 17   | 18   | 18   | 19   | 23   | 23   | 23   | 26   |
| D          | 22   | 23   | 23   | 23   | 23   | 23   | 24   |      |
| Total      | 62   | 64   | 64   | 65   | 69   | 73   | 84   | 87   |

Figure 2 describes the timing change of the secondary index values of the provincial power system. The change of any curve can obtain the correspond timing development characteristics and the static evaluation results under a single time cross section. For example, apart from the B type indexes of this provincial power system, the remaining secondary indicators reached the maximum annual development in 2016, reflecting the excellent development of the province between 2015 and 2016.
3.2. Membership Feature Calculation

According to the above research, the ridge distribution membership function is used to describe the fuzzy relationship between secondary indexes and all the levels. This paper presupposes that the actual number of the power system is N=3, which represents the development level of ‘health’, ‘sub-health’ and ‘early warning’ respectively. Table 2 shows the results of membership index in 2015. It can be seen that different secondary index membership vectors indicate the different degree of convergence to each state, and contain the trend influence of transferring between states. Among them, the maximum membership criterion is used to judge. It can be seen that the C type indicators are better than A type and D type indicators. In view of the overall state of the power system development, the actual state of the current time cross section is reflected by the membership matrix composed of four secondary indicators, so the comparison cannot be directly judged.

Table 2. Results of membership index in 2015.

| Type | Early Warning | Sub-health | Health |
|------|---------------|------------|--------|
| A    | 0.6537        | 0.3463     | 0      |
| B    | 0             | 0.8624     | 0.1376 |
| C    | 0             | 0          | 1      |
| D    | 0.3115        | 0.6885     | 0      |

Considering the regular characteristics of the power system development, use the cluster analysis to dig out the membership matrix properties of every time section, in order to obtain the overall actual state trend of the power system. Use observation value I, II, III, IV to represents the results. Each observed value represents the converging category to the actual state. Among them, the secondary index membership matrix of observation value IV has the maximum probability of approaching a better level, the minimum probability of approaching the worst level. The observation value III and II decreases in turn at the degree of approach. The observation value I has the maximum probability of approaching the worst level, which is contrary to the observation value IV. The example results are shown in Table 3.

Table 3. Matrix feature of the power system secondary index.

| Time  | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|-------|------|------|------|------|------|------|------|------|
| Matrix feature | I    | II   | I    | I    | II   | III  | IV   | III  |

Through the above clustering analysis, the secondary index convergence of each state level has been maximum mined and performed, realizing the transformation from traditional evaluation score classification to rating classification. The observation types contain mapping relationships with different state levels, also have sequence properties and can constitute the observed sequences of the hidden Markov model.
3.3. Hidden Markov Model Calculations

Through the characteristic division of the membership matrix in the above research, it partly reveals the relationship between the actual power system development state and the secondary index set. Hidden Markov model is used to excavate the development level of the secondary index set under the full sequence. The hidden state of the Markov model is $S_1$, $S_2$, $S_3$, determined as the early warning, sub-health and health level. Use Baum-Welch algorithm to get the hidden Markov model parameters as shown in Figure 3 and Figure 4.

![Figure 3. Hidden state transition probabilities.](image1.png)

![Figure 4. Hidden state observation probabilities.](image2.png)

It can be seen from Figure 3 that: (1) There is a high probability (46.65%) that the power system development transferring from early warning to sub-health in this province. (2) When the power system in this province is in sub-health, the probability of maintaining this state in the future is 40.81%; while the probability of falling back to the warning state is slightly greater than the probability of transferring to health. (3) When the power system is actually in the healthy state, it has a high probability of maintaining the current state; the future probability of transferring to sub-health is twice as high as the warning level.

It can be seen from Figure 4 that: (1) When the power system is in an early warning state, the probability of the output observation value IV is near zero. This shows that the early warning state of power system is obviously easy to identify. (2) When the grid is in sub-health, the probability of having observation value II is 56.45%; while the system is healthy, the probability of output observation IV and III is 12.67% and 43.96% respectively. It is not difficult to see the observation value II and III are in the middle type of the membership matrix feature. They have a certain mapping relationship with the states at all levels of the power system, which can be reflected in the change of the output observation probability. (3) When the power system is in a healthy state, the probability of output observation IV is 23.86%.

4. Conclusion

The rapid development of the power system in recent years has changed structure and operation mode of the system, it also affects the establishment and selection of indicators in the comprehensive evaluation of the power system. In the diagnosis of power system development, the temporal and spatial differences of power system development are reflected in the increase and decrease of the evaluation indicators. The dynamic evaluation index system can consider the impact of the index increase on the evaluation results, it also considers more information than the fixed index structure to make the evaluation results more practical. The dynamic index system constructed in this paper is still suitable for future evaluation research.

As for the comprehensive evaluation methods, they are focusing on the weight assignment problem between different indicators, and the optimization results are limited to the score ranking of evaluation objects. The hidden Markov model is used to determine the comprehensive evaluation results, and
replaced the traditional comprehensive evaluation with the mode of probability evaluation. Compared with the traditional evaluation of the score value ranking method, the hidden Markov model makes the power system state level more intuitive.

The case analysis of this paper takes the historical data of a certain province as an example, and the grade results of the actual development diagnosis in the past 8 years are in line with the reality, which will help to explore the change law of its development trend and predict its future change trend. The proposed system development classification index is conducive to intuitively representing the evaluation results. It also can be used as new index parameters to assist the realization of related system digital information technology.

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