Research on Matter Element Model in Power Grid Analysis

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Abstract. With the increasing complexity of power system grid structure and development environment, the dimensions and factors that need to be considered in the power grid status analysis also become complex. It is necessary to judge the aspects of power grid that need to be improved through the analysis results. This paper constructs an evaluation index system of power grid, including safety reliability, operation efficiency, operation margin of power grid, power grid structure and equipment level. Based on the index system, an evaluation model combining matter-element model and entropy weight method is proposed. Matter element model can not only quantitatively judge the development level of power grid, but also find out the weakness of power grid and put forward the direction of its improvement. Finally, a case study is proposed to show that the matter element model analysis in power grid comprehensive evaluation is feasible and has a good evaluation accuracy.

Keywords: Power grid analysis; Index system; Matter element model.

1. Introduction
On March 15, 2021, General Secretary Xi Jinping proposed the major deployment of building New-Energy-Dominant Power System, which is of great guiding significance to the transformation and development of China’s energy and power system [1]. Realizing the targets of “carbon peak and neutrality” and building New-Energy-Dominant Power System are pioneering systematic projects that will have significant impacts on power system planning, construction and operation. Therefore, it is necessary to assess and compare the development status of different power grids comprehensively, find out the shortcomings and solutions, and provide a basis for power grid planning and investment decision-making [2]. These can be achieved by establishing index system and evaluating models which reflecting various characteristics of the power grid.

At present, researches on power grid analysis and evaluation have achieved some results. The methods used in the previous researches are mainly fuzzy analysis. Existing studies established some index systems and calculated the membership degrees of each index and used the principle of fuzzy mathematics to quantify the relationship between the object to be evaluated and the grade interval [3]-[6]. However, the relevant index systems are not comprehensive, and the fuzzy evaluation cannot deal with the problems when membership degrees are the same.

In order to solve such problem, researcher proposed the Matter Element Analysis [7] which discover the rules and methods of handling with contradictions in the real world. This method solved the problem of approximate membership degrees, and could be used to grading development status and describe the changing trend of things. This method has been applied in many fields [8]-[11]. In a recent research, authors applied matter element analysis on a multidimensional power grid development diagnostic index system, and used AHP 1-9 scale method to achieve the final result [12]. However, this diagnostic index system focused more on benefit assessment and the weights of indexes were calculated by a subjective method.
Based on the analysis mentioned above, this paper reconstructs the power system development diagnostic index system from five dimensions which can comprehensively and objectively reflect the technical characteristics of a power grid. These dimensions are safety and reliability, operation efficiency, grid operation margin, grid structure and equipment level. The matter element model and correlation degree is used to quantify the development level of each index and overall power grid. Then the matter element model for power analysis is established and the entropy weight method is used to determined weights between different indexes. Finally, the effectiveness of this method is verified by a case analysis, and overall 26 provincial power grids within the State Grid operating area are graded and classified by the model presented. The key influencing factors and development suggestions are also determined for each type of the provincial power grid.

2. Power Grid Analysis Index System

In order to analysis and evaluate the development status of power grid, a multidimensional index system should be established. When constructing this index system, in addition to meeting the requirements of systematicness, comprehensiveness, operability and dynamism, it is also necessary to take availability of data into consideration. The data sources need to be existing information systems or official statistics to ensure that the data used is true and the analysis is reliable.

Based on the principle of index system construction, the power grid development status is evaluated from five dimensions which are safety and reliability, operation efficiency, grid operation margin, grid structure and equipment level. Each dimension not only influences each other, but also restricts each other. This three-tier index system established is shown in Table 1 below.

| Target Code | Index |
|-------------|-------|
| Power grid development level $c$ | | |
| Safety and reliability $c_1$ | Pass rate of N-1 Rule at 220kV and above (%) $c_{11}$ |
| | Pass rate of N-2 Rule at 220kV and above (%) $c_{12}$ |
| | Proportion of 500(750)kV nodes where the short-circuit current exceeds 80% of circuit breaker’s capacity (%) $c_{13}$ |
| | Proportion of 220(330)kV nodes where the short-circuit current exceeds 80% of circuit breaker’s capacity (%) $c_{14}$ |
| | Urban power supply reliability (%) $c_{15}$ |
| | Rural power supply reliability (%) $c_{16}$ |
| Operation efficiency $c_2$ | Annual average load rate of 500(750)kV equipment (%) $c_{21}$ |
| | Annual average load rate of 220(330)kV equipment (%) $c_{22}$ |
| | Annual average load rate of 110-35kV equipment (%) $c_{23}$ |
| | Annual average load rate of 10kV equipment (%) $c_{24}$ |
| Grid operation margin $c_3$ | 500kV capacity-load-ratio $c_{31}$ |
| | 220kV capacity-load-ratio $c_{32}$ |
| | Proportion of expandable 500kV substation capacity (%) $c_{33}$ |
| | Proportion of expandable 220kV substation capacity (%) $c_{34}$ |
| Grid structure $c_4$ | 10(20)kV line interconnection rate (%) $c_{41}$ |
| | Transformer availability factor at 110kV and above (%) $c_{42}$ |
| Equipment level $c_5$ | Transmission line availability factor at 110kV and above (%) $c_{51}$ |
| | Grid intelligence level (%) $c_{52}$ |

In this index system, under the premise of considering the power grid transfer capacity, the safety and reliability dimension reflects the power grid operation security and stability level at different voltage levels, as well as and the power supply reliability level of different areas. The operation efficiency dimension reflects the capacity utilization of transmission lines and transformers at different voltage levels. The grid operation margin dimension reflects the matching degree of power grid scale and load demand at different voltage levels, and analyzes the adaptability of transmission lines and substations construction to load growth. The grid structure coordination dimension reflects the power grid
structure morphology by analyzing 10(20)kV transmission lines interconnection rate. The equipment level dimension reflects the operation, maintenance and intelligent level of equipment.

3. Principle of Matter Element Analysis
The matter-element analysis is a combination of qualitative and quantitative methods that can be used when solving incompatible problems. The basic composition of the matter element analysis method is “matter element” which is composed of “names, characteristics, and values” in an orderly manner, and can be used to describe the magnitude of a certain characteristic of things. In this method, features in things to be evaluated need to be quantitatively expressed by functional relationships (quantitative indexes). Then these quantitative metrics are linked to the grade to be evaluated with correlation functions. The correlation coefficient calculated is a number ranging from $-\infty$ to $+\infty$, it describes the degree to which things belong to the certain evaluation interval. When the coefficient is positive, the larger the coefficient, the higher the degree; when the coefficient is negative, the larger the coefficient, the higher the possibility of things transforming into this evaluation interval. In this way, the development level and trend of things can be studied by the matter-element analysis.

Using the matter-element model to quantitatively assess a power grid with multiple characteristic indexes is not simply to obtain a comprehensive score using iterative indexes, but to consider the inherent relevance of each index and the development levels. Since the grades of the indexes are obtained according to the relevant standards, regulations and actual measurements, the subjective one-sidedness of the traditional methods which based on scores is avoided.

4. Matter Element Model for Power Grid Analysis
In this paper, matter element models are used to achieve quantitative rating of indexes in different dimensions. The objective weight coefficients of indexes inside each dimension is calculated by entropy weight method.

4.1. Matter Element Model
The matter element model describes a given object with matter N, its character c and quantity value v. The ordered combination comprises these three parameters is expressed as:

$$R= (N, c, v)$$  \hspace{1cm} (1)

This combination is known as the matter element. If matter N has n characters $c_1, c_2, ..., c_n$ and corresponding quantity values $v=[x_1, x_2, ..., x_n]$, then it is called an n-dimension matter element, which is expressed by the following matrix:

$$R = \begin{bmatrix} N & c_1 & x_1 \\ & c_2 & x_2 \\ & \vdots & \vdots \\ & c_n & x_n \end{bmatrix}$$  \hspace{1cm} (2)

The evaluation results of diagnostic indexes are divided into five levels ($j=1, 2, ..., 5$) in accordance with their distributing intervals between maximum and minimum value. Then, follow the specific steps in matter-element analysis, three representations of classical domain element, joint domain element, and matter element to be rated are established.

4.1.1. Determine classical domain element. The classical domain element stands for the range of values of the evaluation index at a certain grade. It can be expressed as:

$$R_j = \begin{bmatrix} N_j & (a_1, b_1) \\ & (a_2, b_2) \\ & \vdots \\ & (a_n, b_n) \end{bmatrix}$$  \hspace{1cm} (3)
In this matrix, $N_j$ is the provincial power grid development level of $j^{th}$ level ($j=1,2,...,5$), $c_i$ is the $i^{th}$ power grid development diagnostic index of the $j^{th}$ level ($i=1,2,...,n$), $(a_i,b_i)$ is the quantity value range of $v_j$ with respect to $c_i$ in the $j^{th}$ level.

4.1.2. Determine joint domain element. The joint domain element represents the value range of all characters of all levels. It can be expressed as:

$$R_p = \begin{bmatrix} P & c_1 & (c_i,d_i) \\ c_2 & (c_i,d_i) \\ \vdots & \vdots \\ c_n & (c_i,d_i) \end{bmatrix}$$  \hspace{1cm} (4)$$

Where, $P$ is the collectivity (total diagnostic indexes) of all development levels, $(c_i,d_i)$ is the quantity value range of $P$ with respect to $c_i$ in all levels. It requires $(a_i,b_i) \subseteq (c_i,d_i)$.

4.1.3. List matter elements to be rated. The matter elements represent the indexes measurement data of the provincial power grid to be rated. It can be expressed as:

$$R_p = \begin{bmatrix} P & c_1 & x_1 \\ c_2 & x_2 \\ \vdots \\ c_n & x_n \end{bmatrix}$$  \hspace{1cm} (5)$$

In this matrix, $P_k$ is the matter (a provincial power grid) to be rated ($k=1,2,...,m$) and $x_i$ is the quantity value of $P_k$ with respect to $c_i$.

4.2. Calculate Correlation Function Values of Index-layer

Here, the similarity between the matter elements to be rated and the classical domain as well as the joint domain is quantified by the correlation function[9].

Set $X_0=(a,b)$, $X=(c,d)$ and $X_0 \subseteq X$, suppose the optimal value of a certain index is $x_0$, the correlation function is expressed as:

$$\rho(x,x_0, X_0) = \begin{cases} \rho(x,x_0, X_0) & \rho(x,x_0, X_0) \leq 0 \\ \rho(x,x_0, X_0)^{-1} & \rho(x,x_0, X_0) > 0 \end{cases}$$  \hspace{1cm} (6)$$

In the equation (6),

$$\rho(x,X_0) = |x - 0.5*(a+b)| - 0.5*(b-a)$$  \hspace{1cm} (7)$$

$$\rho(x,X) = |x - 0.5*(c+d)| - 0.5*(d-c)$$  \hspace{1cm} (8)$$

The value of $\rho(x,x_0, X_0)$ can be calculated by left-side or right-side distance equation. The choice of the equation is determined by the position of optimal value $x_0$ inside the interval $X_0=(a,b)$. Simplified left-side and right-side distance equations applicable in power grid analysis.

The simplified left-side distance equation:

$$\rho(x,x_0, X_0) = \begin{cases} a-x, & x \leq a \\ x-b, & x > a \end{cases}$$  \hspace{1cm} (9)$$

The simplified right-side distance equation:

$$\rho(x,x_0, X_0) = \begin{cases} a-x, & x \leq b \\ x-b, & x > b \end{cases}$$  \hspace{1cm} (10)$$

According to the feature of the optimal value of each index, the indexes can be divided into three types[13]. For the first type index, the smaller the value, the better the performance of the power grid, and Equation (9) should be applied [14]. For the second type index, the larger the value, the poorer the
performance, and Equation (10) should be applied [12]. For the third type index, the optimal value is an interval and the farther the actual value is from the optimal interval, the worse the performance will be. Therefore, it is necessary to determine whether to use the left-side or the right-side distance equation according to the relationship between actual measurement and the optimal value range.

The correlation function has the following properties: if the correlated function value is greater than 0, it means that the rated index conforms to the characteristics of a certain level and the larger the value, the greater the degree of conformity. Otherwise, if the correlated function value is less than 0, it means that the rated index does not meet the characteristics of a certain level but has the conditions for conversion to meet the level selected. The larger the value, the greater the conversion trend [15].

4.3. Calculate Correlation Function Values of Code and Target Layer

In this paper, the objective weight coefficients in the index-layer is determined by the entropy weight method and the subjective weight coefficients of code-layer are determined by Delphi method. Let the weight coefficient vector of index-layer is \( W = [w_1, w_2, ..., w_n] \). Then the weight coefficient of the indexes in code and target layer can be calculated by weighted operation:

\[
K_A = W_B \times K_B
\]

Where, \( K_A \) is the correlation value vector of upper layer, \( K_B \) is the correlation value vector of lower layer, \( W_B \) is the weight coefficient vector corresponding to the correlation value vector of lower layer.

Entropy weight is an objective weight calculation method using the idea of information entropy. It determines the weight of each index according to their variation and dispersion degree. The entropy of each index represents the amount of information it contained. The smaller its information entropy, the greater the variation degree of the index, the greater its impact or weight on the evaluation. The entropy weight method determine the weight of each index and ensure that the indexes can reflect the majority information inside the actual measurement vectors which avoids the subjective interference and gives out more reliable results.

After obtaining the final correlation value for each level, the certain level with the largest correlation represents the development status of the power grid. Since the magnitude of the correlation values can reflect the association of the power grid development to each level, different provincial power grids belonging to the same development level can be compared horizontally according to the correlation values.

5. Example Analysis and Application

In recent years, the digital, intelligent, and informatization level of the power system as well as the information systems of the power system have been continuously improved[16]. Internal information systems, such as Supervisory Control And Data Acquisition (SCADA), Energy Management System (EMS), Electricity Information Collection System and Power Equipment Monitoring System, form reliable data sources for indexes calculation and matter-element method application.

This paper evaluates the development status of 26 provincial power grids within State Grid Co. in China. Taking a provincial power grid as an example, the feasibility of the index system and matter-element model established is verified, then the results of all 26 provincial power grid are compared and classified in the following content.

A total five development levels of each index from poor to excellent are expressed as Level 1-5. Standard for each level classification and measured value of each index of a provincial power grid is shown in Table 2 below.
Table 2. Classification of indexes and measured value of Provincial Power Grid X.

| Index Type No. | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 | Measurement |
|---------------|---------|---------|---------|---------|---------|-------------|
| c₁₁-c₁₂      | I [80,92] | [92,94] | [94,96] | [96,98] | [98,100] | 100         |
| c₁₃          | II [60,80] | [45,65] | [30,45] | [15,30] | [0,15]  | 19.6        |
| c₁₄          | II [40,50] | [30,40] | [20,30] | [10,20] | [0,10]  | 28.5        |
| c₁₅          | I [99.9,99.9] | [99.92,99.94] | [99.94,99.96] | [99.96,99.98] | [99.98,100] | 99.965      |
| c₁₆          | I [99.55,99.65] | [99.65,99.75] | [99.75,99.85] | [99.85,99.95] | [99.95,1] | 99.806      |

The classical domains (level division intervals) of five levels of each index in the index-layer were determined. For example, the classical domain of Level 5 (relatively highest development level) is:

\[
R_{5} = \begin{bmatrix}
N_5 & c_{11} (98,100) \\
& c_{12} (98,100) \\
& \vdots \\
& c_{53} (95,100)
\end{bmatrix}
\]

Where, \( R_{5} \) is the matter-element of Level 5 evaluation interval, \( N_5 \) indicates the development level of power grid is Level 5, \( c_{11} \) is the first index which is “pass rate of N-1 Rule at 220kV and above”, (98,100) means the value range of Level 5 with respect to “pass rate of N-1 Rule at 220kV and above” is from 98% to 100%.

The joint domain (maximum and minimum value) of all levels of indexes is expressed as \( R_{p} \):

\[
R_{p} = \begin{bmatrix}
N & c_{11} (0,100) \\
& c_{12} (0,100) \\
& \vdots \\
& c_{66} (0,100)
\end{bmatrix}
\]

Where, \( N \) indicates total development level of power grid, \( c_{11} \) is the first index which is “pass rate of N-1 Rule at 220kV and above”, (0,100) means the overall value range with respect to “pass rate of N-1 Rule at 220kV and above” is from 0 to 100%.

The matter-element to be rated is expressed as \( R \):

\[
R = \begin{bmatrix}
N_0 & c_{11} 100 \\
& c_{12} 100 \\
& \vdots \\
& c_{66} 95.56
\end{bmatrix}
\]
In this matrix, $N_0$ indicates the measured values to be rated; $c_{11}$ is the first index which is “pass rate of N-1 Rule at 220kV and above” and its actual measurement is 100%.

Substituting matter-element models into equations (6)-(10), the correlation function values of each index with respect to different levels can be calculated. Part of the results are shown in Table 3 below.

**Table 3.** Correlation function value and weight coefficients.

| Code Layer | T-C Weight | Index Layer | C-I Weight | Correlation with Development Levels |
|------------|------------|-------------|------------|-------------------------------------|
|            |            | $c_{11}$    | 0.0205     | $k_1$ -1.0000 $k_2$ -1.0000 $k_3$ -1.0000 $k_4$ -1.0000 $k_5$ 1.0000 |
|            |            | $c_{12}$    | 0.3210     | $k_1$ -1.0000 $k_2$ -1.0000 $k_3$ -1.0000 $k_4$ -1.0000 $k_5$ 1.0000 |
|            |            | $c_{13}$    | 0.2342     | $k_1$ -0.6742 $k_2$ -0.5656 $k_3$ -0.3483 $k_4$ 0.6967 $k_5$ -0.1888 |
|            |            | $c_{14}$    | 0.0973     | $k_1$ -0.3485 $k_2$ -0.0652 $k_3$ 0.0750 $k_4$ -0.2833 $k_5$ -0.4625 |
|            |            | $c_{15}$    | 0.1614     | $k_1$ -0.5632 $k_2$ -0.4176 $k_3$ -0.1264 $k_4$ 0.1691 $k_5$ -0.2996 |
|            |            | $c_{16}$    | 0.1657     | $k_1$ -0.4452 $k_2$ -0.2233 $k_3$ 0.3722 $k_4$ -0.1853 $k_5$ -0.4261 |
|            |            | $c_{21}$    | 0.4780     | $k_1$ -0.3669 $k_2$ -0.1373 $k_3$ 0.1894 $k_4$ -0.2071 $k_5$ -0.4053 |
|            |            | $c_{22}$    | 0.1339     | $k_1$ -0.4533 $k_2$ -0.2711 $k_3$ 0.4066 $k_4$ -0.0787 $k_5$ -0.3518 |
|            |            | $c_{23}$    | 0.1523     | $k_1$ -0.3664 $k_2$ -0.1352 $k_3$ 0.1853 $k_4$ -0.2098 $k_5$ -0.4073 |
|            |            | $c_{24}$    | 0.2358     | $k_1$ -0.0053 $k_2$ 0.0054 $k_3$ -0.4973 $k_4$ -0.6649 $k_5$ -0.7487 |
|            |            | $c_{31}$    | 0.2979     | $k_1$ -0.6375 $k_2$ -0.5167 $k_3$ -0.2750 $k_4$ 0.5500 $k_5$ -0.2368 |
|            |            | $c_{32}$    | 0.1689     | $k_1$ -0.8375 $k_2$ -0.7833 $k_3$ -0.6750 $k_4$ -0.3500 $k_5$ 1.1667 |
|            |            | $c_{33}$    | 0.2556     | $k_1$ -0.5395 $k_2$ -0.3860 $k_3$ -0.0790 $k_4$ 0.0938 $k_5$ -0.3137 |
|            |            | $c_{34}$    | 0.2776     | $k_1$ -0.5382 $k_2$ -0.3842 $k_3$ -0.0763 $k_4$ 0.0901 $k_5$ -0.3144 |
|            |            | $c_{41}$    | 1.0000     | $k_1$ -0.4528 $k_2$ -0.2703 $k_3$ 0.4055 $k_4$ -0.0795 $k_5$ -0.3520 |
|            |            | $c_{51}$    | 0.2669     | $k_1$ -0.7993 $k_2$ -0.5985 $k_3$ -0.1970 $k_4$ 0.3251 $k_5$ -0.2740 |
|            |            | $c_{52}$    | 0.3103     | $k_1$ -0.3154 $k_2$ 0.5000 $k_3$ -0.0730 $k_4$ -0.3820 $k_5$ -0.5365 |
|            |            | $c_{53}$    | 0.4228     | $k_1$ -0.8520 $k_2$ -0.7780 $k_3$ -0.5560 $k_4$ -0.1120 $k_5$ 0.1443 |

Based on the entropy weight method and actual index values of 26 provincial power grids, the objective weight coefficients of each index in different dimensions between index-layer and code-layer can be calculated and shown in the column “C-I Weight” of Table 3. The weight coefficients of each dimension is obtained by the judgment of experts and shown in the column “T-C Weight” of Table 3.

The other weight coefficient vector can be obtained with the same method. Substituting each weight coefficient and correlation value into equation (11), the correlation value of the certain provincial power grid development level in respects to five levels can be obtained. The result is expressed as:

$$K = \begin{bmatrix} -0.5647 & -0.3892 & -0.1475 & -0.1251 & -0.1399 \end{bmatrix}$$

According to the principle of maximum correlation, the final development level diagnosed in this example is Level 4 (good level). By further analyzing the level of each index obtained, main problems existed and transforming trend can be found. For example, the development level of “annual average load rate of 10kV equipment” is Level 2 (acceptable level). In some residential areas of the example province, the 10kV distribution transformers adopt relatively higher capacity standards, but the housing occupancy rate is still relatively low, resulting in low efficiency of residential distribution transformers. Besides, the regional power load annual growth rate has been lower than planned in the recent years, affecting the overall efficiency of 10kV equipment in the power grid. The development level of “transmission line availability factor at 110kV and above” is also Level 2 (acceptable level). The reason is that the province encountered extreme weather such as icing disasters during the evaluation year, and the overhead line failure rate was relatively high.

The trend of each index can provide a reference for the subsequent improvement of development level. For example, the development level of “proportion of 220(330)kV nodes where the short-circuit current exceeds 80% of circuit breaker’s capacity” is Level 3 (moderated level) and the trend of turning into Level 2 is greater than the trend of turning into Level 4. Therefore, indexes showing signs of deterioration should be focused on and improved.
Based on the same approach, the power grid development level of other provinces can be analyzed and classified in four categories. The first category provincial power grid has a highest development level, with various indexes are good or excellent, and most of the indexes show a trend of shifting to upper levels. Power grid in Jiangsu Province belongs to this category. In the future, it is necessary to promote electric energy substitution continuously, improve power supply services, and maintain equipment efficiency. The second category provincial power grid has a relatively high development, but the level of various indicators is significantly different, indicating that the power grid development is unbalanced. Such provincial power grids include Beijing, Zhejiang, Shanghai, and Tianjin, etc. In the third category provincial power grid, the development indexes are relatively balanced. This category includes Shandong, Fujian, and Hubei, etc., they need to maintain the sustainable development of the power grid while optimizing the allocation of resources. The last category includes Xinjiang, Ningxia and Qinghai, etc. These provincial power grids need to be further strengthened in order to comprehensively improve the level of development.

6. Conclusion

Based on the principle of index system construction, this paper reconstructs the power grid analysis index system includes five dimensions which are safety and reliability, operation efficiency, grid operation margin, grid structure and equipment level. This paper presents a novel approach to applying matter element model and entropy weight model in provincial power grid analysis. This approach provides more accurate evaluation results for power grid development diagnosis and can also be used to predict development trend of each index and the overall development situation, as well as provides a basis for defining improvement priorities and establishing development policies. However, this method cannot make a more detailed comparison of different power grids within the same development level. Further research can be carried out on the problems of index evaluation and classification standards in the matter-element model, as well as combination research with traditional evaluation methods such as fuzzy evaluation method.

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