Comprehensive Risk Assessment Method of Power Grid Based on Grey Relational Weight Game Theory

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Abstract: Taking the risk assessment of power system which include new energy grid and AC/DC hybrid structure as the research object, the paper proposes a comprehensive risk assessment method based on game theory and grey relational projection. Firstly, by analyzing the risk factors faced by modern power grids, the risk assessment index system is reconstructed from three aspects, grid structure, operational status and energy supply. Secondly, by creating combination weighting model based on game theory, the subjective weight values and the objective weight values of indexes are integrated to eliminate the weight deviation caused by single weighting method. Thirdly, based on grey relation projection model, the projection values of risk index samples on ideal states are calculated, and the overall risk of samples is represented by its superiority to negative ideal state. The proposed method could identify operation modes with high risk for power grid, which is significant to safe and stable operation of the power grid. Finally, by case analysis, the effectiveness of the proposed method is proved.

Keywords: Power grid; risk assessment indexes; game theory; grey relational projection; comprehensive risk assessment.

1. Introduction

Nowadays, because of the increasing penetration rate of new energy sources and the gradual formation of AC/DC hybrid structure, the risk faced by China's State Grid have become increasingly diversified[1]. On the one hand, due to the large number of new energy power plants, the traditional power supply structure has changed[2], which leads to the grid being vulnerable to the random fluctuation of new energy[3]. It is more prone to the problem of out of voltage limit, out of power limit and insufficient spinning reserve. On the other hand, the continuous construction of DC transmission projects has changed the static structure of the power grid[4]. Because of the large transmission power and complicated control methods, DC systems are more prone to large-scale cascading failures which will cause serious loss of load[5]. Significant changes in grid situation lead to difficulties in grid dispatching and frequent accidents, so the nation has attached great importance to the issue of grid security[1].

In order to assess risk level of the grid, numerous indexes have been proposed[6]. And a large number of researches have been made on the comprehensive risk assessment of power grid, which is a typical multi-objective decision-making problem. Chao Pei[7] uses the AHP to calculates the final comprehensive risk value, but this weighting method of risk indexes are greatly influenced by the subjective preference. Zhian Zeng[8] used the deep neural network to carry out the comprehensive risk assessment of the power grid. However, this method still has a large subjectivity in the selection of parameters, and the establishment process of network is
complicated. Shi Zhiping[9] constructed the matter-element extension model for comprehensive risk assessment of power grids. Meng Li[10] used grey correlation projection method to evaluate the power grids. Peiqing Liu[11] proposed a risk assessment method of power grid security based on both component importance and operation state.

Overall, All of the above studies have promoted the development of comprehensive risk assessment for power grids. However, the risk index systems used at present need to be improved to consider more risk factors faced by power grid. And the comprehensive risk assessment model has the problem of sample dependence or subjective bias.

A comprehensive risk assessment method for power grid based on game theory and grey relational projection is proposed in the paper. Firstly, a new risk assessment index system is reconstructed. Secondly, in order to improve the one-sidedness of the traditional index weighting method, the game theory is introduced into the grey relational projection model, a comprehensive risk assessment method which combined the game theory with the grey relational projection is proposed. Finally, by selecting the operation mode with highest risk in a power grid, the case analysis shows the correctness and effectiveness of the proposed assessment method.

2. Risk Assessment Index System Construction

Combined the new situation with the risk indexes existed, grid risk assessment index system is reconstructed from the perspectives of grid structure, operational state and energy supply.

1) Multi-feed short circuit ratio index

\[
R_i = \sum_{E_{i \in \Omega}} P(E_i) \sum_{j=1}^{H} \left[ \frac{1}{Z_{eqii}P_{bi} + \sum_{j \neq i} Z_{eqij}P_{bj}} \right]
\]

Where \( P(E_i) \) is the probability of grid state \( E_i \); \( \Omega \) is the grid risk assessment status set; \( Z_{eqii}, Z_{eqij} \) are the equivalent self-impedance value of DC transmission line \( i \) and its equivalent mutual impedance index with the DC line \( j \); \( P_{bi}, P_{bj} \) are respectively the rated power of the DC lines \( i \) and \( j \); \( H \) is the number of DC lines included in the grid.

2) New energy node degree

According to the complex network theory in paper [12], average node degree is a index which can reflect strength of the connection between the grid nodes, so the node degree of the new energy node is defined as the average degree of nodes with new energy plants.

\[
R_2 = \sum_{E_{i \in \Omega}} P(E_i) \sum_{i=1}^{N_{ne}} \frac{d_i}{N_{ne}}
\]

Where \( d_i \) is the node degree of the node \( i \) with new energy plants; \( N_{ne} \) is the sum of nodes with new energy plants.

3) Loss of Load

\[
R_3 = \sum_{E_{i \in \Omega}} P(E_i) \frac{P_c}{P_t}
\]

Where \( P_c \) is the lost load of power grid, kW; \( P_t \) is the rated load of power grid, kW.

4) Out of power

\[
R_4 = \sum_{E_{i \in \Omega}} P(E_i) \sum_{i=1}^{B} \frac{1}{B} \left[ \frac{P_{ai} - P_{bi}}{P_{ai}} \right]
\]

Where \( B \) is sum of grid lines; \( P_{ai} \) is actual power of line \( i \), kW; \( P_{bi} \) is rated power of line \( i \), kW.

5) Deviation of voltage
Where $N$ is sum of grid nodes; $U_{ai}$ is actual voltage value of node $i$, kV; $U_{Ni}$ is rated voltage of the node $i$, kV.

6) Spinning reverse

$$R_k = \sum_{i \in A} P(E_i) \frac{K}{K_N}$$  \hspace{1cm} (6)

Where $K$ is the actual spinning reserve of the grid, kW; $K_N$ is the rated spinning reserve of the grid, kW.

7) Energy penetration rate

$$R_i = \sum_{i \in A} P(E_i) \frac{S_{nr}}{S_N}$$  \hspace{1cm} (7)

Where $S_{nr}$ is the installed capacity of new energy, kW; $S_N$ is the total installed capacity of the grid, kW.

8) Load abnormal fluctuation

$$R_k = \sum_{i \in A} P(E_i) \frac{P_a - P_p}{P_p}$$  \hspace{1cm} (8)

Where $P_a$ is the actual load of the grid, kW; $P_p$ is the predicted load of the grid, kW.

3. Grey Relational Game Weighting Model

The basic idea of game theory can be used to determine the weight of the index, which can achieve a balance between various weighting methods\(^{[13]}\).

The grey relational projection model\(^{[14]}\), which has the characteristic of fully excavating sample space information, is apply to solve the decision-making problems with multi-target.

3.1. Game Weighting Model

If an index system contains $m$ indexes, $n$ basic weight vectors $W_i = (w_{i1}, w_{i2}, \cdots, w_{im})$, $i = 1, 2, \cdots, n$ can be obtained after $n$ weighting methods are used, and then the combined weight vector consisting of $n$ basic weight vectors is:

$$W = \sum_{i=1}^{n} \lambda_i W_i$$  \hspace{1cm} (9)

Where $\lambda_i$ is the coefficient of the basic weight vector $i$. In order to let deviation between integrated weight vector and each basic weight vector to the minimum, the game weighting model can be constructed by game theory:

$$\min \left\| \sum_{i=1}^{n} \lambda_i W_i - W_i \right\|_2, \hspace{0.5cm} i = 1, 2, \cdots, n$$  \hspace{1cm} (10)

Where $\lambda^T = (\lambda_1, \lambda_2, \cdots, \lambda_n)$ are coefficient of the combination weight vector of the index. However, it may not satisfy the condition of $\lambda_i > 0$ and $\sum_{i=1}^{n} \lambda_i = 1$, so it should be normalized by equation (11) to enhance the practicability of the game weighting model.
\[ \mu = \frac{1}{\sum_{j=1}^{n} \lambda_j} \left[ |\lambda_1| + |\lambda_2| + \cdots + |\lambda_n| \right] \]  

(11)

Where \( \mu \) is the normalized coefficient vector. Therefore, the final optimal combination weight vector is \( W_0 = \sum_{i=1}^{n} \mu W_i \).

3.2. Grey relational Projection Model

If an object to be evaluated contains \( m \) indexes, and \( k \) index samples have been obtained, the initial index sample matrix \( X = (x_{ij})_{k \times m} \) can be formed, and the positive ideal solution \( Y^* = \{y^+_{01}, y^+_{02}, \ldots, y^+_{0m}\} \) and the negative ideal solution \( Y^- = \{y^-_{01}, y^-_{02}, \ldots, y^-_{0m}\} \) of the sample can be obtained\[15\]. Therefore, the grey correlation coefficient of the index sample to the positive(negative) ideal states is

\[
\begin{align*}
\rho^+ &= \frac{\min_k \min_m |y^+_{oj} - x_{ij}| + \rho \max_m |y^+_{oj} - x_{ij}|}{\max_k \max_m |y^+_{oj} - x_{ij}|} \\
\rho^- &= \frac{\min_k \min_m |y^-_{oj} - x_{ij}| + \rho \max_m |y^-_{oj} - x_{ij}|}{\max_k \max_m |y^-_{oj} - x_{ij}|}
\end{align*}
\]

(12)

Where \( \rho^+ \) is the grey correlation coefficients of the index \( j \) in the sample \( i \) and the positive ideal states; \( \rho^- \) is the grey correlation coefficients of the index \( j \) in the sample \( i \) and the negative ideal states; \( \rho \) is the resolution coefficient, generally takes 0.5; \( |y^+_{oj} - x_{ij}| \) is the absolute differences between the index \( j \) in the sample \( i \) and the positive ideal states; \( |y^-_{oj} - x_{ij}| \) is the absolute differences between the index \( j \) in the sample \( i \) and the negative ideal states.

Based on the grey correlation coefficient \( \rho^+ \) and the index weight \( w_j \), the projection of the sample \( i \) on the ideal state solution can be calculated:

\[
\begin{align*}
P^+_i &= \frac{1}{\sqrt{\sum_{j=1}^{m} (w_j)^2}} \sum_{j=1}^{m} w_j \rho^+_j w_j \\
P^-_i &= \frac{1}{\sqrt{\sum_{j=1}^{m} (w_j)^2}} \sum_{j=1}^{m} w_j \rho^-_j w_j
\end{align*}
\]

(13)

Where \( P^+_i \) is projection of sample \( i \) on the positive ideal solution ; \( P^-_i \) is projection of sample \( i \) on the negative ideal solution.

4. Comprehensive Risk Assessment Method for Power Grid Based on Game Theory and Grey Relational Projection Method

The comprehensive risk assessment method combined game empowerment with gray-related projection is proposed as follows:

1) Select the target power grid for risk assessment, and calculate the risk index according to the risk index system, and form the initial risk index set \( R = (r_j)_{1 \times n} \).

2) Determine the combination weight vector of risk indexes based on the game weighting method. The paper selects the expert scoring method as subjective weighting method; it is the most commonly
used weight method in the power grid risk assessment. It combines practical experience from multiple grid experts, so it can more realistically reflect the importance of each index to the grid risk. Furthermore, the calculation process of the proposed method is simpler. It has no problems that the weight is difficult to determine if there are many indexes. By hiring multiple experts to score the indexes, the subjective weight vector is obtained as \[ W_1 = (w_{11}, w_{12}, w_{13}, \ldots, w_{1n}) \].

The anti-entropy weight method is a more objective weight method, under the premise that it can reflect the different importance of indexes, and has a less sensitivity than entropy weight method [14], so it can achieve higher sample information utilization. Furthermore, it has a clearer mathematical model and an intuitive calculation process than the neural network method. The objective weight vector from anti-entropy weight method is \[ W_2 = (w_{21}, w_{22}, w_{23}, \ldots, w_{2n}) \]. The calculation formula can be found in the literature [16].

Substituting \[ W_1 \] and \[ W_2 \] into the game weighting model, Finally, the index weight vector based on the game weighting model is \[ W_0 = \mu W_1 + \mu_2 W_2 = [w_{01}, w_{02}, \ldots, w_{0n}] \].

3) Calculating the projection on the positive ideal solutions and the negative ideal solutions of risk index samples through grey relational projection model. For convenience of analysis, the initial risk index sample set \( R_i = (r_{ij})_{k \times 8} \) is processed to form a standardized risk index sample set \( R' = (r_{ij})_{k \times 8} \). The standardized processing formula is as follows:

\[
\begin{align*}
    r'_{ij} & = \begin{cases} 
        \frac{r_{ij} - r_{ijmin}}{r_{ijmax} - r_{ijmin}} & \text{cost indexes} \\
        \frac{r_{ij} - r_{ijmin}}{r_{ijmax} - r_{ijmin}} & \text{benefit indexes} 
    \end{cases} \\
    & = \begin{cases} 
        \frac{r_{ij} - r_{ijmin}}{r_{ijmax} - r_{ijmin}} & (i = 1, 2, 3, \ldots; j = 1, 2, 3, 8) 
    \end{cases}
\end{align*}
\]

(14)

Where \( r'_{ij} \) is the value of index \( j \) in the sample \( i \) after normalization; \( r_{ij} \) is the value of index \( j \) in the sample \( i \) before normalization. \( r_{ijmax} \) is the maximum of index \( j \); \( r_{ijmin} \) is the minimum of index \( j \).

Then, each index is transformed into a cost risk index, and its positive ideal solution is \( Y'_+ = \{0, 0, \ldots, 0\} \); negative ideal solution is \( Y'_- = \{1, 1, \ldots, 1\} \). Substitute the elements \( r'_{ij} \) of the risk index sample set into the formula (12), the grey correlation coefficient \( r'_{ij} \) can be obtained.

Substitute grey correlation coefficient \( r'_{ij} \) and the combination \( W_0 \) into the equation (13), the projection \( P'_+, P'_-, (i = 1, 2, \ldots, 8) \) on the positive and negative ideal solutions of each sample can be calculated.

4) Characterize the grid risk by calculating the superiority of the sample to the negative ideal solution. In order to consider \( P'_+, P'_- \) at the same time, the comprehensive risk of the sample is expressed by calculating the superiority (\( g_i \)) of the negative ideal solution [17]. The formula is as shown in equation (15):

\[
g_i = \frac{(P'_+ - P_0)^2}{(P'_+ - P_0)^2 + (P'_- - P_0)^2}
\]

(15)

\( P_0 \) is the length of the positive and negative ideal state vector respectively, and the formula is shown as equation (16):

\[
P_0 = 1 \left( \sum_{j=1}^{n} w_j \right) \left( \sum_{j=1}^{n} w_j^2 \right)^{-1/2}
\]

(16)
The larger $g_i$ is, the closer the distance between the sample $i$ and the negative ideal solution is, which means that comprehensive risk is higher.

5) Sample risk ranking.
According to the $g_i$, the risk index sample can be sorted in size, and then the grid operation mode with relatively highest risk can be selected.

5. Case Analysis
The correctness and effectiveness of the comprehensive risk evaluation method is proved by selecting the operation mode with the highest risk among the five operation modes of a 500kV power grid.

The subjective weight vector calculated by the expert scoring method is: $W_1 = (0.100, 0.055, 0.270, 0.120, 0.115, 0.155, 0.060, 0.125)$; The objective weight vector calculated by the anti-entropy weight method is $W_2 = (0.070, 0.081, 0.237, 0.138, 0.105, 0.087, 0.085, 0.197)$; the combination weight vector finally obtained by the game weighting model is $W_0 = (0.091, 0.063, 0.260, 0.125, 0.112, 0.134, 0.068, 0.147)$.

![Figure 1. Index weight values distribution.](image)

It can be seen from Fig. 1 that the weights of the indicators obtained by subjective weight and objective weight are quite different.

The projection values of the risk indexes for the positive and negative ideal states and the superiority for the negative ideal state of the five operating modes are shown in Tab. 1.

**Table 1.** Projection values and superior degree for index data.

| Mode  | $P_i^*$ | $P_i'$ | $g_i$ |
|-------|---------|--------|-------|
| Mode1 | 0.304   | 0.168  | 0.130 |
| Mode2 | 0.365   | 0.135  | 0.010 |
| Mode3 | 0.337   | 0.152  | 0.047 |
| Mode4 | 0.137   | 0.359  | 0.985 |
| Mode5 | 0.238   | 0.195  | 0.377 |

From Tab. 1, it can be seen that the five operating modes can be sorted by size of the superiority for the negative ideal state as fellows: mode 2 < mode 3 < mode 1 < mode 5 < mode 4, so the operation mode with the greatest relative risk is mode 4. The calculation results is consistent with the actual operation of the power grid, which show the effectiveness of the method.

6. Conclusion
The game weighting model is used to avoid the limitation of single weighting method. The case analysis shows that the index weight obtained by using this method achieves an equilibrium
point between the subjective and objective weights, combines advantages of the two kinds of weighting methods.

After obtaining the weight of the index, the gray correlation projection model is used to calculate the comprehensive risk of the power grid, which can fully consider the mutual influence between the indexes and the spatial information of the index's samples. The case analysis shows that the proposed method could calculate risk value of operation modes for power grid, which verifies the correctness and credibility of the method. The results obtained by the proposed method are of practical significance to eliminate the risks of power grid in time and guide the power grid dispatching planning.

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