A hierarchical fuzzy comprehensive evaluation algorithm for running states of an electromechanical system

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ABSTRACT
A fuzzy hierarchical comprehensive evaluation algorithm including fuzzy matrix and comprehensive evaluation matrix calculation thought is proposed to accurately evaluate the running state of an electromechanical system. The analytic hierarchy process is included in the algorithm, which calculates the state of each subsystem from top to bottom and the states are used as the evaluation factor of the upper system. The idea of degradation degrees is introduced to standardize the indicators. The paper carried out the simulation experiment for the electromechanical system with a model number of JKMD-4 × 4(Z). The experimental results show that the established state evaluation model can accurately judge the operation state of the system with not too much data.

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Hierarchical fuzzy; state evaluation algorithm; degradation degree; analytic hierarchy process; synchronous motor; hoist

1. Introduction
Large electromechanical system mainly refers to the system that includes mechanical equipment, electrical equipment, sensor components and so on, and pushes the actuator to carry out complex actions through the controller. Due to the complex structure, frequent changes in operating conditions, and poor working conditions, an electromechanical system appears various types of faults, making it difficult for maintenance staff (Li & Yang, 2013; Wang et al., 2017). In a mine hoist, the synchronous motor drive system is an important part to provide power and precise control.

In recent years, in order to monitor the states of the electrical drive system of the hoist in real time and provide timely maintenance advice to avoid unnecessary disasters and losses, scholars have studied the fault diagnosis of the hoist, mainly researching the diagnosis technologies of the hoist and its corresponding critical equipment. Using the Internet of Things to diagnose the fault of the hoist and basing on the improved Dezert-Smarandache theory, fault diagnosis reasoning can be performed and remote data transmission and fault diagnosis can be achieved (Li, Xie, et al., 2018). Based on the proposed new MMC modular multilevel converter, the change of the measuring point voltage was obtained by changing the output terminal voltage, and the open and short circuit faults were detected (Haghazari et al., 2016). The graphical monitoring language of LabVIEW was used to design the condition monitoring and fault diagnosis system of the elevator bearings (Wan et al., 2011). Methods for fault diagnosis include DS evidence theory, support vector machine, Bayesian network, and fault detection methods based on parameter comparison.

In terms of health assessment of the mine hoist system, there are not enough articles up to now. However, there are still numerous applications of health assessment in generator sets and helicopters. Li, Meng, et al. (2019) was based on Three-level fuzzy comprehensive assessment of the health assessment of the mine hoist system, using the practicability of neural network verification methods. Li, Li, et al. (2019) is about the health assessment of a generator based on the vector machine using the least squares evaluation index for health assessment. In the researches on helicopters, Nedelkoa et al. (2019) employed actual curves as examples to implement the health assessment based on probabilistic methods; Serafini et al. (2019) realized the health assessment of helicopter blades by variance analysis, which showed a high safety margin. The former was based on diagnostic signs and the latter was evaluated by numerical simulation of aerodynamic analysis of the rotorcraft by a multi-body dynamics solver. In terms of health management, researchers studied electrical systems and aircraft engines. Through physical modelling and root cause analysis of faults, it is possible to better trouble shoot and research aircraft engines based on PHM (Liu et al., 2018).

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Xu et al. (2015) established a sensor optimization model for PHM through the selection of aircraft engines sensors, and then verified the positive feasibility of the algorithm. Based on the fault demonstration mechanism through the selection and optimization of PHM system testing, the method improved the level of health management (Qiu et al., 2013). Whether it is the health evaluation of the hoist, or the health evaluation of the generator set and the helicopter, they all collect data around the ultimate goal of the health evaluation. Then based on certain methods such as: vector machine-based, fuzzy comprehensive evaluation, probability-based, Physical modelling, etc., the studies reached the health assessment for operating status evaluation of the synchronous motor drive system or other equipment.

Hierarchical fuzzy evaluation methods are widely used in learning robot control, construction goals and strategies, control systems, wind turbines, and power loads. The approach used in the paper was based on extending Hierarchical Fuzzy Rule-Based Systems, which learned a controller with a variable internal representation for both supervised and reinforcement learning problems while interacting with the environment (Waldock & Carse, 2016). Liu et al. (2019) built the combination of multi-objective and optimization strategies and improved the comprehensive fuzzy evaluation to realize the ecological operation decision of the reservoir and the control system on the instance of Learning Management System. Li et al. (2013) employed real time state assessment, hierarchical fuzzy evaluation of grid-connected power generation systems to improve operational reliability. A new layered fuzzy evaluation based on neural network was proposed to realize the forecast of electric power load (Vellasco et al., 2004). Especially in mine hoist system, the study (Li, Meng, et al., 2019) proposed a combination of three-level fuzzy comprehensive evaluation and back propagation neural network calculation method, which has strong practicability.

The hierarchical fuzzy comprehensive evaluation method can make an overall evaluation of things or objects that are subject to multiple factors. Through accurate digital means to process the fuzzy evaluation, the content of the contained information can be more scientific and close to the actual conditions without too much reliance on experimental data. It can not only accurately describe the evaluated object, but also further process it to obtain reference information. Therefore, the method is used to comprehensively evaluate the synchronous motor drive system.

The rest of the paper is organized as follows: Section 2 introduces the hierarchical fuzzy comprehensive evaluation model. Section 3 researches membership functions and degradation degree analyses. Section 4 demonstrated a case. Section 5 summarizes the paper.

## 2. The hierarchical fuzzy comprehensive evaluation algorithm

The state assessment process of the electromechanical system constructed in the paper is illustrated in Figure 1. Firstly, according to the working principle and fault analysis of an electromagnetic system, the index system of the system is obtained. By the operating conditions and historical data, the weights of evaluation indexes and factors of each layer are allocated. The evaluation factors are standardized for the obtained data. Then, their deterioration degrees (DDs) are calculated. If the values are larger than 0.9, the result will be evaluated as medium or poor. Otherwise, by the corresponding membership functions, the work can calculate the evaluation status with the evaluation algorithm model.

The running state of each system (device or subsystem) can be evaluated by its subordinate indicators through the fuzzy evaluation model. Then the state result can be used as an indicator to judge the state of the upper equipment. The comment collection is divided into four operational status levels:

\[
V_i = [V_1, V_2, V_3, V_4], i = 1, 2, 3, 4 \\
V_i = \{\text{excellent, good, medium, poor}\}
\]

The description of the four operating status levels is demonstrated in Table 1.

**Excellent**: The item’s working state is stable; each component works well; the failure possibility is very low.

**Good**: The item has been running for a period, some electrical components have a certain degree of aging. But the test data of power off and on is normal; the working performance is generally stable; the possibility of fault occurrence is low; the maintenance is not necessary.

**Medium**: The possibility of failure increases somewhat, yet it will not pose a threat to the safe operation temporarily; it is necessary to analyse and judge the specific abnormal types of electrical components.

**Poor**: The item’s working state has hit a critical stage; it will pose a threat to the safe operation; the maintenance is urgently needed.

### Table 1. Comments collection of an electromagnetic system.

| Comment     | Working state       | Components aging degree | Failure possibility | Examination and reparation |
|-------------|---------------------|-------------------------|--------------------|---------------------------|
| Excellent   | Stable              | Very low                | Very low           | No                        |
| Good        | Good for a long time| A certain degree        | Low                | No                        |
| Medium      | Normal              | No serious damage       | Increasing         | No                        |
| Poor        | Abnormal            | High or abnormal        | High               | Yes                       |

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 poorest(V4) Abnormal High or abnormal Yes
 Medium(V3) Normal No serious damage Increasing No
 Good(V2) Good for a long time A certain degree Low No
 Excellent(V1) Stable Very low Very low No

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The hierarchical fuzzy comprehensive evaluation method can make a comprehensive evaluation of things or objects that are subject to multiple factors. Through accurate digital means to process the fuzzy evaluation, the content of the contained information can be more scientific and close to the actual conditions without too much reliance on experimental data. It can not only accurately describe the evaluated object, but also further process it to obtain reference information. Therefore, the method is used to comprehensively evaluate the synchronous motor drive system.
Figure 1. The state evaluation process of the MHSS.

Poor: Running or testing data from the main electrical components is abnormal dramatically; faults may occur; it is advisable to cut off the power supply and overhaul the system, finding the cause of abnormal conditions or abnormal components; the engineers consider replacing the specific equipment if necessary.

2.1. Weight collection A of evaluation factors

Using analytic hierarchy process (AHP), we can obtain the weight values corresponding to each factor (Wang, Chen, et al., 2018; Leng et al., 2017). AHP is a method that combines qualitative and quantitative analysis, which compares the influence degrees of the same level of factors on the previous level of factors. According to the 1–9 scale method, the two elements of the same level are compared in pairs. After a series of solving steps, the weight value of each factor can be obtained. Therefore, it transforms the qualitative problem into a quantitative one to solve the standard qualification. Since the AHP does not require a large amount of experimental data that depends on the research object, the process of solving the weights of various factors is simple and widely used.

2.2. Hierarchy fuzzy relation evaluation algorithm (Jin et al., 2017; Wang, Han, et al., 2018)

According to the multi-level idea of AHP, the whole project is divided into several sub projects. The authors must compute the lowest evaluation indicators from the reverse direction. Sub indicators for evaluating the operation status of each sub project level are classified into several levels. Generally, we can implement the local comprehensive evaluation of a certain device from the lower level indicators, and gradually get the entire comprehensive evaluation matrix.

The bottom fuzzy relation matrix is defined as follows:

\[
R_{Xij \cdot k} = \begin{bmatrix}
\mu_{Xij \cdot k_{11}} & \cdots & \cdots & \mu_{Xij \cdot k_{14}} \\
\vdots & \ddots & \cdots & \vdots \\
\vdots & \cdots & \ddots & \vdots \\
\mu_{Xij \cdot k_n \cdot k_1} & \cdots & \cdots & \mu_{Xij \cdot k_n \cdot k_4}
\end{bmatrix}
\] (1)
where $\mu_{X_{ij,k}}$ represents the membership degree of the project, $X_{ij,k}$, $n_{ij,k}$ represent the number of impact indicators of the item $X_{ij,k}$. The first row represents the performances of a certain unit belonging to $V_1$ (excellent), $V_2$ (good), $V_3$ (medium), and $V_4$ (poor), respectively. By the weight values, the paper can obtain the fuzzy relation matrixes at the lower level.

The comprehensive evaluation model is as follows:

$$B_{Xij} = A_{Xij} \cdot R_{Xij} = A_{Xij} \begin{bmatrix} A_{X_{ij,1}} \cdot R_{X_{ij,1}} \\ \vdots \\ A_{X_{ij,n}} \cdot R_{X_{ij,n}} \end{bmatrix} = \cdots (2)$$

where $A_{X_{ij}}$ is the weight value of the subproject layer $X_{ij}$ connected with the parent project. The number of impact indicators of the project $X_{ij}$ is represented by $n_{ij}$. $R_{X_{ijk}}$ is the next lower fuzzy relation matrix. Obviously, if the fuzzy relation matrix of a certain layer $R_{X_{ijk}}$ is known, we can calculate the operation state of the project according to the corresponding weight values $A_{X_{ij}}$.

The lower fuzzy relation matrix can be calculated by Equation (1) with field data, historical data records and test data. Then the operation status of each subproject can be evaluated by Equation (2) combined with the weight values. Next, the evaluation matrix of each subproject forms the fuzzy relation matrix of the layer, consequently, the comprehensive evaluation matrix of the layer is calculated to get the operation status of the layer. Finally, the operation status performance evaluation of the whole system can be obtained.

Through the above evaluation process, the final evaluation result set $B_{Xij}$ can be achieved. Using the maximum membership method, the evaluation element $V_i$ corresponding to the largest value in the set is taken to obtain the judgment result (Ma et al., 2014). In other words

$$V = \{ V_i | V_i \rightarrow \text{max}(b_j) \} (3)$$

For instance, the value in the result set corresponding to the second element is largest, which indicates the state is $V_2$ (good).

3. Degradation degrees (DDs) and membership functions

A membership function is the fuzzy relationship between the evaluation factors and the evaluation state. When the membership degree of each parameter is determined, the corresponding original data should be preprocessed. Due to the different dimensions and magnitudes of each indicator in the evaluation index system of the electromechanical system, inconsistent scale indicators cannot be compared and analyzed. In order to eliminate the differences between the dimension and magnitude of the indicators, the paper introduces the concept of degradation degree (DD) to standardize each indicator (Wang, Han, et al., 2018; Ma et al., 2014). The DD of an indicator refers to the degree of deterioration of the current state of the device compared to the faulty state under the same operating condition, whose value range is [0, 1]. After preprocessing the original data, the membership degree can be calculated via the membership function. For the temperature, insulation, electrical characteristics and other quantifiable indicators, the use of semi-trapezoidal and triangular membership distribution function is shown in Figure 2. The comment collection is: $V = \{V_1, V_2, V_3, V_4\}$; quantization domain: $\xi = \{\xi_1, \xi_2, \xi_3, \xi_4\}$.

3.1. Degradation degree (DD) function

In the evaluation index system, the indicators are divided into two categories: the smaller the better type (e.g. bearing temperature); intermediate type (e.g. excitation current).

(1) For the index of the smaller the better type, the DD function is calculated by Equation (4):

$$g(x) = \begin{cases} 0 & x < x_{\min} \\ \frac{x - x_{\min}}{x_{\max} - x_{\min}} & x_{\min} < x < x_{\max} \\ 1 & x > x_{\max} \end{cases} (4)$$

where $x_{\min}$ and $x_{\max}$ are the threshold values for evaluating the index parameters, respectively.

Figure 2. Triangular and semi-trapezoidal membership functions.
For the index of the intermediate type, the DD function is calculated by Equation (5):

$$g(x) = \begin{cases} 
1, & x < x_{\text{min}} \\
x - x_{\text{min}}, & x_{\text{min}} \leq x < \alpha \\
\frac{x - \alpha}{x_{\text{max}} - \beta}, & \beta < x \leq x_{\text{max}} \\
1, & x > x_{\text{max}} 
\end{cases}$$

(5)

where $x_{\text{min}}$ and $x_{\text{max}}$ are the upper and lower limit values of the evaluation index parameters; $\alpha$ and $\beta$ are the allowable fluctuation ranges for the normal operation of the evaluation index.

### 3.2. Membership functions

In the fuzzy comprehensive evaluation of the evaluation object, each element in the fuzzy relation matrix $R$ is the degree, to which the influencing factors of the evaluation object belong to the elements in the comment set. The membership degree is calculated by the membership function. Therefore, in order to accurately evaluate the evaluation object, it is important to choose the appropriate membership function. Because the membership functions of the triangle and semi-trapezoidal combination are simple and relatively easy to calculate, the results obtained are less different from other more complex membership functions. Therefore, the paper selects the membership function of the combination of triangle and semi-trapezoid to calculate the membership degree of each index, and its distribution is shown in Figure 2.

In Figure 2, $\xi_i (i = 1, 2, 3, 4)$ is the fuzzy boundary interval about the DD of a variable $x$ (DDx). By Equations (4) and (5), the DD calculation is performed on the online monitoring data. According to the DD distribution functions of the triangular and semi-trapezoidal combination in Figure 2, we can determine the fuzzy boundary intervals of the four state levels. Finally, the membership function of the DD for each state grade is established.

For example, for the temperature rise of the excitation winding, the membership functions $\mu_1(x) \sim \mu_4(x)$ based on the DDx in each level state are determined as follows:

$$\mu_1(x) = \begin{cases} 
1, & x < 0.5 \\
0.7 - x, & 0.5 \leq x \leq 0.7 \\
0.2, & x > 0.7 
\end{cases}$$

(6)

$$\mu_2(x) = \begin{cases} 
x - 0.5, & 0.5 \leq x \leq 0.7 \\
0.2, & 0.85 - x, \\
0.15, & 0.7 \leq x \leq 0.85 \\
0, & x < 0.5 \text{ or } x > 0.85 
\end{cases}$$

(7)

$$\mu_3(x) = \begin{cases} 
x - 0.7, & 0.7 \leq x \leq 0.85 \\
0.15, & 0.9 - x, \\
0.05, & 0.85 \leq x \leq 0.9 \\
0, & x < 0.7 \text{ or } x > 0.9 
\end{cases}$$

(8)

$$\mu_4(x) = \begin{cases} 
x - 0.85, & 0.85 \leq x \leq 0.9 \\
0.05, & 0.9 - x, \\
1, & x > 0.9 
\end{cases}$$

(9)

In Equations (6)–(9): $\mu_1(x) \sim \mu_4(x)$ respectively indicate the membership functions of the temperature rise in the excitation winding, which corresponds to the DDx in the four levels.

Similarly, the membership functions of the stator current and the temperature rise of the stator windings relative to the DDx are obtained by introducing the data pre-processing method of the DD and combining the membership function of triangle and half trapezoid.

Due to the limited space of the article, the other membership functions corresponding to the other evaluation indicators are not listed here.

### 4. Case analysis

The structure diagram of a mine hoist synchronous motor drive system (MHSS) is shown in Figure 3. It is mainly composed of three links: a synchronous motor, a frequency converter, a shaft and other equipment.

According to the main equipment failures and characteristics of the MHSS, the monitoring parameters that can accurately reflect the fault characteristics are selected as the evaluation indexes. The operating state evaluation index system of the MHSS is illustrated in Figure 4. The index system is divided into four layers from top to bottom. The performance of a certain unit or component is comprehensively evaluated by its performance indicators. The performance of the upper layer is obtained from the bottom index, and the performance evaluation of each part is obtained step by step. In the end, the state performance of the whole system is obtained. The top index is mainly composed of three parts: the synchronous motor (X1), the frequency converter (X2) and the main shaft (X3). E.g. the frequency converter has four secondary level indicators, respectively for the active rectifier unit X21, the capacitor group unit X22, the inverter unit X23, the cooling system X24. Each secondary level index is made up of its corresponding tri-grad index. Namely, for a certain indicator $X_1 \ldots n$, the digit number of subscripts represents the series of indicator.

The AHP is applied to calculate the weights of the evaluation indicators of the MHSS, as shown in Table 2. The number of evaluation factors which each layer contains
Figure 3. Structure diagram of the MHSS.

Table 2. Weight values of the evaluation index.

| Index | Weight value of the index (Ax...) |
|-------|----------------------------------|
| X1    | (0.0837,0.1385,0.2328,0.5450)   |
| X2    | (0.3934,0.1451,0.3660,0.0955)   |
| X3    | (0.75,0.25)                      |
| X11   | (0.4,0.6)                        |
| X12   | (0.4,0.6)                        |
| X13   | (0.4645,0.2967,0.1094,0.1094)    |
| X14   | (0.75,0.25)                      |
| X21   | (0.5,0.5)                        |
| X22   | (0.6667,0.3333)                  |
| X23   | (0.5,0.25,0.25)                  |
| X24   | (0.75,0.25)                      |
| X111  | (0.3333,0.6667)                  |
| X112  | (0.5,0.5)                        |
| X121  | (0.3333,0.6667)                  |
| X122  | (0.5,0.5)                        |

decides the one of weight values. The sum of all the weight values of each layer is 1.

Figure 5 demonstrates the flow path of the model. The lower fuzzy relation matrixes are composed of the lower evaluation matrix.

The paper took the MHSS with a model number of JKMD-4 × 4(Z) in a coal mine in Henan Province, China as an example to analysis. Through surveys and measurements, the authors collected the monitoring data of the MHSS in the hoist JKMD-4 × 4(Z), where two data samples are demonstrated in the following tables. The proposed fuzzy comprehensive evaluation methodology is carried out to analyse the running state of the MHSS. The corresponding technical parameters of the type of hoister are listed in Table 3.

Table 3. JKMD-4 × 4(Z) technical parameters.

| Model | JKMD-4 × 4(Z) | AC synchronous motor |
|-------|---------------|----------------------|
| Model | JKMD-4 × 4(Z) | Model | TBP2500-20/3150 |
| Boost speed | 9.4 m/s | Rated power | 2500kW |
| Maximum static tension | 700kN | Rotating speed | 45r/min |
| Maximum static tension difference | 270kN | Rated voltage | 3150V |
| Motor bearing vibration intensity | 1.5 | Frequency | 7.5Hz |
| Motor bearing temperature X142 (°C) | 50.2 | Power factor | cos θ = 1.0 |

4.1. The synchronous motor’s running state evaluation

The monitoring data of the synchronous motor are demonstrated in Table 4. The evaluation indicators are standardized according to the DD function of each evaluation index, and the DD of each evaluation index is calculated.

Taking Sample 1 in Table 4 as an example, the running state of the synchronous motor is analysed according to...
the calculation process of the hierarchical fuzzy comprehensive evaluation.

From Table 4, the stator current 440.3 A and the stator winding temperature rise 75.1 K shown with light blue highlight, the terminal temperature rise and the terminal discharge deterioration value obtained in column 5 in Table 6 are 0.19, 0.72 respectively. The DD values are substituted into the membership function under the four operating state levels in Table 4. By Equation (1), the fuzzy relation matrix can be obtained as:

\[ R_{X11} = \begin{bmatrix} 0.73 & 0.27 & 0 & 0 \\ 0 & 0.87 & 0.13 & 0 \end{bmatrix} \]

From Table 2, the weight sets of \( A_{X11} = (0.3333, 0.6667) \), \( A_{X112} = (0.5, 0.5) \) and \( A_{X11} = (0.4, 0.6) \) are got. According to Equation (2), we can calculate the local comprehensive evaluation state of the stator as \( B_{X11} \)

\[ B_{X11} = A_{X11} \cdot R_{X11} = A_{X11} \begin{bmatrix} A_{X11} \\ A_{X112} \end{bmatrix} \cdot \begin{bmatrix} R_{X11} \\ R_{X112} \end{bmatrix} = (0.4, 0.6) \begin{bmatrix} 0.2433 & 0.6700 & 0.0867 & 0 \\ 0.3750 & 0.2750 & 0.3500 & 0 \end{bmatrix} = (0.3223, 0.4330, 0.2447, 0) \]
Figure 5. Flow chart of the comprehensive hierarchical evaluation algorithm.

In view to $B_{X11} = \{b_{111}, b_{112}, b_{113}, b_{114}\}$, $b_{112} = \max(b_{ij})$, we can judge the stator is in good state by Equation (3).

Likewise, the local comprehensive evaluation state of the rotor can be calculated. The DD values of the four evaluation indexes of the excitation in Table 4 are respectively analysed and processed. The fuzzy relation matrix $R_{X121}$ and $R_{X122}$ are:

$$R_{X121} = \begin{bmatrix} 0 & 0.7250 & 0.2250 & 0 \\ 0 & 0.8 & 0.2 & 0 \\ 0.25 & 0.75 & 0 & 0 \end{bmatrix} \quad \text{(11)}$$

$$R_{X122} = \begin{bmatrix} 0 & 0.65 & 0.35 & 0 \\ 0.25 & 0.75 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$B_{X12} = A_{X12} \cdot R_{X12} = A_{X12} \begin{bmatrix} A_{X121} \cdot R_{X121} \\ A_{X122} \cdot R_{X122} \end{bmatrix} = \begin{bmatrix} 0.0750 & 0.7300 & 0.1950 & 0 \end{bmatrix}$$

For the excitation unit, the fuzzy relation matrix $R_{X13}$ is $4 \times 4$.

$$R_{X13} = \begin{bmatrix} 0 & 0.3000 & 0.7000 & 0 \\ 0.4200 & 0.5800 & 0 & 0 \\ 0.7500 & 0.2500 & 0 & 0 \\ 0 & 0.7250 & 0.2750 & 0 \end{bmatrix}$$

From Table 3, the weight set of $A_{X13} = (0.4845, 0.2967, 0.1094, 0.1094)$, we can calculate the local comprehensive evaluation state of the excitation unit as $B_{X13}$

$$B_{X13} = A_{X13} \cdot R_{X13} = \begin{bmatrix} 0.2067 & 0.4241 & 0.3692 & 0 \end{bmatrix} \quad \text{(12)}$$

For the motor bearing, the fuzzy relation matrix $R_{X14}$ and the local comprehensive evaluation matrix $B_{X14}$ are:

$$R_{X14} = \begin{bmatrix} 0 & 0.7 & 0.3 & 0 \\ 0.9 & 0.1 & 0 & 0 \end{bmatrix}$$

$$B_{X14} = A_{X14} \cdot R_{X14} = \begin{bmatrix} 0, 0.75, 0.25, 0 \end{bmatrix}$$

The above-calculated membership degree of stator, rotor, excitation unit and motor bearing is taken as the fuzzy relation matrix $R_{X1}$ of synchronous motor. $R_{X1}$ can be calculated.

$$R_{X1} = [B_{X11}^T, B_{X12}^T, B_{X13}^T, B_{X14}^T]^T \quad \text{(14)}$$

The weight vector corresponding to the four components of the synchronous motor $A_{X1} = (0.0837, 0.1385, 0.2328,
0.5450) is shown in Table 3. Therefore, we can calculate the comprehensive evaluation state of the whole synchronous motor as $B_{X1}$

$$B_{X1} = A_{X1} \cdot R_{X1}$$

$$= (0.0855, 0.6448, 0.2697, 0)$$  \hspace{1cm} (15)

According to the comment set of the MHSS, the maximum membership degree of 0.6448 corresponds to the operating state of the synchronous motor is 'good', which indicates that the performance of synchronous motor system is basically stable, the possibility of failure is very low, and maintenance measures are not needed.

For the monitoring sample 2 of the synchronous motor in Table 4, the same process is used to evaluate the running state of the synchronous motor. From the calculation of the DD results of each evaluation index, it is found that the DD the temperature rise of the collector ring is $g = 0.92$. Therefore, the operating state of the synchronous motor corresponding to the sample 2 is 'poor', and it is necessary to immediately stop the inspection and eliminate the fault.

4.2. The frequency converter’s running state evaluation

The monitoring data of the inverter is shown in Table 5. According to the DD function of each evaluation index obtained in Section 3, the DD values of each evaluation index are calculated.

Still taking the Sample 1 in Table 5 as an example, the running state of the converter is analysed according to the calculation process of the hierarchical fuzzy comprehensive evaluation illustrated in Figure 6.

By the principle of maximum membership, the maximum membership degree is 0.5247. It is clear the operating state of the inverter is 'excellent'. The converter has stable working performance and can continue to operate without any maintenance measures.

For the monitoring Sample 2 of the converter in Table 4, the process is no longer verbose. The calculated data are shown in Table 6, and the final result is that the operating state of the inverter is 'excellent'.

### Table 5. Monitoring data of the inverter.

| Evaluation index                  | Sample 1 | Sample 2 | DD1  | DD2  |
|-----------------------------------|----------|----------|------|------|
| DC bus voltage X211 (V)          | 4450.7   | 5139.3   | 0.39 | 0.24 |
| Rectifier IGBT temperature X212 (°C) | 46.4     | 67.1     | 0.37 | 0.54 |
| Capacitor temperature X221 (°C)  | 30.2     | 44.8     | 0.5  | 0.75 |
| Capacitor terminal voltage X222 (V) | 2225.3   | 2569.7   | 0.39 | 0.38 |
| Inverter IGBT temperature X231 (°C) | 72.5     | 69       | 0.58 | 0.55 |
| Output current X232 (A)          | 448.9    | 522.3    | 0.32 | 0.32 |
| Output voltage X233 (V)          | 2896.2   | 3392.3   | 0.33 | 0.47 |
| Frequency converter operating temperature X241 (°C) | 25       | 24.8     | 0.62 | 0.62 |
| Water conductivity X242 (μs/cm)  | 0.19     | 0.14     | 0.38 | 0.28 |

![Figure 6](image.png)
According to the hierarchical fuzzy algorithm, the status evaluation of each subsystem can lead to the status evaluation of the whole system.

5. Conclusion

The hierarchical fuzzy comprehensive evaluation algorithm model including fuzzy matrix and comprehensive evaluation matrix calculation thought is presented and constructed for the MHSS. The authors established the index system of state evaluation composed of four layers and primary indexes, several secondary and tertiary indexes, etc. through the failure analysis of each component of the MHSS. The proposed hierarchical fuzzy comprehensive evaluation algorithm not only evaluate each subsystem according to four operating state levels, but also comprehensively evaluate the global system according to the evaluation results of each system. Moreover, the evaluation process don’t acquire too much reliance on experimental data.

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| Table 6. Evaluation results of inverter with Simple 2. |
| Evaluation index                  | Excellent | Good | Medium | Poor |
| DC bus voltage X211               | 1        | 0    | 0      | 0    |
| Rectifier IGBT temperature X212   | 0.8      | 0.2  | 0      | 0    |
| Capacitor temperature X221        | 0        | 0    | 0.5    | 0.5  |
| Capacitor terminal voltage X222   | 0.6      | 0.4  | 0      | 0    |
| Inverter IGBT temperature X231    | 0.75     | 0.25 | 0      | 0    |
| Output current X232                | 0.4      | 0.6  | 0      | 0    |
| Output voltage X233                | 0.27     | 0.73 | 0      | 0    |
| Frequency converter operating     | 0        | 0.8  | 0.2    | 0    |
| temperature X241                   |          |      |        |      |
| Water conductivity X242            | 0.6      | 0.4  | 0      | 0    |
| Inverter status evaluation result BX2 | 0.5960  | 0.2930 | 0.0627 | 0.0483 |
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