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Hydropower Unit State Evaluation Model Based on AHP and Gaussian Threshold Improved Fuzzy Comprehensive Evaluation

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Abstract: Because a single monitoring index cannot fully reflect the overall operating status of the hydropower unit, a comprehensive state evaluation model for hydropower units based on the analytic hierarchy process (AHP) and the Gaussian threshold improved fuzzy evaluation is proposed. First, the unit equipment was divided into a hierarchical system, and a three-tier structure system (target layer-project layer-index layer) of the unit was constructed, and the weight of each component in the system was determined by the comprehensive weighting method. Secondly, according to the characteristics of the normal distribution of the historical health data of the unit, the upper and lower limits of the index were determined based on the Gaussian threshold principle, the real-time monitoring index degradation degree was calculated according to the index limit, and the degradation degree was applied to the fuzzy evaluation model to obtain the fuzzy judgment matrix. The result of assessment was divided into four sections: good, qualified, vigilant, and abnormal. Finally, combined with the unit hierarchical structure system, the weighted calculation of the fuzzy judgment matrix of each indicator, the overall fuzzy judgment matrix of the upper-level indicators of the unit was obtained, and the operating status of the unit was judged according to the matrix. Taking a real power plant unit as an example, the model was verified, and compared with other evaluation methods, the effectiveness and advantages of the proposed method were verified. In addition, the method proposed in this paper effectively solved the problems of index weighting and index limit determination in the existing model of unit condition evaluation.

Keywords: AHP; combination weighting; gaussian threshold; fuzzy comprehensive evaluation; fuzzy membership

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1. Introduction

The hydropower unit is the key equipment for the transformation of hydropower energy. In recent years, with the continuous development of hydropower industry, the installed capacity of power stations is growing, the structure of the unit is becoming more complex, and most of the units put into early operation have entered the middle and late service life, so a higher requirement for maintenance and maintenance is currently being put forward. Therefore, it is of great significance to evaluate the running state of the hydropower unit reasonably and discover the hidden safety risks of the unit in time to ensure the stable operation of the unit.

Condition monitoring and fault diagnosis are essential links to ensure the safe and stable operation of hydropower units. Most domestic power stations have installed real-time and effective condition monitoring systems. The real-time operation of the units can be determined by judging whether the monitoring index exceeds the limit.

At present, fault diagnosis mainly focuses on feature extraction and trend prediction of monitoring signals of units, and the characteristic quantity of monitoring signals, especially vibration signals, is extracted by the signal processing method to judge the operating state and fault type of units [1,2]. At present, most of the studies focus on single-point signal analysis, focusing on local diagnosis, lack of evaluation, and analysis of the whole condition of the unit. There are many monitoring points in the condition monitoring system of hydropower units, and there are many normal samples, but few fault samples. How to use the existing monitoring data to fully and effectively evaluate the units is a problem that needs to be further studied in the field of hydropower.

The combination of hierarchical analysis and fuzzy comprehensive evaluation based on fuzzy mathematics is a research hotspot in the field of equipment condition evaluation. Due to its clear structure, distinct hierarchy, and strong adaptability to complex systems, the analytic hierarchy process (AHP) is widely used in risk assessment, resource allocation, equipment evaluation, and other fields [3,4].

Xuan et al. [5] conducted a comprehensive study on the evaluation of distributed integrated energy systems (IES). They proposed energy use quality elements to address the high energy supply requirements of users in distributed IES, and these elements were characterized using the supply–demand imbalance rate indicator. To achieve a comprehensive performance evaluation, the authors combined the analytic hierarchy process (AHP) with the information entropy method, which allowed for a balanced consideration of both subjective and objective evaluation methods. The verified calculation examples show that the comprehensive evaluation by the AHP-information entropy method can effectively consider all elements' roles. It provides a new idea for the research on the impact of distributed IES energy storage on the energy use quality of the system and the construction and operation optimization of the comprehensive performance evaluation indicator of the system. In order to realize the quantitative analysis and prediction of the operation state of the transformer, Niu et al. [6] built and interchange complex matter element between dissolved gases in transformer oil and typical faults. The analytic hierarchy process (AHP) and maximum information entropy were used to determine the subjective and objective weights influencing the transformer health level, respectively. This method provides a good guiding value for the elimination of transformer faults, overhaul decisions, and online predictions. Du, Yue, et al. [7] proposed a comprehensive risk assessment method based on equipment condition and entropy was proposed to evaluate the power network. Firstly, a model of the power network is established, considering the key risk factors including equipment condition, network structure, loads, natural and weather, etc. Then, the AHP method was used to determine the subjective weight, while the entropy method was applied to obtain the objective weights. After that, the combined weights were calculated based on subjective and objective weights. Last, the effectiveness of the model was proved by two study cases, the weights parameters in the model can be applied in the other risk assessment of power networks. To address the subjective nature of the simple analytic hierarchy process (AHP), JunPing, LUO, et al. [8] introduced the AHP-entropy method to determine the weight allocation for each index in the intelligent distribution room. In their research, the authors proposed, for the first time, a health status assessment method for intelligent distribution rooms based on the AHP-entropy weight method. By considering multiple aspects and incorporating the AHP-entropy method, their approach overcame the limitations of subjective analysis and offers a more objective assessment. The example presented demonstrates the feasibility of their proposed method, highlighting its practical applicability and potential in real-world scenarios. Kong et al. [9] employed the analytic hierarchy process (AHP) and entropy weighting method to reduce weight bias. To address the drawback of traditional weighted processes, which may overshadow important information, they proposed a mechanism for incorporating important information triggering weight fusion and weight modification to ensure the accuracy of the evaluation results. They transformed the status assessment results of fuzzy membership degrees into evaluation scores, determined the corresponding status levels, and accurately evaluated the status of secondary equipment. The authors conducted a status evaluation and result analysis of four types of secondary relay protection devices, validating the rationality of the proposed comprehensive status evaluation model. In the aerospace field, Niu et al. [10] addressed the challenge of material selection in the aerospace industry. Considering the characteristics of materials used in spacecraft and their operating environment, they established a quantitative scoring model for aerospace material application verification based on the analytic hierarchy process (AHP) and entropy weighting method. By combining AHP-entropy combination weighting, they integrated subjective and objective methods to determine the comprehensive weight of coating materials. Finally, they quantitatively scored the overall performance of materials using a fuzzy comprehensive evaluation method. Xia et al. [11] addressed the issue of inadequate matching between the weight of bridge parts and components and their actual conditions in bridge technical evaluations. They utilized the analytic hierarchy process (AHP) and entropy weighting method to construct a comprehensive weight analysis system for bridge parts and components. By applying AHP to analyze the subjective weight of bridge parts and components and employing the entropy weighting method to analyze bridge structural health monitoring data, they obtained a weight system that considers both subjective and objective factors. The analysis results demonstrated that the weight fusion method provided results that comprehensively considered both subjective and objective factors, resulting in a weight system that is closer to engineering reality and reasonably reflects the weight of bridge parts and components. Fang et al. [12] aimed to address the evaluation criteria for various design options during the ship shafting design phase and improve the cost-effectiveness of the ship shafting system over its lifecycle. They utilized the triangular fuzzy analytic hierarchy process (AHP) and entropy weighting method to determine the subjective and objective weights of indicators. They applied the fuzzy comprehensive evaluation method to comprehensively evaluate two design options. The research findings provide new theoretical support for improving the quality of shafting system design.

It is also partially used in the field of hydropower. The evaluation index system and evaluation model of hydropower units are constructed by AHP [13], and the application of this method in the health evaluation of hydropower units was expounded. The fuzzy comprehensive evaluation method can accurately evaluate multi-index and multi-level complex systems, and better deal with unquantifiable boundary problems. It has been gradually applied in the evaluation of large-scale equipment and construction schemes [14]. In terms of equipment evaluation, the condition evaluation method combined with hierarchical analysis and fuzzy comprehensive evaluation has been widely used in the condition evaluation of wind turbines and large power transformers [15], but rarely seen in the field of hydropower, and related studies have only begun to rise in recent years. However, most of the current research relies too much on expert experience and a lack of objectivity. It is difficult to determine the limit value of the index. The limit value of the monitoring quantity of different types of units is not specified in the industry regulations and factory regulations, and the limit range of some monitoring indicators is not clear, which cannot be effectively evaluated. The corresponding relationship between index deterioration degree and fuzzy membership interval is not reasonable [16,17]. The application of each new weighting method is described in depth in literature [18], thus providing valuable knowledge to researchers and practitioners in the field of multi-criteria decision-making. In our research, we adopted the AHP method to generate criteria weights because it enables us to capture the subjective judgments and preferences of experts involved in the decision-making process. These weights are crucial as they reflect the relative importance of each criterion in our model. To enhance the robustness of our decision-making model, we further incorporated the entropy method. The entropy method complements the AHP by quantifying the information content and consistency of the pairwise comparisons. It helps us assess the reliability and consistency of the judgments made by the decision-makers. By combining the AHP with the entropy method, we ensure that our criteria weights are derived from expert judgments and possess consistency and reliability.

Aiming at the deficiency of current research on equipment condition evaluation in the field of hydropower, this paper proposes a comprehensive condition evaluation model of hydropower units, which combines AHP and Gaussian threshold values to improve fuzzy evaluation. The hierarchical structure system of the unit was determined by the AHP, and the subjective weight of each component was calculated. The objective weight of each component was calculated by the entropy weight method according to the historical data of the monitoring system, and the comprehensive weight was finally obtained by combining the subjective and objective weights. The entropy weight method considers the information content of each criterion in the decision-making process, quantifies the information provided by each criterion, and enables decision-makers to assign weights accordingly. This approach ensures that criteria with higher information content are given more weight, resulting in a more efficient and accurate decision-making process. Secondly, according to the historical data of the unit, the upper and lower limits of each monitoring index of the unit are determined by the Gaussian threshold method, and the deterioration degree of the real-time monitoring index is calculated. The deterioration degree is introduced into the fuzzy evaluation model, and the state levels in the model are divided into four types. The corresponding relationship between the deterioration degree of the index and the state level is established according to the characteristics of the index interval in the Gaussian threshold method, and the fuzzy judgment matrix of each index is finally obtained. The index fuzzy judgment matrix is weighted to obtain the overall fuzzy judgment matrix of the system, and the operating state of the unit is judged according to the principle of maximum membership degree. The evaluation model is used to evaluate the actual power station unit. The results show that the model can accurately judge the operation state of the unit, and the evaluation results are consistent with the actual operation condition.

The rest of this paper is organized as follows: Section 2 provides the method theory of the AHP. Section 3 demonstrates the discussion of the method. In Section 4, using a conventional power station as an example, the model is used to evaluate the operation status of the unit at different times. Finally, concluding remarks are presented in Section 5.

2. Method Theory

2.1. Analytic Hierarchy Theory

The core of the AHP is to decompose the complex system according to the principle from the whole to the local level, and then construct the judgment matrix and solve the maximum feature root of the matrix and the corresponding feature vector, and obtain the index weight of each layer. The specific process is as follows:

(1) Establish the hierarchical structure model. According to the structural characteristics of the research object, multiple indicators contained in the object to be evaluated are stratified in order according to different attributes.

(2) Construct a judgment matrix. Assume that the layer has a monitoring index $V_1, V_2, \ldots\ldots, V_n$, judging the importance between the two indicators by expert experience. The importance of V_i relative to V_j is expressed on a scale of 1–9, Be denoted as $C_{\ddot{v}}$. The 1–9 scale regulations are shown in Table 1, where $C_{ji} = \frac{1}{C_{\ddot{v}}}$, and $C_{ii} = 1$, $i,\ j = 1,\ 2,\ KK,\ N$.

Table 1. 1–9 scale method.

C_{ij}	Meaning
1	Equally important
3	Slightly important
5	Obviously important
7	Particularly important
9	Absolutely vital
2, 4, 6, 8	Median value

Then the judgment matrix:

$$C = (C_{\ddot{v}})_{n\times n} = \begin{bmatrix} C_{11} & L & C_{1n} \\ M & O & M \\ C_{n1} & M & C_{nn} \end{bmatrix} \quad (1)$$

(3) Weight calculation and consistency test. Calculate the maximum eigenvalue λ_{max} of the judgment matrix and the corresponding eigenvector $(x_1, KK, x_n)^T$. The corresponding index weight vector $w = (w_1, KK, w_n)^T$ can be obtained by normalizing the feature vector. The calculation method is:

$$w_i = \frac{x_i}{\sum_{j=1}^{n} x_j} \quad (2)$$

After the judgment matrix is constructed, it needs to be tested for consistency, and the consistency test index CI is defined:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (3)$$

If $CI = 0$, then the judgment matrix has complete consistency; if CI approaches 0, then it has good consistency; if CI is larger, the consistency is worse. Define the consistency ratio:

$$CR = \frac{CI}{RI} < 0.1 \quad (4)$$

In the formula, the value of RI is related to the order of the judgment matrix, and the value is referred to Table 2.

Table 2. The table for the value of RI.

Order of Matrix	1	2	3	4	5	6
RI	0	0	0.58	0.9	1.12	1.24
Order of matrix	7	8	9	10	11	
RI	1.32	1.41	1.45	1.48	1.51	

If the judgment matrix does not meet the consistency condition $(CR > 0.1)$, the judgment matrix needs to be modified until it meets the consistency condition.

2.2. Comprehensive Empowerment Theory

Entropy is mainly used to describe the uncertainty of information. It originates from thermodynamics and is a measure of the uncertainty of a system in information theory [19]. If there is more information in an information system, the uncertainty of the information system will be smaller, and thus the entropy will be smaller. On the contrary, if the information contained in the information system is smaller, the uncertainty of the information system will be greater, and thus the entropy will be greater. The entropy weight method is to determine the weight of the index by the information contained in the index and the entropy value of the index. If the entropy of an index is larger, it means that it contains less information, its variability is more minor, and its weight is more minor. Conversely, if the entropy of an index is low, its weight will be high. Specific steps are as follows [20]:

(1) Construct the evaluation matrix according to the relevant information of the object to be evaluated. When the index number is m, the initial evaluation matrix A is obtained when the evaluation scheme is n:

$$A = \left(a_{ij}\right)_{m\times n} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{21} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & a_{12} \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \tag{5}$$

where a_{ij} is the evaluation value of the i index of the j evaluation object.

(2) Dimensionless A is transformed into a standard matrix $\left(b_{ij}\right)_{m\times n}$.

Different indicators have different units of measurement, so accurate comparisons cannot be made. In order to make each evaluation indicator have a consistent dimensionless interval, dimensionless processing is required. The mean value method can be used for dimensionless processing, so that each index data interval is between 0 and 1.

$$b_{ij} = \frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}} \tag{6}$$

The normalized matrix obtained after processing is B:

$$B = \left(b_{ij}\right)_{m\times n} = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{21} & \cdots & b_{2n} \\ \vdots & \vdots & \vdots & b_{12} \\ b_{m1} & b_{m2} & \cdots & b_{mn} \end{bmatrix} \tag{7}$$

(3) Calculate the entropy value e_i of the index:

$$e_i = -k\sum_{j=1}^{n} b_{ij}\, lnb_{ij}(i = 1,\ 2,\ \ldots,\ m;\ j = 1,\ 2,\ \ldots, n) \tag{8}$$

where $k = \frac{1}{lnn};\ j = 1,\ 2,\ \ldots, n; b_{ij} = 0,\ b_{ij}lnb_{ij} = 0$.

(4) Determine index entropy weight γ_i:

$$\gamma_i = \frac{1 - e_i}{\sum_{i=1}^{m}(1 - e_i)}\ i = 1,\ 2,\ \ldots,\ m \tag{9}$$

Combining the subjective weight w obtained by the AHP with the objective weight obtained by the entropy weight method, the comprehensive weight ω of the index is obtained. The comprehensive weight should be as close as possible to the subjective weight and objective weight, but not to any of them. This paper determines the comprehensive weight based on the principle of minimum discrimination information [21]. This principle will select a new distribution to replace the original distribution and ensure that the difference between the new distribution and the original distribution is as small as possible. Therefore, this paper determines the calculation method of comprehensive weight ω_i as follows:

$$\omega_i = \frac{\sqrt{w_i\gamma_i}}{\sum_{j=1}^{n}\sqrt{w_j\gamma_j}} \tag{10}$$

Then the comprehensive weight vector is $\omega = \left(\omega_1, KK, \omega_n\right)^T$.

2.3. *Fuzzy Evaluation of Hydropower Unit Equipment*

2.3.1. Gaussian Threshold Method

Suppose $x : N\left(\mu,\ \sigma^2\right)$, then the probability distribution function of x is:

$$\begin{array}{l} P(\mu-\sigma,\ \mu+\sigma) = 0.6826 \\ P(\mu-2\sigma,\ \mu+2\sigma) = 0.9544 \\ P(\mu-3\sigma,\ \mu+3\sigma) = 0.9974 \\ P(\mu-4\sigma,\ \mu+4\sigma) \approx 1 \end{array} \tag{11}$$

Due to the randomness of measurement errors, the monitoring signals of hydropower units have obvious normal distribution characteristics [22,23]. For a monitoring index $V_i = \{V_i(1), V_i(2)K, V_i(t)K, V_i(m)\}$ of the unit, according to Formula (10), the probability of any group of real-time monitoring value $V_i(t)$ falling in the interval $[\mu - 3\sigma,\ \mu + 3\sigma]$ is 99.74%. The probability of falling outside the interval is 0.26%. That is, the index monitoring value falls in the interval $[\mu - 3\sigma,\ \mu + 3\sigma]$ is a small probability event. In the normal operation of hydropower units, small probability events are almost impossible to occur, so $[\mu - 3\sigma,\ \mu + 3\sigma]$ is taken as the normal operation limit of the monitoring index of the units, $[\mu - 4\sigma,\ \mu + 4\sigma]$ is taken as the overall limit value of unit monitoring index, and μ is the optimal value, where:

$$\begin{array}{l} \mu = \mathrm{mean}(V_i) = \frac{1}{m}\sum\limits_{t=1}^{m} V_i(t) \\ \sigma = \sqrt{\frac{1}{m}\sum\limits_{t=1}^{m}\left(V_i(t) - \mu\right)^2} \end{array} \tag{12}$$

2.3.2. Fuzzy Evaluation Theory

Fuzzy mathematics is a tool to explore the inherent law of fuzzy problems through mathematical methods. The fuzzy comprehensive evaluation method is based on fuzzy mathematics, the measured value of the unit, and the evaluation standard after fuzzy transformation to attain the comprehensive evaluation results of the system, the evaluation results have the characteristics of scientific, accurate, and authentic. In fuzzy evaluation, fuzzy transformation is realized by building a membership function. At present, there is no unified membership function construction method. The triangular-semi-trapezoidal membership function distribution is simple and similar to the results obtained by other more complex membership functions, so it has been widely used in the fuzzy evaluation of equipment [24]. The traditional triangular-semitrapezoidal membership function is shown in Figure 1.

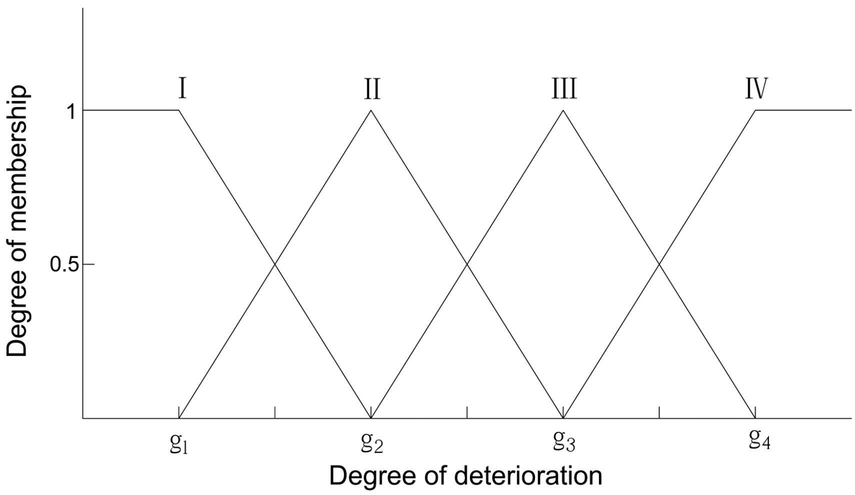

Figure 1. Triangular semi-trapezoidal membership function.

In Figure 1, I to IV are different states of the object to be evaluated. The membership degree of the equipment state is f, and the deterioration degree of the indicator is g. For the index of the bigger and better type, the calculation method of deterioration degree is:

$$g = \begin{cases} 1, & v < \alpha_1 \\ \dfrac{\beta_1 - v}{\beta_1 - \alpha_1}, & \alpha_1 < v < \beta_1 \\ 0, & v > \beta_1 \end{cases} \tag{13}$$

where v is the measured value of the index; β_1 is the optimal value of the index; α_1 is the lower limit of the index, and $\alpha_1 < \beta_1$. Correspondingly, the deterioration degree of the index of the smaller and better type is calculated as follows:

$$g = \begin{cases} 0, & v < \alpha_2 \\ \dfrac{v - \alpha_2}{\beta_2 - \alpha_2}, & \alpha_2 < v < \beta_2 \\ 1, & v > \beta_2 \end{cases} \tag{14}$$

where α_2 is the optimal value of the index; β_2 is the upper limit value of the index, and $\alpha_2 < \beta_2$.

The Gaussian threshold method is used to determine the operating limit of unit monitoring index as $[\mu - 4\sigma,\ \mu + 4\sigma]$ and the optimal value as μ. If the measured value of the indicator is $\in [\mu - 4\sigma,\ \mu]$, the larger the better the type of indicator, and the deterioration degree of the indicator is calculated as shown in Equation (13). Similarly, if the measured value of the indicator is $\in [\mu,\ \mu + 4\sigma]$. In this case, the smaller the better type of index, and the deterioration degree of the index is calculated as shown in Equation (14).

The evaluation states of the unit and indicators are divided into four levels: state I: good, state II: qualified, state III: attention, state IV: abnormal. Each state evaluation grade of the unit is shown in Table 3.

Table 3. State evaluation table of hydropower unit.

Evaluation State	State Description
good	The scoring object is normal and no action is required.
up to standard	The scoring object is normal, but tends to be close to the operating limit. No action is required.
notice	The scoring object is normal, but close to the operating limit. Attention should be paid to it.
abnormal	The score object exceeds the threshold and is abnormal. Take measures immediately.

Based on the triangular semi-trapezoidal membership function, the membership degree of each monitoring index belonging to each evaluation level of the hydropower unit is obtained. When the traditional triangular semi-trapezoidal membership function is used for equipment evaluation, the value of deterioration degree $g_1 : g_4$ is mostly determined according to expert experience [15], and the corresponding relationship with different evaluation levels lacks reasonable explanation. To solve this problem, the unit index limit determined by the Gaussian threshold method is divided into four sections, which are:

$$[\mu - \sigma,\ \mu] \cup [\mu,\ \mu + \sigma],$$

$$[\mu - 2\sigma,\ \mu - \sigma] \cup [\mu + \sigma,\ \mu + 2\sigma],$$

$$[\mu - 3\sigma,\ \mu - 2\sigma] \cup [\mu + 2\sigma,\ \mu + 3\sigma],$$

$$[\mu - 4\sigma,\ \mu - 3\sigma] \cup [\mu + 3\sigma,\ \mu + 4\sigma]$$

where $\mu \pm \sigma$, $\mu \pm 2\sigma$, $\mu \pm 3\sigma$, and $\mu \pm 4\sigma$ are the range boundary value. The corresponding relationship between boundary value and the membership of each state level is shown in Table 4.

Table 4. Boundary conditions of membership function.

State / **Boundary Value** / **Degree of Membership**	μ	$\mu \pm \sigma$	$\mu \pm 2\sigma$	$\mu \pm 3\sigma$	$\mu \pm 4\sigma$
good	100%	50%	0	0	0
up to standard	0	50%	50%	0	0
notice	0	0	50%	50%	0
abnormal	0	0	0	50%	100%
degree of deterioration	0	0.25	0.5	0.75	1

According to the corresponding relation in Table 4, the improved triangular half-trapezoid membership function is constructed, as shown in Figure 2.

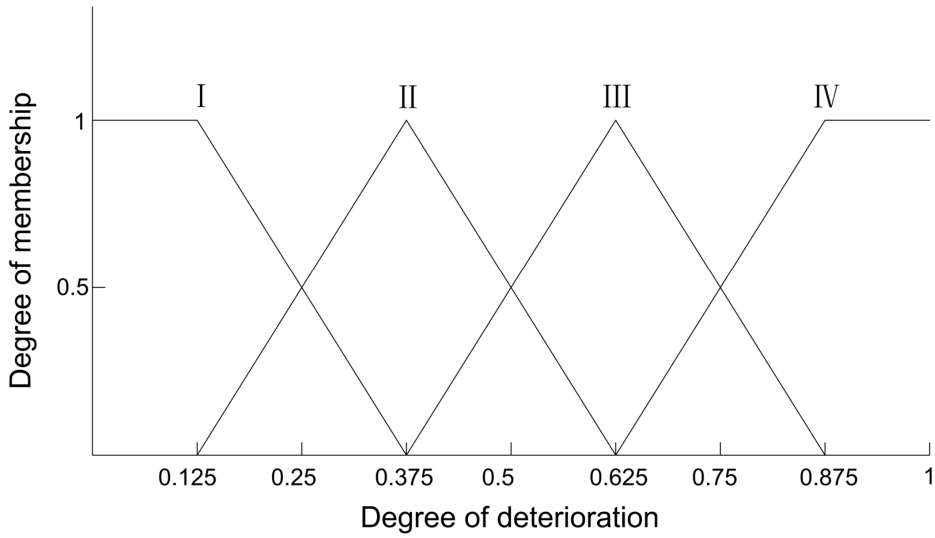

Figure 2. The triangular half-trapezoidal membership function after the improved Gaussian threshold.

The corresponding analytic expression is:

$$
\begin{aligned}
f_1 &= \begin{cases} 1, & g < 0.125 \\ -4g + 1.5, & 0.125 < g < 0.375 \\ 0, & g > 0.375 \end{cases} \\
f_2 &= \begin{cases} 0, & g < 0.125 \\ -4g - 0.5, & 0.125 < g < 0.375 \\ -4g + 2.5, & 0.375 < g < 0.625 \\ 0, & g > 0.625 \end{cases} \\
f_3 &= \begin{cases} 0, & g < 0.375 \\ -4g - 1.5, & 0.375 < g < 0.625 \\ -4g + 3.5, & 0.625 < g < 0.875 \\ 0, & g > 0.875 \end{cases} \\
f_4 &= \begin{cases} 0, & g < 0.625 \\ 4g - 2.5, & 0.625 < g < 0.875 \\ 1, & g > 0.875 \end{cases}
\end{aligned}
\tag{15}
$$

where $g_1 = 0.125$, $g_2 = 0.375$, $g_3 = 0.625$, and $g_4 = 0.875$. According to Equation (14), the fuzzy evaluation matrix $M = (f_1, f_2, f_3, f_4)^T$ was constructed to determine the membership degree of the current value of the index relative to each state. The fuzzy evaluation matrix of each index is weighted to obtain the fuzzy evaluation matrix of the upper layer.

3. Method Discussion

The flow of this evaluation model is shown in Figure 3. The overall process is divided into two phases: offline and online.

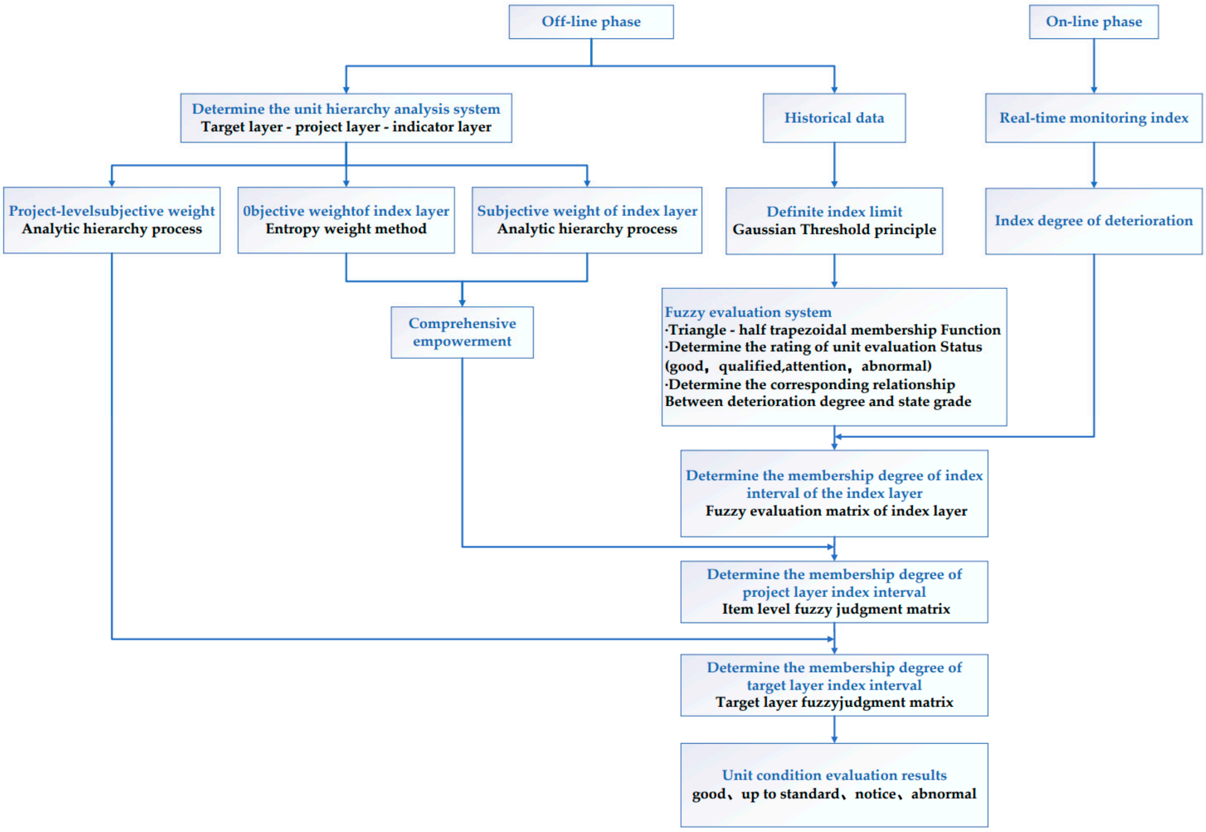

Figure 3. Algorithm flow of hydropower unit state evaluation model.

Off-line stage: (1) According to the unit structure and measuring point layout, the hierarchical analysis system of hydropower units was determined, and the units were divided into three layers from top to bottom: target layer, project layer, and index layer. (2) Use AHP and entropy weight method to determine the comprehensive weight of each layer. (3) The operating limits of unit indexes are determined based on the Gaussian threshold method. (4) The unit project evaluation level is divided into four states: good, qualified, attention and abnormal, and the corresponding relationship between the index limit and the membership of each state level is determined. Based on the triangular half-ladder membership function, the fuzzy evaluation system of the unit was constructed.

In the online stage: (1) Calculate the real-time deterioration degree of monitoring indicators according to the operating limits of indicators. (2) The membership degree of the index in the membership function relative to each state interval was calculated according to the deterioration degree, and the fuzzy evaluation matrix of the index was constructed. (3) The fuzzy evaluation matrix of each index layer is weighted to calculate the fuzzy evaluation matrix of the item layer. (4) The fuzzy evaluation matrix of the project layer is weighted to calculate the fuzzy evaluation matrix of the target layer. (5) According to the principle of maximum membership degree, the fuzzy evaluation matrix is used to evaluate the whole state of the unit.

State Grid enterprise standard Q/GDW 11966.1—2019 (Hydraulic Turbine Generator Unit Condition Evaluation and Maintenance Guidelines) has stipulated the overall condition evaluation rules of the conventional turbine; that is, when all components of the unit are evaluated as normal, the overall evaluation is normal. When the state of any component is attention state, abnormal state, or critical state, the overall evaluation shall be the most serious state among them. According to this standard, this paper takes the most serious neutron project evaluation result of the project layer as the final state of the unit system.

4. Numerical Application

Taking the No. 3 unit of a conventional power station as an example, the model was used to evaluate the operation status of the unit at different times. It is known that this unit is an axial flow paddle unit with a rated power of 200 MW. It is known that the lining falling off in the runner chamber occurred in this unit at the end of August 2015, and the faulty part belongs to the hydraulic turbine system, and the unit is always in rated operating conditions before and after the failure. Therefore, the operating state of the turbine system of unit 3 in this period was evaluated. According to the structure of the turbine system of No. 3 unit and the arrangement of measuring points, the hierarchical analysis system of the turbine system was determined, as shown in Figure 4.

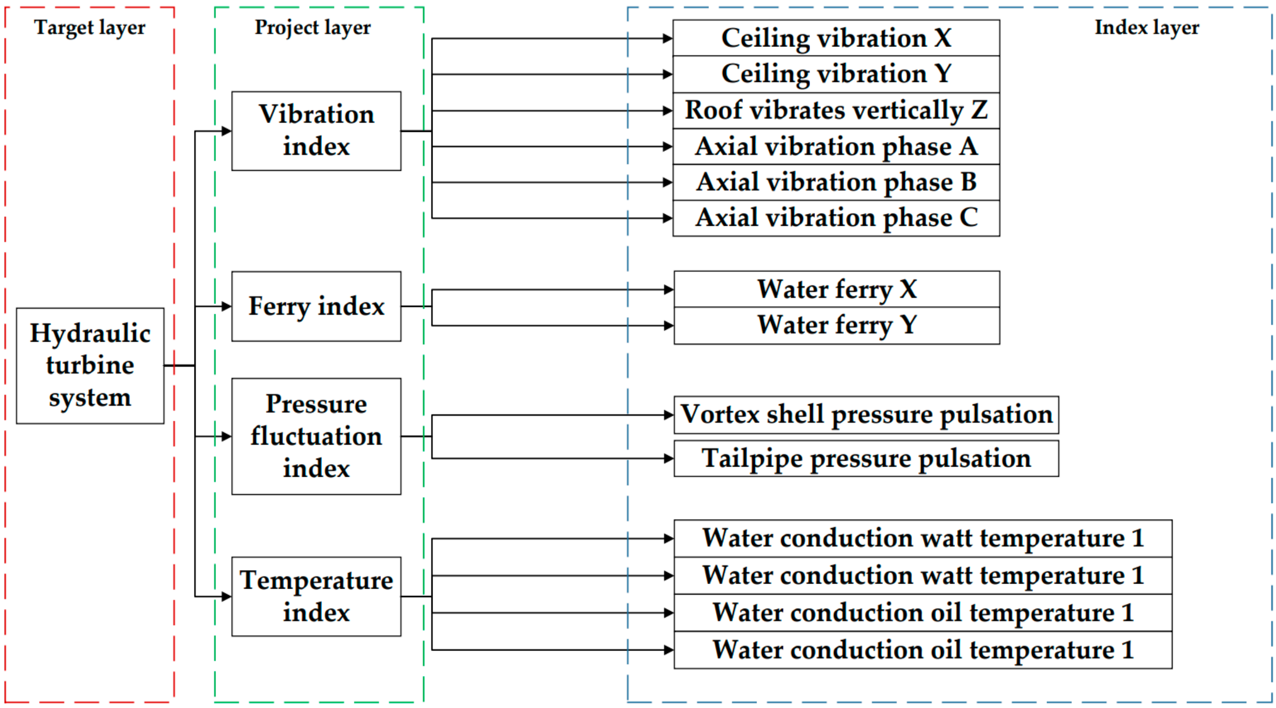

Figure 4. Hierarchical analysis system of turbine system of unit 3.

4.1. Construction of Hierarchical Analysis System

The system was divided into three layers, and the monitoring quantity covers vibration, pendulum, pressure pulsation and temperature indexes, which can fully reflect the overall state of the turbine system.

The literature [25] provides a detailed analysis of the change process of the unit from normal to fault, and it can be concluded that the unit has been in normal operation state before August 20. According to the analysis results, the monitoring system selected the data of each measuring point of the turbine system during the period from early August to August 20 as normal samples, and each measuring point contained 200 groups of data which used to calculate the objective weights and limits of indicators.

4.2. Weight Calculation

(1) Weight calculation of index layer

1. Vibration index

There are six vibration indexes, including the vibration of the top cover and the vibration of shafting. It is generally believed that all indexes are equally important to the state stability of the turbine system, so the subjective weight is 1/6. The entropy weight method in Section 2.2 was used to calculate the objective weight of the index, and the subjective and objective weights were finally substituted into Equation (10). Then the comprehensive weight vector of the vibration index is:

$$\omega_A = (0.1858, 0.1699, 0.1760, 0.1328, 0.1675, 0.1679)^{\mathrm{T}}$$

2. Pendulum index

The pendulum index includes the X and Y direction indexes of water conductance pendulum, which are subjectively considered to be of the same importance, so the subjective weight is 1/2. Then the comprehensive weight vector of pendulum index is:

$$\omega_B = (0.4927, 0.5073)^T.$$

3. Pressure pulsation index

Pressure pulsation indexes include volute pressure pulsation and tailpipe pressure pulsation, both of which are considered equally important subjectively with a subjective weight of 1/2.

Then the comprehensive weight vector of pressure pulsation index is:

$$\omega_C = (0.3447, 0.6553)^T.$$

4. Temperature index

Temperature indexes include four indexes: the water guide tile temperature and water guide oil temperature. The subjective weight of each index is 1/4, so the comprehensive weight vector of temperature index is:

$$\omega_D = (0.2333, 0.2436, 0.2925, 0.2306)^T.$$

(2) Project level weight calculation

The project layer includes vibration, pendulum, pressure pulsation, and temperature four categories of indicators. The AHP was used to determine the weights of various indexes. The indexes of vibration, wobble, and pressure pulsation were fast variable characteristic quantities, which were more sensitive to reflect the state of the unit. Therefore, in terms of importance, vibration index = wobble index = pressure pulsation index > temperature index. According to the scale method 1–9 in Section 2.1, the judgment matrix of the project layer is determined as:

$$C = (C_{ij})_{4\times 4} = \begin{bmatrix} 1 & 1 & 1 & 2 \\ 1 & 1 & 1 & 2 \\ 1 & 1 & 1 & 2 \\ 1/2 & 1/2 & 1/2 & 1 \end{bmatrix}$$

After passing the consistency test according to Formulas (3) and (4), the judgment matrix is substituted into Formula (2), and the weight vector of the item layer is:

$$\omega = (0.2857, 0.2857, 0.2857, 0.1429)^T.$$

4.3. Fuzzy Evaluation

The literature [25] analyzed the evolution process of unit No. 3 from normal to fault by constructing the deterioration index based on the unit's axial vibration signal. The changing trend of the deterioration index over time is shown in Figure 5.

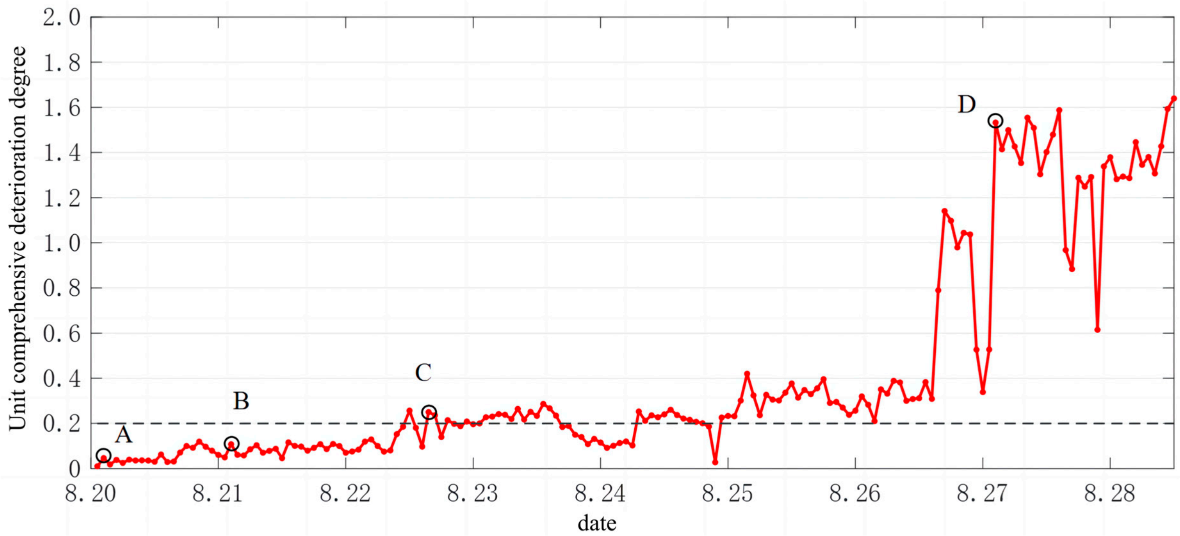

Figure 5. Variation trend of unit deterioration index.

According to the analysis results of the literature [25], an indicator greater than 0.2 was considered as the beginning of the fault. Four representative time points, A, B, C and D, were selected, and the fuzzy evaluation method proposed in Section 2.3 was used to conduct an overall evaluation of the state of the turbine system. The monitoring values of indicators at each moment point are shown in Table 5. The limit value of indicators was determined according to the Gauss threshold method in Section 2.3.1. Normal samples of indicators were put into Equation (11), and finally $[\mu - 4\sigma,\ \mu + 4\sigma]$ was determined as the limit value of indicators.

Table 5. Monitoring data of turbine system of unit 3 under rated working conditions.

Monitoring Index	Monitoring Value				Index Population Limit		
	Time A	Time B	Time C	Time D	Lower Limit	Upper Limit	Reference
Roof vibration X (μm)	27.97	29.28	28.51	22.51	23.2	35.45	29.33
Roof vibration Y (μm)	30.10	29.54	28.72	27.04	24.63	36.52	30.57
Roof vibrates vertically Z (μm)	0.98	1.32	1.31	0.93	0.54	1.57	1.06
Axial vibration A (μm)	104.44	111.03	126.04	241.61	91.68	110.55	101.11
Axial vibration B (μm)	96.52	100.28	107.93	175.84	88.06	102.39	95.22
Axial vibration C (μm)	94.06	98.43	107.04	190.02	84.42	100.68	92.55
Water deflection X (μm)	230.97	184.94	190.79	292.84	140.83	312.63	226.73
Water deflection Y (μm)	185.19	159.40	150.03	180.68	91.67	267	179.33
Volute inlet pressure pulsation (kpa)	0.46	0.65	0.44	0.48	0.03	1.45	0.74
Tailpipe outlet pressure pulsation (kpa)	0.23	0.15	0.22	0.18	0.05	0.32	0.18
Water conduction tile temperature 1 (°C)	61.19	61.07	61.06	61.14	62.16	66.46	64.31
Water conduction tile temperature 2 (°C)	61.24	61.12	61.10	61.14	61.71	66.04	63.88
Water conducts oil temperature 1 (°C)	58.2	58.00	57.99	58.05	56.63	60.76	58.7
Water conducts oil temperature 2 (°C)	58.98	58.87	58.94	58.84	57.45	61.63	59.54

The fuzzy evaluation results of each index of the project layer of the turbine system at different times are shown in Table 6. According to the guidelines for the overall condition evaluation of conventional turbines in the industry regulations, this paper took the most serious condition of the index evaluation results of the project layer as the final evaluation state of the turbine system. As can be seen from Table 6, the evaluation results of vibration and pendulum indexes of the unit at moment A were good, while the evaluation results of pressure pulsation and temperature indexes were the worst, which was the qualified state. Therefore, the overall state of the system at this moment point was qualified, and the overall evaluation results of the turbine system at the moment B~D were obtained similarly.

Table 6. Fuzzy evaluation matrix and evaluation results of turbine system at each moment.

Time	Project Level Index	Item Level Fuzzy Evaluation Matrix	Evaluation Result	System Overall Evaluation Results
A	Vibration class	[0.7122, 0.2877, 0, 0]	good	up to standard
	Pendulum class	[1, 0, 0, 0]	good	
	Pressure pulsation class	[0.1870, 0.8036, 0.0094, 0]	up to standard	
	Temperature class	[0.4220, 0.5780, 0, 0]	up to standard	
B	Vibration class	[0.3102, 0.1141, 0.3227, 0.2529]	notice	notice
	Pendulum class	[0.2995, 0.4808, 0.2197, 0]	up to standard	
	Pressure pulsation class	[0.7429, 0.2571, 0, 0]	good	
	Temperature class	[0.1450, 0.8550, 0, 0]	up to standard	
C	Vibration class	[0.2227, 0.2251, 0.0839, 0.4682]	abnormal	abnormal
	Pendulum class	[0.0826, 0.8319, 0.0855, 0]	up to standard	
	Pressure pulsation class	[0.4460, 0.5540, 0, 0]	up to standard	
	Temperature class	[0.1442, 0.8558, 0, 0]	up to standard	
D	Vibration class	[0.0907, 0.1061, 0.1491, 0.6540]	abnormal	abnormal
	Pendulum class	[0.5073, 0, 0.2077, 0.2850]	good	
	Pressure pulsation class	[0.8896, 0.1104, 0, 0]	good	
	Temperature class	[0.1973, 0.8027, 0, 0]	up to standard	

As can be seen from Table 6, as time goes by, the overall evaluation status of the turbine system of the unit gradually changed from qualified to abnormal, reflecting the deterioration trend of the unit's health status. Moment A was qualified, indicating that the unit was qualified as a whole and did not need maintenance. The vibration index at time B was the attention state, and then the whole unit was the attention state, and it needed to pay more attention during operation. If the evaluation result of vibration index at time C was abnormal, it indicated that the turbine system had a fault and needed to be stopped for maintenance as soon as possible. At moment D, the vibration index deteriorated further. At this time, the turbine system failure continued to develop, and the abnormal symptoms of the unit were obvious, which required an immediate shut-down for maintenance.

By comparing Figure 5, it can be found that the unit deterioration degree at moment A maintains a very low level, and at this time the unit was normal as a whole. At moment B, the unit deterioration degree was close to the limit, and the unit had a deterioration trend. At moment C, the unit deterioration degree exceeded 0.2, which indicated that the unit has a fault. Through the analysis and comparison of Figures 5 and 6, it can be seen that the state evaluation model of the hydropower unit based on hierarchical analysis and Gaussian threshold improved fuzzy comprehensive evaluation can accurately evaluate the state of the hydropower unit. The difference between the two is that the deterioration early warning index in Figure 5 focuses on judging whether the unit fails, while the evaluation model can evaluate the operating state of the unit in more detail while judging whether the unit fails, and formulate the corresponding maintenance and treatment plan according to different states.

Further analysis of the vibration indicators in Table 6 that change greatly over time, as shown in Figure 6, showed that the state of the vibration indicators of the turbine system continues to deteriorate during the period A~D, reflecting the evolution process of the unit vibration from normal to fault.

Table 7 shows the state evaluation results of turbine system by weighting the fuzzy evaluation matrix of unit project layer with traditional methods. It can be seen that the evaluation results of the turbine system at time C and D by this method were still good or qualified, but in practice, the unit had broken down at this time and needed to be stopped for maintenance. By contrast, the results obtained by the unit equipment health evaluation strategy proposed in this paper are more in line with the actual situation.

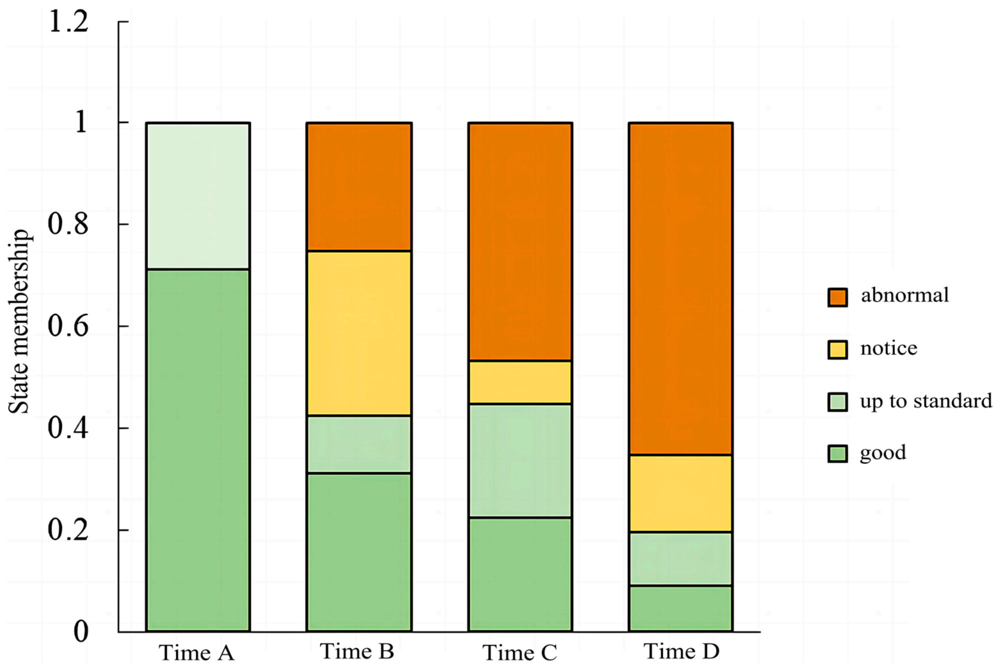

Figure 6. Fuzzy-evaluation results of vibration indexes of hydraulic turbine system.

Table 7. Fuzzy-evaluation results of turbine system obtained by weighted item layer.

Global Fuzzy Evaluation Matrix	Evaluation Result
$[0.6029, 0.3944, 0.0027, 0]$	good
$[0.4107, 0.3656, 0.1514, 0.0723]$	good
$[0.2353, 0.5826, 0.0484, 0.1338]$	up to standard
$[0.4532, 0.1766, 0.1019, 0.2683]$	good

4.4. Comparison of Methods

The proposed evaluation method was compared with the fuzzy evaluation method, which relies on the traditional guidelines to verify the advantages of this method in the evaluation of the health status of hydropower units. According to the unit model and relevant working parameters, the upper and lower limits of each measuring point of the turbine system of the unit under steady-state operating conditions were determined by referring to industry guidelines and power station operation regulations [26,27]. As the regulations of the national standard for monitoring the vibration, wobble, and pressure fluctuation of hydropower units are too general and broad, and only have general reference value, the upper limits were the second-level alarm limits stipulated in the actual regulations of the power station. In terms of temperature, the water guide bearing of the unit was babbitt alloy tile. According to GB/T 7894-2009 (Basic Technical Conditions of the Water turbine Generator), the maximum temperature limit was 75 °C under normal conditions.

As can be seen from Table 8, in this case, the smaller the monitored quantity was, the better the indicator was. Equation (14) was used to calculate the deterioration degree of each indicator.

Table 8. Monitoring index limits of the turbine system.

Monitoring Quantity—Peak-to-Peak Value	Lower Limit	Upper Limit
Top vibrates in X direction (μm)	0	70
Top vibrates in Y direction (μm)	0	70
Roof vibrates vertically (μm)	0	90
Axial vibration in A direction (μm)	0	300
Axial vibration in B direction (μm)	0	300
Axial vibration in C direction (μm)	0	300
Water conductance X to swing (μm)	0	450
Water conductance Y to swing (μm)	0	450
Volute pressure pulsation (kpa)	0	5
Tailpipe pressure pulsation (kpa)	0	5
Water conduction tile temperature 1 (°C)	25	75
Water conduction tile temperature 2 (°C)	25	75
Water conduction oil temperature 1 (°C)	25	75
Water conduction oil temperature 2 (°C)	25	75

According to the literature [16,28], it was determined that the corresponding membership function of each monitored quantity is shown in Figure 7 when the discipline guidelines were relied on.

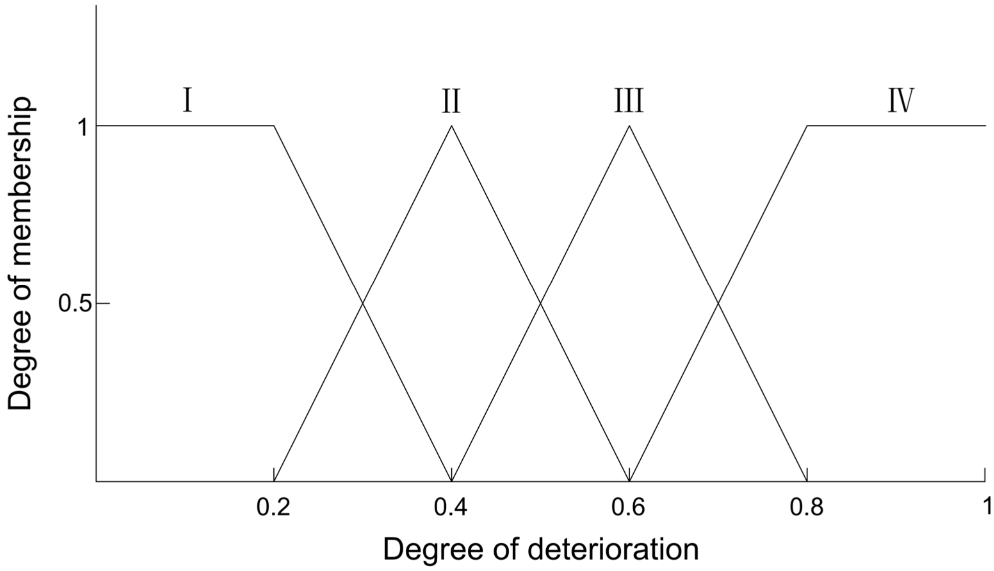

Figure 7. Membership function based on traditional procedural guidelines.

The fuzzy evaluation method which relies on the traditional rules was used to evaluate the health state of the turbine system at time A~D, and the results are shown in Table 9. It can be seen that the unit status evaluation results at moments A to D were all attention, while the unit anomalies could be judged at moments C and D through the deterioration index analysis in Figure 5 and the actual situation on site, which obviously failed to reflect the evolution process of unit status over time. It is worth noting that from time A, the evaluation result of temperature indexes was attention. However, according to the operation procedures of the power station, without considering the changing trend, the temperature of the water guide tile/oil temperature of the unit should be considered normal when it is above or below 60 °C. Therefore, it is necessary to readjust the temperature quantity to the degree function according to the actual situation, which further increases the complexity of the evaluation. In contrast, the evaluation result of the unit state based on the improved fuzzy comprehensive evaluation of the Gaussian threshold was more consistent with the actual situation, and could reflect the actual operating state of the unit more truly and effectively.

Table 9. Fuzzy evaluation results of hydraulic turbine system based on guidelines.

Time	Project Level Index	Item Level Fuzzy Evaluation Matrix	Evaluation Result	System Overall Evaluation Results
A	Vibration class	$[0.3490, 0.6145, 0.0364, 0]$	up to standard	notice
	Pendulum class	$[0, 0.6917, 0.3083, 0]$	up to standard	
	Pressure pulsation class	$[1, 0, 0, 0]$	good	
	Temperature class	$[0, 0, 0.5183, 0.4817]$	notice	
B	Vibration class	$[0.3113, 0.6529, 0.0357, 0]$	up to standard	notice
	Pendulum class	$[0.1161, 0.8568, 0.0271, 0]$	up to standard	
	Pressure pulsation class	$[1, 0, 0, 0]$	good	
	Temperature class	$[0, 0, 0.5320, 0.4680]$	notice	
C	Vibration class	$[0.2460, 0.7250, 0.0289, 0]$	up to standard	notice
	Pendulum class	$[0.1690, 0.7720, 0.0591, 0]$	up to standard	
	Pressure pulsation class	$[1, 0, 0, 0]$	good	
	Temperature class	$[0, 0, 0.5319, 0.4681]$	notice	
D	Vibration class	$[0.2606, 0.2827, 0.2958, 0.1608]$	notice	notice
	Pendulum class	$[0, 0.5035, 0.3715, 0.1250]$	up to standard	
	Pressure pulsation class	$[1, 0, 0, 0]$	good	
	Temperature class	$[0, 0, 0.5295, 0.4705]$	notice	

5. Conclusions

In view of the lack of effective and perfect overall equipment condition evaluation methods in the field of hydropower, this paper used the theory of analytic hierarchy and fuzzy evaluation to build a hydropower unit condition evaluation model. Taking a power plant unit as the experimental object, it was verified that the model could effectively and accurately judge the operating state of the unit and provide effective support for the unit condition monitoring and fault warning. The main conclusions and features of this paper were as follows:

(1) The AHP and entropy weight method were used to determine the subjective and objective weights of each sub-item of the unit. While respecting the expert experience, the historical monitoring data were fully utilized to make the weight results more reasonable;

(2) According to the normal distribution of unit monitoring values in the big data mode, the limit values of each monitoring index of the unit were determined based on the Gaussian threshold, and the characteristics of the unit were fully taken into account, which solved the problem that it was difficult to accurately obtain the limit values of indicators of different power stations, different types of units, and different unit working conditions simply depending on the existing industry regulations and national standard mode;

(3) The index limits determined based on the Gaussian threshold were divided into sections, and the corresponding relationship between the section and each evaluation level of the triangular half-trapezoidal fuzzy evaluation function was established, so that the membership function design had a more scientific mathematical basis. The lack of reasonable explanation of the membership function caused by the general designation of the corresponding relationship between the deterioration degree and the state membership degree in fuzzy evaluation was avoided;

(4) In view of the weight transfer attenuation phenomenon of the bottom index in the hierarchical analysis system, the evaluation status of the middle layer was taken as the basis for evaluating the overall status of the unit system, which effectively solved the disadvantage that the variable weight method could not accurately reflect the influence degree of multiple abnormal indicators on the overall status of the equipment.

The comprehensive state evaluation model of hydropower units proposed in this paper, which combines AHP and Gaussian threshold fuzzy evaluation, were effectively verified on the actual units, and compared with the fuzzy evaluation method relying on traditional procedures, the results showed that the method can evaluate the operating state of the system more accurately, and the overall evaluation results of the system are more consistent with the actual state.

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References

1. Wang, W.; Chen, Q.; Liang, X.; Yue, X.; Dou, J. A Novel Multidimensional Frequency Band Energy Ratio Analysis Method for the Pressure Fluctuation of Francis Turbine. *Math. Probl. Eng.* **2018**, *2018*, 3494785. [CrossRef]
2. Hu, X.; Xiao, Z.; Liu, D.; Jiang, W.; Liu, D.; Yuan, X. Fault Diagnosis of Hydropower Units Based on VMD-CNN. *Water Resour. Power* **2020**, *38*, 137–141.
3. Yucesan, M.; Kahraman, G. Risk evaluation and prevention in hydropower plant operations: A model based on Pythagorean fuzzy AHP. *Energy Policy* **2019**, *126*, 343–351. [CrossRef]
4. Wei, Z.; Lu, Y.; Wang, P.; Ma, T.; Zhao, S. Application of Grey Correlation Theory based on CRITIC Method in Autonomous Vehicles Test and Evaluation. *J. Mech. Eng.* **2021**, *57*, 99–108.
5. Xuan, K.; Hao, Y.; Liang, Z.; Zhang, J. Research on the evaluation of distributed integrated energy system using improved analytic hierarchy process-information entropy method. *Energy Sources Part A Recovery Util. Environ. Eff.* **2022**, *44*, 10071–10093. [CrossRef]
6. Niu, G.; Hu, Z.; Hu, D. Health Analysis and Prediction of Transformers Based on SVM and Physical Element Information Entropy. *J. Hunan Univ. (Nat. Sci.)* **2019**, *46*, 91–97.
7. Du, Y.; Shi, C.; Ma, G.; Chang, F.; Xu, B.; Fan, Y.; Sun, Z. Risk assessment model of power network based on equipment condition and entropy combined weight method. In Proceedings of the 2017 IEEE Electrical Insulation Conference (EIC), Baltimore, MD, USA, 11–14 June 2017; IEEE: Piscataway, NJ, USA, 2017.
8. Luo, J.; Sun, G.; Shang, C.; Chen, L.; Li, B.; He, J. Health Status Evaluation of Intelligent Power Distribution Room based on AHP-Entropy method. In Proceedings of the 2020 15th IEEE Conference on Industrial Electronics and Applications (ICIEA), Kristiansand, Norway, 9–13 November 2020; IEEE: Piscataway, NJ, USA, 2020.
9. Kong, J.; Zhu, H.; Pan, Y.; Li, Y.; Xiang, Y.; Hou, K. Comprehensive Evaluation of Secondary Equipment Status in Intelligent Substations Based on Real-time Information. *J. Mech. Electr. Eng. Technol.* **2023**, *52*, 221–226.
10. Niu, H.; Liu, B.; Gao, H.; Li, Y.; Xing, Y. Comprehensive Evaluation of Aerospace Material Application Verification Based on AHP-Entropy Combination Method. *Aerosp. Mater. Technol.* **2023**, *53*, 22–29.
11. Xia, Z.; Jing, Q.; Gao, W.; Liu, Z.; Zhang, Y. Analysis of Weight System for Bridge Components Based on Weight Fusion Method. *Sci. Technol. Eng.* **2023**, *23*, 2171–2180.
12. Fang, S.; Liu, J.; Gu, Z.; Zhang, R. Research on Evaluation Method of Ship Shafting System Design. *Ship Sci. Technol.* **2023**, *45*, 141–146.
13. Mao, C.; Miao, X.-G.; Cui, Y.; Chen, M.; Liu, Z.; Li, L. Application of Analytic Hierarchy Process in Health Evaluation of Small Hydroelectric Units. *Mech. Electr. Tech. Hydropower Stn.* **2019**, *42*, 1–4+28+80.
14. Zhang, W.; Li, B.; Liu, Z.; Zhang, B. Application of improved fuzzy comprehensive evaluation method in karst groundwater quality evaluation: A case study of Cengong county. *Earth Sci. Inform.* **2021**, *14*, 1101–1109. [CrossRef]
15. Wan, S.; Wan, J.; Zhang, C. Comprehensive Evaluation of Wind Turbine Performance Evaluation Based on Grey Theory Variable Weight Fuzzy Mathematics. *Acta Energiae Solaris Sin.* **2015**, *36*, 2285–2291.
16. Liu, R.; Xiang, W.; Yu, Y.; Jing, Y. Hydropower Generating Unit Operating State Evaluation Based on Variable Weight Analytic Hierarchy Process. *Mech. Electr. Tech. Hydropower Stn.* **2015**, *38*, 55–59.
17. Wan, J. Research and Application of Pump-Turbine Synthetic State Assessment. Master's Thesis, Huazhong University of Science & Technology, Wuhan, China, 2018.
18. Ayan, B.; Abacıoğlu, S.; Basilio, M.P. A Comprehensive Review of the Novel Weighting Methods for Multi-Criteria Decision-Making. *Information* **2023**, *14*, 285. [CrossRef]

19. Jin, Z. *Information Theory*; Beijing Institute of Technology Press: Beijing, China, 1991.
20. Qiu, W. *Management Decision and Applied Entropy*; China Machine Press: Beijing, China, 2002.
21. Sun, J. *Modern Pattern Recognition*; Higher Education Press: Beijing, China, 2008; pp. 526–538.
22. Zhang, F.; Pan, L.; An, X. Study on statistical characteristics of stability parameters and monitoring alarm thresholds of hydro generator units. *J. Hydropower Gener.* **2013**, *32*, 269–272+293.
23. Gui, Z.; Zhang, H.; Sun, H.; Zhang, F. Research and application of early warning model for vibration deterioration of hydropower units. *J. Water Resour.* **2018**, *49*, 216–222.
24. Zhang, K.; Hao, W.-N.; Yu, X.-H.; Jin, D.-W. A Multitasking Genetic Algorithm for Mamdani Fuzzy System with Fully Overlapping Triangle Membership Functions. *Int. J. Fuzzy Syst.* **2020**, *22*, 1–17. [CrossRef]
25. Liu, D.; Lai, X.; Hu, X.; Xiao, Z. Research on online assessment method of condition deterioration of hydropower units based on vibration signal. *J. Water Resour.* **2021**, *52*, 461–473.
26. China Institute of Water Resources and Hydropower Research; Harbin Electric Machinery Factory Co. *Evaluation of Mechanical Vibration of Hydroelectric Power Plant and Storage Pumping Station Units*; General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China: Beijing, China; China National Standardization Administration Committee: Beijing, China, 2016; p. 40.
27. Harbin Grand Electric Machinery Research Institute. *Measurement and Evaluation of Radial Vibration of Rotating Machinery Shafts—Part 5: Hydroelectric Power Plant and Pumping Station Units*; General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China: Beijing, China; China National Standardization Administration Committee: Beijing, China, 2008; p. 20.
28. Liao, R.; Wang, Q.; Luo, S.; Liao, Y.; Sun, C. A fuzzy integrated evaluation model for power transformer operating condition. *Power Syst. Autom.* **2008**, *385*, 70–75.