Quantitative Evaluation Method of Turbine Virtual Maintenance Based on Improved AHP

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Abstract. In order to evaluate the training process of steam turbine virtual maintenance for personnel training more reasonably, a quantitative evaluation method of turbine virtual maintenance based on improved analytic hierarchy process (AHP) is proposed in this paper. This paper establishes a set of evaluation index system and gives the quantitative algorithm of the corresponding index according to the characteristics of virtual maintenance of steam turbine equipment. The traditional AHP is also improved without consistency checking, which avoids the blindness of artificial adjustment of the judgment matrix and makes it easier and faster to get the weight value of the index. Under the balanced consideration of all evaluation factors, the evaluation of operators is completed, and the results of the comprehensive evaluation are more objective and credible. This method has been applied to a virtual maintenance training and assessment platform of steam turbine in thermal power plant, and the validity of the method has been verified.

Introduction

At present, there are still some key technical difficulties in virtual maintenance, analysis and evaluation of steam turbine equipment in thermal power plants, which limit its development and application in the design and use of steam turbine equipment. Therefore, in order to test the training effect, improve the training efficiency and improve the training quality, it is urgent to study the evaluation technology effectively applied to the maintainability design of steam turbine equipment [1]. Nowadays, there are many evaluation methods proposed at home and abroad. Among them, AHP method can express and deal with expert knowledge and subjective experience in quantitative form, so as to minimize the drawbacks caused by subjective assumptions. By using improved AHP to determine the weights of indicators at all levels and introducing quasi-optimal transfer matrix, it avoids blindly adjusting the judgment matrix after the consistency test is not satisfied, and greatly reduces the amount of calculation [2,3].

Based on this, this paper will establish a virtual maintenance evaluation system for turbines, analyze the quantitative methods of each evaluation index, and propose a quantitative evaluation method for virtual maintenance of turbines based on improved AHP. Finally, the application of the developed virtual maintenance training and assessment platform for steam turbines shows that the evaluation results are consistent with the actual situation, which effectively solves the evaluation problem of maintenance training in virtual maintenance system.

Evaluation Index System and Corresponding Quantitative Method

Evaluation Index System

According to the characteristics of virtual maintenance of steam turbines, the evaluation system shown in Fig.1 is determined. The evaluation model is divided into three layers: target layer, criterion layer and index layer [4]. The criterion layer includes three indexes: time index, objects index and regulations index.
Time Index. The time index evaluates the maintenance process from the aspect of time factor. Five indicators are determined according to the general process of turbine maintenance: preparing time $C_1$, disassembling time $C_2$, repairing time $C_3$, reloading time $C_4$ and checking time $C_5$. The sum of the five indexes is the total maintenance time. The system records the operation time of each step and divides the operation into five categories according to the content of each step. For the $i$ indicator of the time index, the quantification algorithm is as follows:

$$q_{ai} = \begin{cases} \frac{s_i}{a_i}, & (a_i > s_i) \\ 1, & (a_i \leq s_i) \end{cases}$$  \hspace{1cm} (1)$$

Among them, $s_i$ is the reference standard value, $a_i$ is the actual value of operation, and $q_{ai}$ is the actual value of quantization.

Objects Index. During the virtual maintenance of steam turbine, the operator maintains the equipment according to the standard maintenance regulations. Therefore, the number of maintenance steps in the whole operation process and the tools used in each step and the parts to be operated are determined. Set the operation step of the whole maintenance process as $n_s$, the number of tools used as $n_{s2}$, and the number of parts operated in the maintenance process as $n_{s3}$. In step $i$, the number of wrong tools selected is set to $k_i$, and the number of wrong parts selected is set to $p_i$. Then the quantization algorithm of object index is:

$$q_{a6} = \begin{cases} 1 - \frac{a_6}{n_{s2}}, & (a_6 \neq 0) \\ 1, & (a_6 = 0) \end{cases} \hspace{1cm} a_6 = \sum_{i=1}^{n_s} k_i \hspace{0.5cm} s_6 = n_{s2}$$  \hspace{1cm} (2)$$

$$q_{a7} = \begin{cases} 1 - \frac{a_7}{n_{s2}}, & (a_7 \neq 0) \\ 1, & (a_7 = 0) \end{cases} \hspace{1cm} a_7 = \sum_{i=1}^{n_s} p_i \hspace{0.5cm} s_7 = n_{s3}$$  \hspace{1cm} (3)$$

Regulations Index. Regulations index is used to evaluate whether the maintenance process conforms to the maintenance rules and procedures, and it includes three indicators: operation violation $C_8$, operation sequence $C_9$ and operation steps $C_{10}$. Actually, safety is the vital factor in the operation of steam turbine equipment in thermal power plants, and the operation violation usually leads to severe casualty and property loss. Therefore, as long as the irregularities appear, the punishment should be significant. The quantitative algorithm for adjusting the operation violation $C_8$ is as follows:

$$q_{a8} = \begin{cases} 0, & (a_8 \neq 0) \\ 1, & (a_8 = 0) \end{cases}$$  \hspace{1cm} (4)$$

Since the standard operating procedures clearly specify the number of steps and the sequence of each step, the more errors the operator has in the actual maintenance sequence or missed steps, the worse the operator's level will be. Considering that the error value of operation sequence in the
standard value is zero and preventing the extreme phenomena in quantization, the quantization algorithm of operation sequence C9 is as follows:

\[
q_{o9} = \begin{cases} 
1 - \frac{a_s}{n_s}, & (a_s \neq 0) \\
1, & (a_s = 0)
\end{cases} \quad (5)
\]

The operation is completed step by step in the virtual maintenance learning and assessment platform of steam turbine, consequently, the actual operation steps of operators will not be higher than the standard value. The quantization algorithm of operation step C10 is as follows:

\[
q_{o10} = \begin{cases} 
\frac{a_{10}}{n_{s1}}, & (n_{s1} > a_{10}) \\
1, & (n_{s1} \leq a_{10})
\end{cases} \quad (6)
\]

**Improved Analytic Hierarchy Process**

**The Principle of Improved Analytic Hierarchy Process**

Analytic Hierarchy Process (AHP) is a systematic analysis method which combines qualitative analysis with quantitative analysis\[5-7\]. In conventional nine-scale analytic hierarchy process, eigenvector method and consistency ratio are used to determine weight and consistency test criteria respectively\[8\]. When the consistency test fails, the judgement matrix needs to be adjusted artificially and then calculated until it passes, which is not only blindness and inaccuracy, but also a large amount of calculation. In this paper, quasi-optimal transfer matrix is introduced to improve the nine-scale AHP. So that it can meet the consistency at the beginning stage and the weight value can be calculated directly, which simplifies the calculation steps and reduces the calculation amount.

\[
b_{ij} = 10^n\frac{1}{\sum_{p=1}^{n}(lg a_{ip} - lg a_{pj})} \quad (7)
\]

Among them, \(b_{ij}\) is the element of row \(i\) and column \(j\) of matrix \(B\), matrix \(B\) is called quasi-optimal transfer matrix of \(A\).

**Steps of Improved Analytic Hierarchy Process**

The steps of the improved Analytic Hierarchy Process are as follows:

1. Constructing hierarchy structure model.
2. Constructing a pairwise judgment matrix \(A\) by using the nine-decimal scale:
   \[
   A = \left( a_{ij} \right)_{n \times n}, \quad i, j = 1,2,\cdots,n, \quad a_{ii} = 1, \quad a_{ij} = \frac{1}{a_{ji}}
   \]
3. Converting to transfer matrix \(C1\):
   \[
c_{1ij} = 10^n\frac{1}{\sum_{p=1}^{n}(c_{1ip} - c_{1jp})} \quad (8)
   \]
4. Constructing the Optimal Transfer Matrix \(C\):
   \[
c_{ij} = \frac{1}{n}\sum_{p=1}^{n}(c_{1ip} - c_{1jp}) \quad (9)
   \]
5. Construction of quasi-optimal transfer matrix \(B\):
   \[
b_{ij} = 10^n c_{ij} \quad (10)
   \]
6. Determining relative weights of indexes:
   \[
   \bar{w}_i = \sqrt[n]{\prod_{j=1}^{n} b_{ij}}, \quad i = 1,2,\cdots,n
   \]
7. Normalizing the relative weight of indexes:
   \[
   w_i = \frac{\bar{w}_i}{\sum_{i=1}^{n} \bar{w}_i}
   \]
Application of Virtual Maintenance Training and Assessment Platform for Steam Turbine

Taking the maintenance task of low pressure cylinder in steam turbine equipment as an example, the evaluation method is applied to verify the evaluation effect. The assessment interface and the operation information record of the operator $x_1$ are as follows:

![Assessment interface and operation information](image)

**Figure 2. The assessment interface and the operation information.**

**Maintenance Data and Corresponding Quantified Values**

By retrieving the information of the expert database and the parts database, referring to the evaluation index system in chapter 2 and the corresponding quantitative methods, we selected the operation information of operators $x_1$, $x_2$, $x_3$, and the data is recorded as shown in Table 1.

| Operator | Index | C1 (min) | C2 (min) | C3 (min) | C4 (min) | C5 (min) | C6 (time) | C7 (time) | C8 (time) | C9 (time) | C10 (step) |
|----------|-------|----------|----------|----------|----------|----------|-----------|-----------|-----------|-----------|------------|
| $x_1$    |       | 0.5      | 1.0      | 3.0      | 1.0      | 0.5      | 10        | 21        | 0         | 0         | 12         |
|          |       | 0.85     | 1.20     | 3.12     | 1.21     | 0.48     | 1         | 2         | 0         | 2         | 11         |
|          |       | 0.588    | 0.833    | 0.962    | 0.826    | 1        | 0.90      | 0.905     | 1         | 0.833     | 0.917      |
| $x_2$    |       | 0.65     | 0.88     | 2.50     | 1.12     | 0.35     | 2         | 2         | 1         | 0         | 10         |
|          |       | 0.769    | 1        | 1        | 0.893    | 1        | 0.8       | 0.905     | 0         | 1         | 0.833      |
| $x_3$    |       | 0.48     | 1.50     | 4.05     | 1.31     | 0.88     | 1         | 0         | 0         | 1         | 12         |
|          |       | 1        | 0.667    | 0.741    | 0.763    | 0.568    | 0.90      | 1         | 1         | 0.917     | 1          |

**Weight Value of Each Evaluation Index**

Referring to the evaluation index system of Fig.1 and using 1~9 ratio calibration method, expert are invited to score and form the judgment matrix and then calculate the weight vector matrix according to the improved AHP. The resulting judgment matrix consists of target layer $A$, criterion layer $A_1$, $A_2$ and $A_3$ respectively.

$$ A = \begin{bmatrix} 1 & \frac{1}{2} & \frac{1}{3} \\ \frac{1}{2} & 1 & \frac{1}{2} \\ \frac{1}{3} & \frac{1}{2} & 1 \end{bmatrix} A_1 = \begin{bmatrix} 1 & \frac{1}{2} & \frac{1}{3} \\ \frac{1}{2} & 1 & \frac{1}{3} \\ \frac{1}{3} & \frac{1}{2} & 1 \end{bmatrix} A_2 = \begin{bmatrix} 1 & \frac{1}{2} \\ \frac{1}{2} & 1 \\ \frac{1}{2} & \frac{1}{3} \end{bmatrix} A_3 = \begin{bmatrix} 1 & \frac{1}{2} \\ \frac{1}{2} & 1 \\ \frac{1}{2} & \frac{1}{3} \end{bmatrix} $$

The corresponding quasi-optimal transfer matrices are $B$, $B_1$, $B_2$ and $B_3$ respectively.
The corresponding normalized weights are \( w, w_1, w_2, w_3 \) respectively:

\[
B = \begin{bmatrix}
1.000 & 1.817 & 0.303 \\
0.550 & 1.000 & 0.550 \\
3.302 & 1.817 & 1.000 \\
\end{bmatrix},
B_1 = \begin{bmatrix}
1.000 & 1.431 & 2.290 & 0.217 & 0.354 \\
1.756 & 1.000 & 4.020 & 0.380 & 0.621 \\
0.437 & 0.249 & 1.000 & 0.095 & 0.155 \\
4.618 & 2.631 & 10.576 & 1.000 & 1.636 \\
2.825 & 1.610 & 6.470 & 0.612 & 1.000 \\
\end{bmatrix},
B_2 = \begin{bmatrix}
1.000 & 0.200 \\
0.550 & 1.000 \\
5.000 & 1.000 \\
1.817 & 3.302 & 1.000 \\
\end{bmatrix}
\]

\[
w = \begin{bmatrix}
0.2030 \\
0.2477 \\
0.5493 \\
\end{bmatrix},
w_1 = \begin{bmatrix}
0.110 \\
0.162 \\
0.041 \\
0.426 \\
0.261 \\
\end{bmatrix},
w_2 = \begin{bmatrix}
0.1667 \\
0.8333 \\
\end{bmatrix},
w_3 = \begin{bmatrix}
0.2966 \\
0.1645 \\
0.5390 \\
\end{bmatrix}
\]

The final index weight is:

\[
W = \begin{bmatrix}
0.0223 \\
0.0329 \\
0.0083 \\
0.08648 \\
0.0530 \\
0.0413 \\
0.2064 \\
0.1629 \\
0.0904 \\
0.2961 \\
\end{bmatrix}
\]

The comprehensive results of operators \( x_1, x_2 \) and \( x_3 \) were as follows:

\[
\text{score} = Q * W^T
\]

According to the expression (8): Score1=0.907 , Score2=0.745 , Score3=0.932.

On the basis of the calculation results above, the comprehensive score of operator \( x_1 \) is 0.907, operator \( x_2 \) is 0.745 and operator \( x_3 \) is 0.932 under the scale of 0~1 respectively.

**Conclusion**

In this paper, a set of steam turbine virtual maintenance evaluation index system is established. According to the characteristics of steam turbine equipment and actual maintenance conditions, complex virtual maintenance evaluation problems are organized and hierarchical, and the identification and quantification methods of indicators are analyzed. An improved analytic hierarchy process (AHP) is also proposed and applied to the evaluation index system, which avoids the blind adjustment of the judgment matrix caused by the failure of consistency test, and makes full use of the expert information, making the evaluation result more precise and reasonable. Finally, this method is applied to the steam turbine virtual maintenance training and assessment platform developed by JA DE Engineering Training Center, and the evaluation results can effectively reflect the real level of operators.

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