The Application of Improved Fuzzy Analytic Hierarchy Process (FAHP) in the Condenser Fault Diagnosis in Power Plant

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Abstract. Since the influential factors of vacuum reduction of condenser are fuzzy and uncertain, the improved FAHP is used. By comparing every two of the influential factors, the fuzzy matrix is constructed. The weight index of influential factors of vacuum reduction of condenser in a certain power plant is calculated out quantitatively. The most important influential factor is found out. And there is a verification which exactly identified the fault of the condenser by using a real instance.

1. Introduction

The condenser is an important equipment of the condensing steam turbine. Whether its operation is good or bad is directly related to the safe and economic operation of the turbine. The condenser vacuum is often lower than the design value during operation because of the design, installation, maintenance, operation and other reasons[1—3]. After the condenser vacuum dropped, it can exhaust the steam temperature elevated, low-pressure cylinder deformation and vibration, then endanger the safe operation of unit. In addition, the vacuum reduction will lead to effective enthalpy drop decrease, the cycle thermal efficiency decreased and reduce the thermal economy of the unit. Therefore, the researchers are generally concerned about the diagnostic techniques about the condenser vacuum reduce. The causes of vacuum reduction of condenser are diverse. Moreover, there are strong fuzziness, uncertainty and coupling among the influencing factors. The application of fuzzy analytic hierarchy process (FAHP) to the fault diagnosis of thermal equipment and systems of power plants shows certain advantages. Due to the strong subjectivity of traditional FAHP in constructing judgment matrix, it contains certain personal preference information and it is not very persuasive. In view of this, this paper makes appropriate improvements to the FAHP, adopts a more objective calculation method to establish the fuzzy judgment matrix, and applies the improved FAHP to the fault diagnosis of vacuum reduction of the condenser in a power station.

2. Fuzzy Analytic Hierarchy Process (FAHP)

The matter-element contains three basic elements in extension theory. Assuming the name of object R is N, the characteristics are C, FAHP [4] is a method based on AHP[5] that combines AHP and fuzzy comprehensive evaluation. It is characterized by applying AHP to determine the weight of each index in the evaluation index system, and using the fuzzy comprehensive evaluation method to evaluate the fuzzy index [6]. The method of fault diagnosis for condenser vacuum reduction using FAHP can be divided into three steps: 1) establishing the hierarchical structure model of the influencing factors of
condenser vacuum reduction; 2) establishing the fuzzy judgment matrix; 3) checking the consistency of the fuzzy evaluation matrix; 4) calculating the weight of each influencing factor of the research object.

The fuzzy evaluation matrix represents the comparison of the relative importance of a factor in the previous layer, the fuzzy relation between the two factors is: "... than... much more important." That is, "which of the multiple factors causing the vacuum reduction of the condenser to be diagnosed is more important, and to what extent?" In order to quantify the relative importance of any two fault elements, the scale method of 0.1—0.9 shown in table 1 can be adopted.

Table 1. 0.1—0.9 scale method

| scale | meanings                          |
|-------|-----------------------------------|
| 0.5   | Factor a_i is as important as factor a_j |
| 0.6   | Factor a_i is slightly more important than factor a_j |
| 0.7   | Factor a_i is significantly more important than factor a_j |
| 0.8   | Factor a_i is more important than factor a_j |
| 0.9   | Factor a_i is most important than factor a_j |
| 0.1, 0.2 | r_ji=1- r_ij                        |
| 0.3, 0.4 |                                     |

3. The establishment of fault sets and symptom sets of condenser

By referring to the existing literatures on low-vacuum fault diagnosis of condenser and a large number of engineering cases, this paper concludes that there are 11 main fault causes for the reduction of condenser vacuum and 19 malfunction symptoms after vacuum reduction. The above 11 fault elements and 19 fault omen elements are described in the form of classical mathematical sets, which can establish the fault set and symptom set of influencing factors for condenser vacuum reduction [7]. As shown below:

fault set \( FAULT = \{F_1, F_2 \cdots F_{11}\} \)

\( F_1 = \) {abnormal operation of circulating pump}; \( F_2 = \) {abnormal operation of condensate pump}; \( F_3 = \) {burst of low pressure heater tube}; \( F_4 = \) {abnormal operation of the pumping equipment}; \( F_5 = \) {rupture of condenser tube bundle}; \( F_6 = \) {condenser tube bundle dirty}; \( F_7 = \) {clogging of condenser tube bundle}; \( F_8 = \) {rear shaft seal steam supply interruption}; \( F_9 = \) {burst of the vacuum system tube bundle}; \( F_{10} = \) {decreased seal water for feed pump}; \( F_{11} = \) {air leakage point in the condenser vacuum system}.

symptom set \( SYMPTOM = \{S_1, S_2 \cdots S_{19}\} \)

\( S_1 = \) {vacuum reduction}; \( S_2 = \) {vacuum decreased slowly}; \( S_3 = \) {abnormal current of circulating pump motor}; \( S_4 = \) {abnormal outlet pressure of circulating pump}; \( S_5 = \) {abnormal motor current of condensate pump}; \( S_6 = \) {abnormal outlet pressure of condensate pump}; \( S_7 = \) {negative differential expansion of turbine rotor}; \( S_8 = \) {increased conductivity of condensed water}; \( S_9 = \) {increased oxygen content in condensation water}; \( S_{10} = \) {raised water level of low pressure heater}; \( S_{11} = \) {increase of condenser end difference}; \( S_{12} = \) {increase of temperature rise of circulating water}; \( S_{13} = \) {decrease of temperature rise of circulating water}; \( S_{14} = \) {increased subcooling of condensation water}; \( S_{15} = \) {decrease of air supply pressure of shaft seal}; \( S_{16} = \) {increase of temperature difference between the air pumped by the pumping equipment and the inlet of cooling water}; \( S_{17} = \) {decrease of pressure difference between the condenser's extraction port and the extraction equipment inlet}; \( S_{18} = \) {abnormal water level of sealed water return tank}; \( S_{19} = \) {high water level of condenser}.

In order to facilitate the application of fuzzy AHP, 11 elements in the fault set are further classified, which can be divided into three types of typical faults. That is: \( B_1 \) related auxiliary machine operation abnormality; \( B_2 \) : poor heat transfer of tube bundle of condenser body; \( B_3 \) : The condenser vacuum system is not compact. Defined \( B = (B_1, B_2, B_3) \) as a criterion layer. \( C_1 = (F_1, F_2, F_3, F_4) \),
4. Application analysis

4.1. The fuzzy membership of the fault element

For the set of symptoms of vacuum reduction of the condenser established above, if a fault cause in the fault set appears, the value of "1" is assigned; otherwise, the value of "0" is assigned. After such logic assignment, a logical relational table consisting of only two logical values of "1" or "0" can be formed, as shown in Table 2. The failure symptoms of a 600MW steam condenser in this study were corresponding to S2, S13, S11, S14, S9, S18 and S16 in the symptom set respectively. The fault symptom vector of the condenser is:

\[ X_j = (010000001010101010) \]

Fuzzy membership degree was calculated by applying the membership function of the equation below to identify the fault vector and the corresponding vectors of each fault element in the fault set. The results were successively: 0.7479, 0.8212, 0.7966, 0.9220, 0.8212, 0.9220, 0.8712, 0.8712, 0.8965, 0.9738 and 0.9478.

\[ \mu_i(x) = \cos \left( \sum_{j=1}^{19} (X_j - X_j^{(i)})^2 \right)^{1/2} \quad (i = 1, 2 \ldots 11) \]

4.2. The assignment rules of fuzzy evaluation matrix

The fuzzy membership degree of 11 fault elements is evaluated successively, that is, the membership degree deviation between each fault element is calculated, and the membership degree deviation matrix corresponding to the factor layer and criterion layer can be obtained.

\[ \Delta(C_1) = \begin{bmatrix}
0 & -7.33\% & -4.87\% & -17.4\%\\
7.33\% & 0 & 2.46\% & -10.08\%\\
4.87\% & -2.46\% & 0 & -12.54\%\\
17.41\% & 10.08\% & 12.54\% & 0
\end{bmatrix} \quad \Delta(C_2) = \begin{bmatrix}
0 & -10.08\% & -5\%\\
10.08\% & 0 & 5.08\%\\
5\% & -5.08\% & 0
\end{bmatrix} \]

\[ \Delta(C_3) = \begin{bmatrix}
0 & -2.53\% & -10.26\% & -7.66\%\\
2.53\% & 0 & -7.73\% & -5.13\%\\
10.26\% & 7.73\% & 0 & 2.6\%\\
7.66\% & 5.13\% & -2.6\% & 0
\end{bmatrix} \quad \Delta(B) = \begin{bmatrix}
0 & -4.96\% & -10.04\%\\
4.96\% & 0 & -5.08\%\\
10.04\% & 5.08\% & 0
\end{bmatrix} \]

Table 2. logic relation table of condenser vacuum reduction fault and symptom

|     | F1 | F2 | F3 | F4 | F5 | F6 | F7 | F8 | F9 | F10 | F11 |
|-----|----|----|----|----|----|----|----|----|----|-----|-----|
| S1  | 1  | 0  | 0  | 0  | 0  | 0  | 0  | 1  | 1  | 0   | 0   |
| S2  | 0  | 1  | 1  | 1  | 1  | 1  | 1  | 0  | 0  | 1   | 1   |
| S3  | 1  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0   | 0   |
| S4  | 1  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0   | 0   |
| S5  | 0  | 1  | 1  | 0  | 1  | 0  | 0  | 0  | 0  | 0   | 0   |
According to the above membership degree deviation matrix, the majority of elements are in the numerical interval (-10%, 10%), while only some elements deviate from this interval. Therefore, the maximum membership deviation value (-17.4%, 17.4) can be divided into 10 sub-intervals (-17.4%, -10%), (-10%, -7.5%), (-7.5%, -5%) (-5%, -2.5%), (-2.5%, 0), (0, 2.5%) (2.5%, 5%) (5%, 7.5%) (7.5%, 10%) (10%, 17.4%). The subinterval is divided into 8 sub-intervals with the length of 2.5%, except the extreme intervals at the left end and the last end. Each subinterval corresponds to the scale from 0.1 to 0.9, and the following assignment rules can be obtained finally:

- If \(0 \leq \Delta(F_i, F_j) < 2.5\%\) given \(r_{ij} = 0.5\)
- If \(-2.5\% \leq \Delta(F_i, F_j) < 0\) given \(r_{ij} = 0.5\)
- If \(2.5\% \leq \Delta(F_i, F_j) < 5\%\) given \(r_{ij} = 0.6\)
- If \(5\% \leq \Delta(F_i, F_j) < 7.5\%\) given \(r_{ij} = 0.7\)
- If \(7.5\% \leq \Delta(F_i, F_j) < 10\%\) given \(r_{ij} = 0.8\)
- If \(10\% \leq \Delta(F_i, F_j)\) given \(r_{ij} = 0.9\)
- If \(-5\% \leq \Delta(F_i, F_j) < -2.5\%\) given \(r_{ij} = 0.4\)
- If \(-7.5\% \leq \Delta(F_i, F_j) < -5\%\) given \(r_{ij} = 0.3\)
- If \(-10\% \leq \Delta(F_i, F_j) < -7.5\%\) given \(r_{ij} = 0.2\)
- If \(\Delta(F_i, F_j) < -10\%\) given \(r_{ij} = 0.1\)

The fuzzy evaluation matrix of the factor layer and the criterion layer can be obtained according to the assignment rule established in the previous section.

\[
R_{C_1} = \begin{bmatrix}
F_1 & F_2 & F_3 & F_4 \\
F_1 & 0.5 & 0.375 & 0.4 & 0.025 \\
F_2 & 0.625 & 0.5 & 0.525 & 0.15 \\
F_3 & 0.6 & 0.475 & 0.5 & 0.125 \\
F_4 & 0.975 & 0.85 & 0.875 & 0.5 \\
\end{bmatrix} \quad R_{C_2} = \begin{bmatrix}
F_5 & F_6 & F_7 \\
F_5 & 0.5 & 0.1 & 0.3 \\
F_6 & 0.9 & 0.5 & 0.7 \\
F_7 & 0.7 & 0.3 & 0.5 \\
\end{bmatrix}
\]
4.3. The Weight calculation of fault cause

It is supposed that the weight vectors of each element in the fault set of vacuum reduction of the condenser to be diagnosed are: \( M = \begin{bmatrix} m_1, m_2, \ldots, m_n \end{bmatrix} \). This vector can be determined by the least square method. It is the solution to the following constraint planning problem:

\[
\begin{align*}
\min_{\mathbf{B}} \quad & z = \sum_{i=1}^{n} \sum_{j=1}^{n} \theta \left( m_i - m_j \right) + 0.5 - r_{ij} \quad \text{subject to} \\
& \sum_{i=1}^{n} m_i = 1, \quad m_i \geq 0, \quad 1 \leq i \leq n
\end{align*}
\]

After solving the above programming problems, the diagnosis results are shown in a histogram, as shown in figure 1. It indicates that the fault element \( F_{10} \) whose weight is much higher than others. Therefore, the main reason for the reduction of the condenser vacuum is "reduction or interruption of the water seal of the feed pump". In addition, fault element \( F_{11} \) and \( F_{6} \) are also heavy weights, which are also major factors influencing the reduction of the condenser vacuum.

![FIG. 1 histogram of the diagnostic results of vacuum reduction of condenser](image)
It can be seen that the diagnosis result of F10= "reduction or interruption of the sealing water of the feed pump" obtained by FAHP is consistent with the conclusions obtained through field experiments. This shows that the model of condenser vacuum reduction established by FAHP in this paper has preliminary feasibility, accuracy and engineering application value.

5. Conclusions
The Fuzzy Analytic Hierarchy Process (FAHP) can avoid the complex linkages between the various factors and the strong fuzziness, uncertainty, and coupling, and it only need the fuzzy consistent matrix which reflects people's thinking judgment and objective facts. We can create a planning problem with binding condition, then complete the quantitative diagnosis by accurately solving the planning problem.

The Fuzzy Analytic Hierarchy Process (FAHP) can obtain a simple concept that a factor is important or unimportant, but also can describe how much the impact of factors resulting in condenser vacuum reduce, while it can obtain relatively minor and the small weight impact factors. The quantification of these factors is able to contribute to the failure prediction and prevention role.

For the failure instance in paper, the final result is "the reduction or interruption of the water pump seal water F10 ". However, we note that the fault element "there are leak point in condenser vacuum system F6 " and "condenser heat exchange tube bundle dirty F11 " are also likely to re-occur the similar failure after a period of running. Therefore, the appropriate treatment measures should be comprehensive, not only the current reasons, but also the weight followed factors. This can certainly reduce the failure incidence of equipment, and improve operation safety and economy of the unit in power plant.

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