



# Condition Assessment of Oil-Immersed Transformers Based on Fuzzy Theory and Combination Weighting of Least Squares

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**Abstract.** Oil-immersed power transformer is the key equipment to maintain the safe and stable operation of the whole power system, it is very important to improve the accuracy of the condition assessment results to keep the power system running safely and stably. Aiming at the problems that the traditional condition evaluation model of oil immersed transformer is difficult to evaluate and the evaluation result is inaccurate. A condition assessment model of oil immersed power transformer based on fuzzy theory and combination weighting of least squares is proposed in this paper. The model combines subjective weightings with objective weightings, and uses the least square method to determine the subjective and objective weight coefficients, which reduces the error impact caused by artificial subjective determination. The final transformer condition assessment results are determined by the fuzzy theory method. Using the oil-immersed transformer test data provided by a power supply company as a sample for experimental verification and analysis. The results show that the method proposed in this paper can accurately evaluate the state of oil-immersed power transformers, which has certain practical significance in engineering.

**Keywords:** Analytic Hierarchy Process · Least Squares · Oil-immersed power transformer · Condition assessment

## 1 Introduction

Oil-immersed power transformer is the critical equipment in the whole power system. It is used to connect power transmission systems of different voltage levels. Its operation status determines whether the power system can operate safely and reliably. In domestic and foreign blackouts, regardless of natural disasters, equipment failures are the main cause of grid failures. Therefore, it is of great significance to evaluate the condition of oil immersed transformers and diagnose the faults of transformers with poor operating conditions in time to ensure the safe and stable operation of the whole power system.

Oil immersed power transformer is a very complex power equipment, and there are many possible problems in its operation. Therefore, there are many assessment indicators involved in its condition assessment, and some changes of each assessment indicator may have a certain impact on its healthy operation state. Therefore, when establishing the condition assessment model of oil immersed power transformer, the relationship between each evaluation indicators must be fully considered [1, 2]. In recent years, domestic and foreign researchers have done a lot of research work on state assessment. Literature [3] used AHP (Analytic Hierarchy Process, AHP) and rough set theory to establish hierarchical indicators for the condition assessment of transformers. Rough set theory data was not easy to deal with, and it was too subjective to determine the weight only by AHP method. Literature [4] used the principal component analysis weighting method to determine the weights of each assessment index, which improved the accuracy of the evaluation results to a certain extent, but only the principal component analysis method determines the weights, ignoring that some other secondary indicators also had a certain impact on the transformer state. Literature [5] used the combination of subjective weighting method and grey clustering to evaluate the transformer status, but it still did not avoid the contradiction of subjective weighting.

Due to the problems of difficult assessment and error of assessment results in the condition assessment of oil immersed power transformers, a condition assessment model of oil immersed power transformer based on fuzzy theory and combination weighting of least squares is proposed in this paper. The model combines subjective weightings with objective weightings, and uses the least square method to determine the subjective and objective weight coefficients. The final transformer condition assessment results are determined by the fuzzy theory method. The results show that the method proposed in this paper can accurately evaluate the state of oil-immersed power transformers, which has certain practical significance in engineering.

## **2 Establishment of Condition Assessment Model for Oil Immersed Transformer**

### **2.1 Establishment of Condition Assessment Indicator System for Oil-Immersed Transformer**

There are many indicators that affect the transformer state, so it is very important to select a comprehensive transformer state assessment indicator system. In order to meet the needs of transformer condition assessment, the assessment system of transformers established in this paper is a two-layer indicator system composed of first-level indicators and second-level indicators. And this paper divides the secondary indicators into three categories: “bigger is better”, “smaller is better” and “intermediate optimal”. Among them, the total hydrocarbon content,  $C_2H_2$  content, furfural,  $H_2$  content, relative CO rate, dielectric loss of oil, dielectric loss of winding, ground current of iron core, and service life are the smaller the better type, the working environment temperature is the intermediate optimal type, and the other indicators are the larger the better type [6–10].

By consulting relevant papers and materials on transformers [11, 12], different initial values and critical values are set according to different assessment indicators. After

determining the assessment indicator system of transformer status, the classification of transformer health status is established. Transformer is an intelligent electrical equipment with a very complex structure. In order to reflect the status of the transformer in more detail, the oil-immersed power transformer condition assessment system established in this paper is shown in Table 1.

**Table 1.** Condition assessment system of oil-immersed power transformer.

First-level indicators	Second-level indicators	Initial values	Critical values
Test characteristic indicators (B1)	furfural, mg/l(B11)	0	0.2
	interfacial tension, Mn/m(B12)	45	19
	polymerisation degree(B13)	1000	250
DGA (B2)	H <sub>2</sub> content, ul/l(B21)	5.8	150
	total hydrocarbon content, l/l(B22)	5.59	150
	C <sub>2</sub> H <sub>2</sub> content, ul/l(B23)	0	10
	CO relative production, %month(B24)	0	100
Inherent electrical characteristic indicators (B3)	breakdown voltage of oil, kv(B31)	60	35
	dielectric loss of oil, %(B32)	0.21	4
	dielectric loss of winding, %(B33)	0.15	0.6
	volume resistivity, 10 <sup>9</sup> Ωm(B34)	65	5
	core earthing current, MA(B35)	10	100
Historical operating environment indicators (B4)	service years(B41)	0	30
	appearance factor(B42)	100	50
	operating ambient temperature(B43), °C	-30	40/-20

## 2.2 Transformer Assessment Indicator Set Data Preprocessing

Oil-immersed power transformer is a complex structure system with a large number of states and most of them are nonlinear [2, 10]. And the dimensions of different state variables are different, which makes it difficult to normalize the set of state variables. For the initial values and critical values of the condition assessment indicators of oil immersed

power transformers described in Table 1, the concept of forward data normalization is introduced for each assessment indicators (The larger the normalized value, the better it is, and the smaller the value, the greater the deterioration), so as to realize the data preprocessing of the transformer condition assessment indicator.

For the larger, the better indicators:

$$x = \begin{cases} \frac{X - X_{down}}{X_{max} - X_{down}} & X > X_{down} \\ 0 & X \leq X_{down} \end{cases} \quad (1)$$

For the intermediate optimal indicators:

$$x = \begin{cases} 1 - \frac{X_b - X}{X_b - X_{best}} & X_{best} < X < X_b \\ 1 - \frac{X - X_a}{X_{best} - X_a} & X_a < X < X_{best} \\ 0 & X \geq X_b \text{ or } X \leq X_a \end{cases} \quad (2)$$

For the smaller, the better indicators:

$$x = \begin{cases} \frac{X_{up} - X}{X_{up} - 0} & 0 < X_{up} \\ 0 & X \geq X_{up} \end{cases} \quad (3)$$

where  $X$  is the actual test value of the evaluation index.,  $X_{down}$  is the lower limit threshold of the larger and better type. Where  $X_{max}$  is the maximum value of the index test data in the group,  $X_a$  and  $X_b$  are the upper and lower limit thresholds of the intermediate optimal type index, respectively,  $X_{best}$  is the optimal value of the intermediate optimal type indicator,  $X_{up}$  is the upper threshold of the smaller and better indicator. The normalization matrix can be obtained by Eqs. (1) to (3).  $X = (x_{ij})_{n \times m}$ .

### 2.3 Establishment of Assessment Indicator Weight Matrix

#### Subjective Empowerment

According to the hierarchy defined by the transformer condition assessment system in Table 1, each indicator element forms a sub-domain with the lower-level indicator elements governed by that indicator element, where all elements form a judgment matrix [13, 14]. The significance of the constructs is quantified in terms of the relative importance among all sublevels of indicators governed by the upper-level indicators. In this paper, the judgment matrix  $D$  is constructed using the 1–9 scale method [15].

The weights of each dimension are the eigenvectors of the maximum characteristic root  $\lambda_{max}$  of the judgment matrix  $D$ . It is normalized and recorded as  $B$ .

$$DB = \lambda_{max}B \quad (4)$$

The consistency validity of the matrix  $D$  is then expressed as:

$$f_{CI} = \frac{(\lambda_{max} - n)}{(n - 1)} \quad (5)$$

Introduce of random consistency metrics  $f_{RI}$  to measure consistency metrics  $f_{CI}$ . Where  $f_{RI}$  is determined by the order of the matrix itself.  $RI = [0 \ 0 \ 0.58 \ 0.90 \ 1.12 \ 1.24 \ 1.32 \ 1.41 \ 1.45 \ 1.49 \ 1.51]$ . Define consistency ratio  $f_{CR}$  as the ratio of the two [16]:

$$f_{CR} = \frac{f_{CI}}{f_{RI}} \tag{6}$$

When  $f_{CR} < 0.1$ , it means the matrix  $D$  passes the consistency validity. After the judgment matrix  $D$  satisfies the consistency requirement, the resulting weight vector is  $A$ .

**Objective Empowerment**

The entropy weighting method can deeply reflect the differentiation ability of transformer condition assessment indexes and determine better weights. Empowerment is more objective, theoretically based, and credible. The entropy weighting algorithm is simple and does not require additional software analysis.

The entropy value of the  $j$ -th indicator is:

$$K_j = \frac{\sum_{i=1}^n v(i, j) \ln(i, j)}{\ln n} \tag{7}$$

where  $v(i, j)$  is the characteristic weight of the  $i$ -th object under the  $j$ -th indicator.

$$v(i, j) = \frac{x^*(i, j)}{\sum_{i=1}^n x^*(i, j)} \tag{8}$$

The entropy weight of the  $j$ -th indicator is:

$$\omega_j = \frac{1 - k_j}{\sum_{j=1}^m (1 - k_j)} \tag{9}$$

**Least Squares Combination Weighting to Determine Comprehensive Weights**

Let the weights of each evaluation index obtained by the AHP method are  $W_1 = [\omega_{11}, \omega_{12}, \dots, \omega_{1m}]$ . The objective weights obtained by the entropy method method are  $W_2 = [\omega_{21}, \omega_{22}, \dots, \omega_{2m}]$ . Then the combined weights determined by least squares are  $W = [\omega_1, \omega_2, \dots, \omega_m]$ . For the normalized standard matrix  $X = (x_{ij})_{n \times m}$ . The evaluation value of the  $i$ -th sample is:

$$g_i = \sum_{j=1}^m \omega_j x_{ij} \ (i = 1, 2, \dots, n) \tag{10}$$

where  $\omega_j$  is the combination weight of the  $j$ -th indicator of  $u$ ,  $x_{ij}$  is the normalized value of the  $j$ -th indicator of the  $i$ th assessment series. In order to minimize the influence of human factors on the error in determining the subjective and objective weight coefficients.

$$\omega = \text{diag} \left[ \sum_{i=1}^n x_{i1}^2, \sum_{i=1}^n x_{i2}^2, \dots, \sum_{i=1}^n x_{im}^2 \right] \quad (11)$$

## 2.4 The Realization of Condition Assessment Method of Fuzzy Comprehensive Evaluation

### Step 1. Determination of index weight

The least squares method is used to determine the combination weights  $W$ . The weight vector of the first-level indicators is noted as  $W = [\omega_1, \omega_2, \dots, \omega_m]$ , The weight vector of secondary indicators is noted as  $W_i = [\omega_{i1}, \omega_{i2}, \dots, \omega_{im}]$ .

### Step 2. The determination of the domain of judgment

The domain of the rating scale is a collection of the evaluation results of each evaluation index [17]. According to the characteristics of oil-immersed power transformers, the evaluation domain is divided into four levels: “good”, “average”, “warning” and “poor”. Then the affiliation is determined, corresponding to  $V = (V_1, V_2, V_3, V_4)$  (Table 2).

**Table 2.** Judging criteria description.

Judging level	Effects
V1	The transformer is operating normally. And there is no tendency of deterioration
V2	There are still a few evaluation factors outside the normal range, but the overall operation is still normal
V3	Nearly half of the transformer indicators have close to or even beyond the critical value, the transformer operating condition is poor, may not be normal operation, the need to organize maintenance as soon as possible
V4	Transformer operating condition is poor, may not be normal operation, need to immediately organize maintenance

### Step 3. Fuzzy evaluation

Perform fuzzy evaluation to improve the reasonableness and accuracy of transformer condition assessment. Considering the respective characteristics of trapezoidal and triangular distributions. In this paper, we use the improved triangular trapezoidal distribution to determine the affiliation degree and obtain a reasonable distribution state.

$$r(v_1) \begin{cases} \frac{v-0.4}{0.2} & 0 \leq v \leq 0.4 \\ \frac{v-v_{i-1}}{v_i-v_{i-1}} & v_{i-1} \leq v \leq v_i \\ \frac{v-v_{i+1}}{(-1)^i(v_{i+1}-v_i)} & v_i \leq v \leq v_{i+1} \\ \frac{v-0.8}{0.2} & 0.8 \leq v \leq 1 \end{cases} \quad (12)$$

The single-factor evaluation matrix is obtained from the fuzzy relationship matrix. Based on the comprehensive weight values of the secondary index factors determined by the least squares combination assignment and the resulting evaluation level affiliation matrix, the evaluation model of the secondary index factors for transformer condition assessment is constructed.

$$B_i = W * R_i = [b_{i1}, b_{i2}, b_{i3}, b_{i4}] \quad (13)$$

where  $W$  is the set of comprehensive index weights,  $R_i$  is the fuzzy evaluation matrix of the  $i$ th scheme.

Based on the evaluation factor model of the secondary indexes and then determine the comprehensive evaluation matrix of the primary factors by Eq. (13). Then according to the principle of maximum subordination can determine the oil-immersed power transformer status evaluation results.

### 2.5 Establishment of Condition Assessment Model for Oil-Immersed Power Transformers

According to the above theoretical introduction, a condition assessment model of oil immersed power transformer based on fuzzy theory and combination weighting of least squares is constructed in this paper. As shown in Fig. 1.

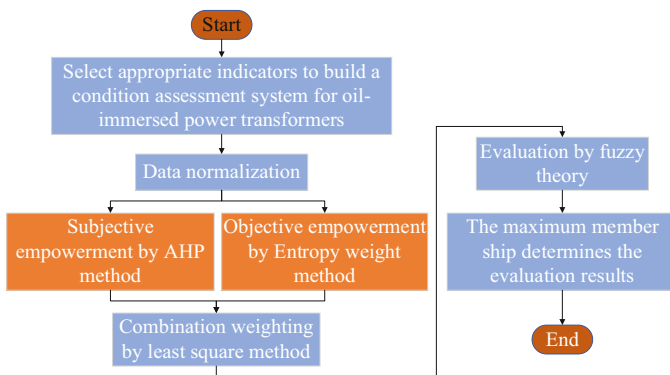


Fig. 1. Condition assessment flow chart for oil-immersed power transformers.

### 3 Example Analysis

#### 3.1 Data Pre-processing

To verify the reliability and accuracy of the evaluation results of the condition assessment model of oil-immersed power transformers based on the combination of fuzzy theory method and least squares assignment. The actual test data of 3 groups of oil-immersed power transformers of 110 kV provided by a power supply station in Hubei Province is used as the test analysis. The data of each assessment index after data pre-processing in Sect. 2.2 are shown in Table 3.

**Table 3.** Normalized results of assessment metric.

	C1	C2	C3		C1	C2	C3		C1	C2	C3
B11	0.5	0.25	0.75	B23	0.2	0.3	0.35	B34	0.36	1	0.89
B12	1	0.76	0.85	B24	0.5	0.21	0.32	B35	0.2	0.34	0.55
B13	1	0.44	0.78	B31	1	0.98	0.25	B41	0.27	0.67	0.5
B21	0.87	0.77	0.49	B32	0.91	0.5	0.4	B42	0.53	0.87	1
B22	0.7	0.41	0.57	B33	0.67	0.6	0.17	B43	0.5	0.4	0.3

#### 3.2 Least Squares Method to Determine the Value of Comprehensive Weights

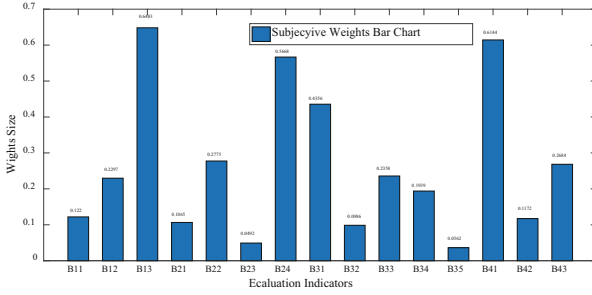
##### Step 1. Subjective Empowerment

Relative ranking of importance of the 15 indicators in Table 1 based on the experience base of transformer experts. Hierarchical analysis was used to construct judgment matrices for the four first-level indicators and 15 second-level indicators according to the 1–9 scale method. The corresponding subjective weights are shown in Table 4.

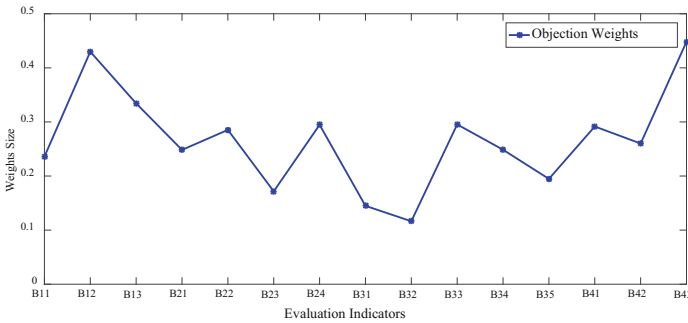
**Table 4.** The corresponding subjective weights are shown

B11	B12	B13	B21	B22	B23	B24	B31
0.1220	0.2297	0.6483	0.1065	0.2775	0.0492	0.5668	0.4356
B32	B33	B34	B35	B41	B42	B43	
0.0986	0.2358	0.1939	0.0362	0.6144	0.1172	0.2684	

The weights of indicators B11–B15 are obtained as shown in Fig. 2. The consistency validity of the above five fuzzy judgment matrices according to the above. The corresponding compatibility indexes were 0.0064, 0.0018, 0.0340, 0.0075, 0.0368, all of which passed the consistency test.



**Fig. 2.** Subjective weighting chart



**Fig. 3.** Objective weighting chart

**Step 2. Objective Empowerment**

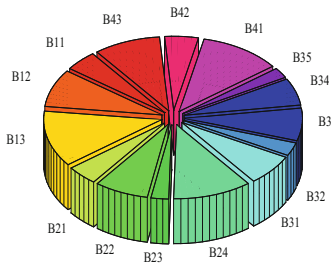
The entropy method can deeply reflect the differentiation ability of transformer status assessment indexes to make the assignment more objective and theoretically based. The weights obtained by applying the entropy weighting method to the 15 indicators in this paper are shown in Fig. 3.

**Step 3. Least squares combination assignment**

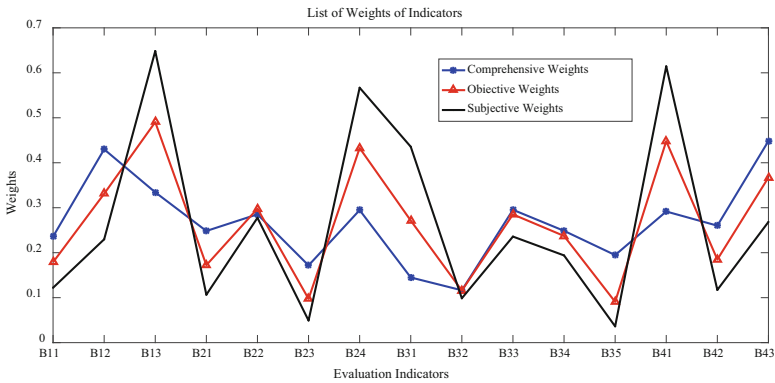
By using the least squares method to obtain the combination weights, the randomness of AHP and the one-sidedness of the entropy weight method can be eliminated as much as possible while maintaining the amount of information of subjective and objective weights. The weights obtained by the combined assignment method are shown in Table 5 (Figs. 4 and 5).

**Table 5.** .

Indicators	B11	B12	B13	B21	B22
Indicator weights	0.0451	0.0835	0.1237	0.0432	0.0747
Indicators	B23	B24	B31	B32	B33
Indicator weights	0.0244	0.1086	0.0667	0.0285	0.0701
Indicators	B34	B35	B41	B42	B43
Indicator weights	0.0583	0.0223	0.1124	0.0464	0.0921



**Fig. 4.** Integrated weighting pie chart.



**Fig. 5.** Comparison of weights.

### 3.3 Transformer Fuzzy Theory Evaluation Results

According to Sect. 2.4 to obtain the assessment results of the three groups of transformer status, and in accordance with the principle of maximum subordination to determine the evaluation level. The results are shown in Table 6.

As can be seen from Table 6, the condition assessment result of the first transformer is “good”, and the transformer is operating normally and there is no tendency of deterioration, only need to go for normal maintenance. The condition of the second transformer was assessed as “average”, it shows that there are still a small number of assessment

**Table 6.** Status assessment results.

	Good	Average	Early Warning	Poor	Score	Results
C1	0.4406	0.3027	0.1804	0.0765	3.1078	Good
C2	0.2403	0.3564	0.2681	0.1354	2.8020	Average
C3	0.1900	0.1819	0.2398	0.3885	2.1739	Poor

factors that are outside the normal range, but the overall operation is still normal. The operating result of the third transformer is “poor”, This means that many indicators of this transformer are close to or even beyond the critical value, transformer operating condition is poor, may not be able to operate normally, the need to immediately organize maintenance. After post-inspection, it was found that the transformer did have line inrush, voltage peak superposition and line short circuit faults, and there was also a certain insulation aging. The subsequent more serious accident was avoided only after the immediate organization of the overhaul.

## 4 Conclusion

The hierarchical analysis method is used to determine the subjective weights, the entropy method to determine the objective weights, and the least squares combination to determine the comprehensive weights. Solve the problem of traditional single subjective weighting or objective weighting with one-sided weighting. The condition assessment model of oil-immersed power transformers based on the combination of fuzzy theory method and least squares weighting proposed in this paper can make accurate assessment of the operating condition of transformers. The case shows that the transformer condition assessment method is feasible and can provide a reference basis for relevant technical personnel. It can provide a reference basis for relevant technical personnel.

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