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A Multi-parameter Comprehensive Analytical Method for Online Assessing Power Transformer Condition

***Abstract**. The effective assessment on the operation condition of power transformer is an important means to conduct the condition maintenance for transformer and to improve the reliability of power system. Based on the amount of information of all kinds of online monitoring conditions obtained from the transformer intelligent components, the assessment model for comprehensive condition of transformer is established in this study through the introduction of extension theory. First, with respect to the disadvantage that there is considerable subjectivity in constructing judgment matrix by the traditional analytic hierarchy process (AHP), a new method is adopted to construct the judgment matrix. The orthogonal experimental design method, finite element simulation as well as AHP are adopted to determine the weighting of condition information index with scientific and objective attitude; next, the framework for comprehensive assessment of transformer condition is established with the extension-based comprehensive assessment method to achieve the qualitative and quantitative assessment on the transformer condition. The method is proved to be correct and valid through analysis of examples.*

***Streszczenie**. W artykule przedstawiono wyniki badań dotyczących opracowania modelu szacowania warunków pracy transformatora. W pierwszym kroku stworzono metodę budowy macierzy orzeczeń, z uwzględnieniem pewnych subiektywności tradycyjnej metody tworzenia tej macierzy (ang. Analytic Hierarchy Process). Do oszacowania wagi wskaźnika informacji o warunkach pracy, wykorzystano metodę eksperymentalną, symulację elementów skończonych oraz AHP. Wykonane badania wykazały poprawność działania metody. **(Wszechstronna, wieloparametrowa metoda analizy do dynamicznego szacowania warunków pracy transformatora)**.*

Keywords: Power Transformer; condition assessment; index weighting; online monitoring
Słowa kluczowe: transformator energetyczny, szacowanie warunków, waga wskaźnika, monitoring online.

Introduction

Power transformer is the hub equipment of power system, and the safety and reliability of power transformer operations are directly related to the stability of power system. For a long time, the operation status of transformer is determined through preventive testing and regular maintenance at home and abroad. According to the relevant standards and experts' operation experiences, the static assessment of the transformer is conducted. However, in practice, it is hard to guarantee the safe and reliable operations of the transformer only depending on the static assessment. Thus, it is an inevitable trend to determine the equipment condition and to implement the condition maintenance through advanced condition monitoring methods.

Due to huge amount of information on the condition of power transformer as well as ambiguity and uncertainty of some factors, the assessment for transformer condition has a considerable uncertainty. Currently, there are various emerging assessment methods for transformer condition, such as Bayesian network, gray theory, neural networks, support vector machines, etc. These methods, due to their difficulty to obtain favorable sampled data in the applications, are used to assess and predict the condition of transformer basically according to a single index, i.e. the gas dissolved in transformer oil. The fuzzy membership functions of indices are determined according to the statistical data and expertise and the integrated decision is made using the fuzzy theory in Literature [2]. However, the above methods may cause incompatible results of the assessment; the gray-level assessment is introduced in Literature [4] to comprehensively evaluate the operation condition of transformer.

Currently, the comprehensive assessment on transformer condition is mostly conducted through preventive test, routine inspection, condition monitoring and other data analysis. This assessment process, which is implemented in the data management platform in the monitoring center, requires interaction with the production management system. And the complete acquisition of relevant data is difficult to realize. According to the technical requirements of the State Grid Corporation on transformer intelligent components, the comprehensive assessment are studied using the various types of real-time condition data obtained from the on-line monitoring of intelligent components in this study to meet the requirements of real-time comprehensive assessment and early warning of the field examination of transformer condition and transformer substation. The shortcomings of current assessment methods are simply introduced. In this study, based on the extension theory, a comprehensive assessment method of transformer condition is put forward through the combination of improved level analysis and extension-based comprehensive assessment.

Basic principle of extension theory

The extension theory was put forward by China scholars Tsai Wen et al in 1983 based on the matter element analysis of extension set. The qualitative and quantitative comprehensive analyses of matters are conducted through studying the extension and its laws and methods as well as calculating the correlation function between matter elements.

A. Basic concept of matter-element

The matter-element (R) is the basic element to describe things, expressed by an ordered triple consisting of thing (N), feature name (C) and the corresponding value (V), i.e. R = (N, C, V).

A thing may have multiple features. If the thing N has n features $\{C_1, C_2, \cdots, C_n\}$ and the corresponding values $\{V_1, V_2, \cdots, V_n\}$, then the n-dimensional matter-element is described as follows:

$$R_n = \begin{bmatrix} N & C_1 & V_1 \\ & C_2 & V_2 \\ & \vdots & \vdots \\ & C_n & V_n \end{bmatrix} \quad (1)$$

B. Extension set theory

In order to quantitatively describe things, the concepts of extension set theory and correlation function are established. The real numbers taken from the (- ∞, + ∞) are used to present a possession of a property; positive numbers present the degree of the said property; negative numbers present non-possession of it; zero means both possession and non-possession of it. The value of correlation function (correlation degree) is used to describe the subordination relation between the elements and set and to express the hierarchical relationship between the elements of set. As the correlation function can be expressed by mathematical formula, the quantitative study on objects is possible

In order to establish the correlation function, the concept of distance between points and range is defined. x is set as a point in the real field (- ∞, + ∞) and $X = \langle a,b \rangle$ is set as an interval in the real field, their relationship can be expressed as follows:

$$\rho(x, X) = \left| x - \frac{a+b}{2} \right| - \frac{1}{2}(b-a) = \begin{cases} a-x, & x \le \frac{a+b}{2} \\ x-b, & x \ge \frac{a+b}{2} \end{cases} \tag{2}$$

Determination of information index eighting of transformer condition

Due to numerous information parameters of transformer condition, the determination of index weighting is a key part to the comprehensive assessment of condition and its accuracy directly affects the accuracy of the final results of the assessment. Currently, it is generally determined depending on the experts' experiences in combination with some mathematical analysis methods. Therefore, it often has human subjectivity.

As the traditional AHP has big subjectivity during the process of structuring judgment matrix, a new method is adopted to construct judgment matrix. According to the orthogonal test design principle, combination of different values is designed, which is analyzed and simulated with finite elements; linear regression analysis is conducted through the evaluation indices and simulation results; the relatively important ratio of each condition information index is obtained through regression coefficients. Thus, the judgment matrix is constructed. Then, AHP is used to calculate the weighting value of each condition information index. The results can reflect the relative importance among the condition information more objectively and effectively.

- **Establishment of comprehensive condition assessment model based on extension evaluation method**

A. Classification of transformer condition levels

Table 1. Level classification of transformer condition and maintenance strategies

Value range	Semantic description of condition level	Condition maintenance strategy
0～0.2	Critical	Immediate maintenance should be conducted.
0.2～0.5	Warning	Maintenance is a priority and should be arranged as soon as possible
0.5～0.8	Normal	Maintenance can be postponed but related plan should be timely made.
0.8～1.0	Good	Maintenance should be postponed.

B. Determination and quantification of condition information indices

To evaluate and determine the operation condition of transformer comprehensively and accurately, the characteristic quantity for reflecting the condition of transformer should be obtained. The assessment on the transformer condition is mainly conducted in this study based on the amount of information of condition obtained from on-line monitoring of transformer. The assessment index system is shown in Figure 1

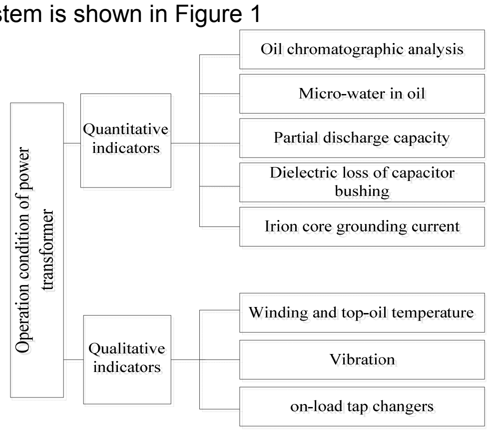

Figure1 Comprehensive assessment index system chart of transformer conditio

As there are both quantitative and qualitative indices in the assessment index system with different dimensions and magnitudes, direct comparison is impossible. Therefore, some different methods should be used to quantify them. For qualitative indices, due to measurement difficulties, the qualitative description is required according to experts' experiences. As a result, the expert scoring method is adopted with scoring range of [0, 1]; for quantitative indices, the concept of relative degree of deterioration is drawn

With respect to very large index, the greater its value is, the more excellent the condition is. The relative degree of degradation is expressed as follows:

$$\chi_i = \begin{cases} 0 & x_i \ge a \\ \dfrac{a-x_i}{a-b} & b \le x_i \le a \\ 1 & x_i \le b \end{cases} \tag{3}$$

Regarding the very small index, the smaller its value is, the more excellent the condition is. Its relative degree of degradation is expressed as follows:

$$\chi_i = \begin{cases} 1 & x_i \ge b \\ \dfrac{x_i-a}{b-a} & a < x_i < b \\ 0 & x_i \le a \end{cases} \tag{4}$$

Where χ_i is the relative degree of degradation of condition information index i; x_i is the actual value of condition information index; a is the good value of the condition information index i; b is the warning value of the condition information index i

C. The extension-based comprehensive evaluation of transformer

The general steps for extension evaluation are as follows:

1) Determination of classical field and section field

Classical field:

$$R_j = \left(N_j, C_i, V_{ji}\right) = \begin{bmatrix} N_j & c_1 & v_{j1} \\ & c_2 & v_{j2} \\ & \vdots & \vdots \\ & c_n & v_{jn} \end{bmatrix}$$

$$= \begin{bmatrix} N_j & c_1 & \langle a_{j1}, b_{j1} \rangle \\ & c_2 & \langle a_{j2}, b_{j2} \rangle \\ & \vdots & \vdots \\ & c_n & \langle a_{jn}, b_{jn} \rangle \end{bmatrix} \quad (5)$$

where, N_j presents the level j in the evaluation grading standards specified by the evaluation object; C_i is the features of evaluation object; V_{ji} is the range of value specified by the features C_i of the corresponding level N_j in the evaluation criteria, i.e. classical field.

Section field:

$$R_p = \left(p, C_i, V_{pi}\right) = \begin{bmatrix} p & c_1 & v_{p1} \\ & c_2 & v_{p2} \\ & \vdots & \vdots \\ & c_n & v_{pn} \end{bmatrix}$$

$$= \begin{bmatrix} p & c_1 & \langle a_{p1}, b_{p1} \rangle \\ & c_2 & \langle a_{p2}, b_{p2} \rangle \\ & \vdots & \vdots \\ & c_n & \langle a_{pn}, b_{pn} \rangle \end{bmatrix} \quad (6)$$

where, p presents all of the levels of evaluation objects; $\{V_{p1}, V_{p2}, \cdots, V_{pn}\}$ is the total range of values of P with respect to $\{c_1, c_2, \cdots, c_n\}$, i.e. the section field of p.

2) Determination of evaluation matter -element

$$R = \left(p_0, C, V\right) = \begin{bmatrix} p_0 & c_1 & v_1 \\ & c_2 & v_2 \\ & \vdots & \vdots \\ & c_n & v_n \end{bmatrix} \quad (7)$$

where, P is the object to be evaluated; v_i is the value of p with respect to c_i, i.e. the measured value of indices with respect to evaluation object.

3) Calculation of correlation function values.

$$K_j(v_i) = \begin{cases} \dfrac{\rho(v_i, v_{ji})}{\rho(v_i, v_{pi}) - \rho(v_i, v_{ji})} & v_i \notin v_{ji} \\ \dfrac{-\rho(v_i, v_{ji})}{\left|v_{ji}\right|} & v_i \in v_{ji} \end{cases} \quad (8)$$

where, $\rho(v_i, v_{ji})$ and K are the distance from v_i (the index i of a certain evaluation object) to interval v_{ji} and v_{pi}, respectively; $K_j(v_i)$ is the degree of correlation between the feature i and the level j. All of the indices under the project constitute the correlation matrix.

4) The degree of correlation of different levels is calculated according to the weight coefficient of each index.

$$K_j(p_0) = \sum_{i=0}^{n} \lambda_i K_j(v_i) \quad (9)$$

Thus the degree of correlation between the evaluation objects and each level is obtained, where λ_i is the weighting value of index c_i, and $\sum_{i=1}^{n} \lambda_i = 1$ 。

5) Determination of the level of evaluation objects

If $K_{j0}(P_k) = \max K_j(P_k)$, the evaluation object belongs to level j_0.

$\overline{K}_j(P_k) = \dfrac{K_j(P_k) - \min K_j(P_k)}{\max K_j(P_k) - \min K_j(P_k)}$ is set, then

$$j^* = \frac{\sum_{i=1}^{m} j\overline{K}_j(P_k)}{\sum_{i=1}^{m} \overline{K}_j(P_k)} \quad (10)$$

j^* is called as the characteristic value of level variable quantity for P_k, which is the further precise expression for the level of the evaluation object.

■ Analysis of examples

Example 1: There was a main transformer of 120MVA and 220KV with mode SFP7-120000/220. The on-line monitoring data in 2008 are as follows: the gas content in transformer oil: $H_2 = 57.0 \times 10^{-6}$, $C_2H_2 = 0.4 \times 10^{-6}$, $CH_4 = 28.0 \times 10^{-6}$, $C_2H_4 = 23.6 \times 10^{-6}$, $C_2H_6 = 9.1 \times 10^{-6}$; the calculated absolute gas production rate of total hydrocarbon gas was 3.7 mL/ d; the relative production rate of total hydrocarbon gas was 2.2%;absolute gas production rate of CO 31.2 mL/d; micro-water content in oil was 16.6mg / L; capacitor bushing dielectric loss was 0.37%; partial discharge capacity was142pC; iron core grounding current was 13mA.

First, the information of various transformer conditions was normalized. Next, the classical field of each condition index and the section field of index system were determined according to the definition of the relative degree of deterioration. At the same time, the weightings of each condition information index were calculated, as shown in Table 2. At last, according to the established model of matter-element, the comprehensive assessment results of the transformer were obtained with formulas (4) and (5), as shown in Table 3.

According to the maximum correlation principle, the transformer could be judged as in "good" condition. Next, the feature value for condition level variable quantity in this case was calculated according to Formula (6), and j=1.66 was obtained. It can be seen that the transformer was between the good and normal conditions and gradually changed toward the normal condition, but each condition value of the transformer was far different from the warning values set forth in "Transformer Pre-test Test Procedures".

Therefore, the possibility of failure was smaller, and it was in the most stable phase in the service cycle of the transformer, thus the maintenance cycle could be properly extended.

Table 2 Weightings of condition information indices

Name	Weighting	Index weightings under this project
Quantitative indices	0.6517	（0.5364，0.1000，0.1584，0.0860，0.1372）
qualitative indices	0.3483	（0.2194，0.1781，0.6025）
Oil chromatographic analysis	（0.1388，0.3154，0.2407，0.1943，0.1108）	

Table 3 Condition assessment results of transformer

Correlation	Condition matter-element	Quantitative index	qualitative index
Good	0.0119	-0.0805	0.1848
Normal	-0.0660	-0.0123	-0.1665
Warning	-0. 5138	-0.4399	-0.6520
Critical	-0.7096	-0.6706	-0.7825

The example analysis showed that the evaluation model could not only effectively and correctly assess the comprehensive condition of transformer with a specific index level given but also further reflect the deviation of the result and the size of deviation through the characteristics of level variable quantity

■ Conclusions

A comprehensive assessment model of transformer condition, which is combined with AHP and based on linear regression and extension theory, is presented in this study. The transformer condition is assessed comprehensively depending on various real-time status information obtained from the on-line monitoring of transformer. The correlation is used in this assessment method, by means of which, the degree of ownership of indicators to the matter element can be simply and effectively analyzed so that the incompatibility between the various indicators is solved. Meanwhile, the entire process of analysis and assessment is built based on the objective and rigorous theories with little influence of human factors. Therefore, the results of the evaluation method are excellent with good differentiation degrees and they provide a reasonable basis for decision-making of transformer condition maintenance

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