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Research on Transformer Condition-based Maintenance System using the Method of Fuzzy Comprehensive Evaluation

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***Abstract*—**This study adopted previous fault patterns, results of detection analysis, historical records and data, and experts' experiences to establish fuzzy principles and estimate the failure probability index of components of a power transformer. Considering that actual parameters and limiting conditions of parameters may differ, this study used the standard data of IEC, IEEE, and CIGRE as condition parameters. According to the characteristics of each condition parameter, relative degradation was introduced to reflect the degree of influence of the factors on the transformer condition. The method of fuzzy mathematics was adopted to determine the subordinate function of the transformer condition. The calculation used the Matlab Fuzzy Tool Box to select the condition parameters of coil winding, iron core, bushing, OLTC, insulating oil and other auxiliary components and factors (e.g., load records, performance history, and maintenance records) of the transformer to establish the fuzzy principles. Examples were presented to support the rationality and effectiveness of the evaluation method of power transformer performance conditions, as based on fuzzy comprehensive evaluation.

***Keywords*—**Fuzzy, relative degradation degree, condition-based maintenance, power transformer

I. INTRODUCTION

MODERN power systems have become increasingly complicated; hence, the reliability of power equipments is directly related to the safe operation of a power system. A large power transformer is one of the main equipments for power system operation. Once a power transformer breaks down, safe operation of the power system will be affected. An evaluation of the power transformer condition is one of the key contents in the condition-based maintenance (CBM) of power equipments. Previous studies have presented achievements in the CBM of transformers; however, most studies focus on electric testing and monitoring the detection analysis of gas dissolved in oil, and only use a single or a few parameters for CBM [1]–[3].

Ali Naderian proposed an effective method to illustrate the comprehensive relationship between the operating conditions of transformers and various tests, operating conditions, and historical equipment information [4]. The operating condition of a transformer is a direct reflection of its normal operating condition. If the transformer breaks down, the corresponding operation parameters will deviate from the normal values. In order to reflect the normal conditions of the transformer, the parameters or results of parameters processing, which can reflect the transformer condition, must be used as the indices to evaluate the transformer condition. Moreover, it is also important to use the effective information in the detection results to evaluate and identify normal conditions of the transformer.

This study aimed to establish evaluation indices of comprehensive factors by adopting the fuzzy theory, and create failure probability indices of transformer components, as based on fuzzy comprehensive evaluation. The normal conditions of a transformer are evaluated by the comprehensive failure probability indices of the components. With this diagnostic system model, the CBM evaluation of a transformer can be realized.

II. BASIC PRINCIPLES AND PROCEDURES OF FUZZY COMPREHENSIVE EVALUATION

Fuzzy comprehensive evaluation refers to the decision-making or comprehensive evaluation of an object or phenomenon, which is affected by multiple factors. It is easy to conduct an evaluation or decision of a certain object or phenomenon if only a single factor is taken into consideration. However, in actual practice, multiple factors should be considered and identified in the evaluation process. As it is difficult to make a decision by applying an ordinary mathematic method, fuzzy comprehensive evaluation of fuzzy mathematics is able to handle the issues of making decisions or evaluations with multiple factors. It is an evaluation method based on existing evaluation standards and fuzzy conversion of the actual measured data or estimated data. Compared to other methods, it is a comprehensive, objective, and integrated method for results evaluation. [5] , [6].

The procedures of fuzzy comprehensive evaluation are as follows: [7]

1) Determine the factors set of the evaluated object: factors sets are composed of the elements of various factors that can affect the evaluated object, and is denoted by U, that is, $U=\{u_1,u_2,\ldots u_n\}$. Each element u_i denotes the corresponding influencing factor. These factors usually have certain degree of fuzziness.
2) Create the comments set: comments sets are composed of the elements of various comprehensive evaluation results of the evaluated object, as set by the evaluators. It is

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denoted by V, that is, V $=\{v_1,v_2,\ldots v_n\}$. Each element denotes the corresponding possible comprehensive evaluation result.

3) Comprehensive evaluation matrix: create a fuzzy mapping from u_i to f(vi). Fuzzy relationship R is determined by f(vi) to obtain the fuzzy evaluation matrix R.
4) Evaluation factors weights shall be created: in order to reflect the significance of each evaluation factor, each factor u_i has a weight, which is represented by a fuzzy subset of U, that is, W= $(w_1,w_2,\ldots w_n)$ $\sum_{i=1}^{n}$ wi =1.
5) Fuzzy comprehensive evaluation: equation of fuzzy comprehensive evaluation is B=W&R. In this equation, & denotes a certain compound calculation with many alternatives. A comprehensive evaluation of weighted average type, denoted by M(+ , □) . in this paper, that is, $b_j = \sum_{i=1}^{m} w_i \; r_{ij}$ (j =1,2, n). B is the fuzzy comprehensive evaluation set. bj (j =1,2, … n). are the fuzzy comprehensive evaluation indices.

III. FUZZY COMPREHENSIVE EVALUATION OF TRANSFORMER FAULTS

In order to make a relatively comprehensive and correct evaluation of the normal operating conditions of a power transformer, characteristic quantities that can reflect transformer conditions are obtained. In general, the life expectancy model of a transformer cannot be directly obtained. The present condition of the equipment is indirectly obtained by analyzing the phenomena occurring during equipment operational processes, or measuring the parameters that can reflect equipment conditions. Quantity of conditions can be obtained by electric testing, non-electric testing, historical operation data, and records of abnormal operations. This parameters calculation considers typical test results such as dissolved gas analysis (DGA), oil quality, furan, bushing condition, physical observations, load history, maintenance work orders, power factor, tap changer and age.

IV. SELECT CONDITION EVALUATION FACTORS

By adopting fuzzy comprehensive evaluation, the subjective arbitration in fault evaluation can be overcome. Each factor affecting the fault can be comprehensively demonstrated to make the evaluation result more rational. In order to obtain comprehensive evaluation factors and authentically reflect the operating condition of a transformer, upon considerations of the feasibility of transformer condition evaluation, condition parameters are selected from each transformer component, including coil winding, iron core, bushing, OLTC, insulating oil, other accessories, and other factors. The evaluation system architecture of transformer conditions is shown in Fig. 1.

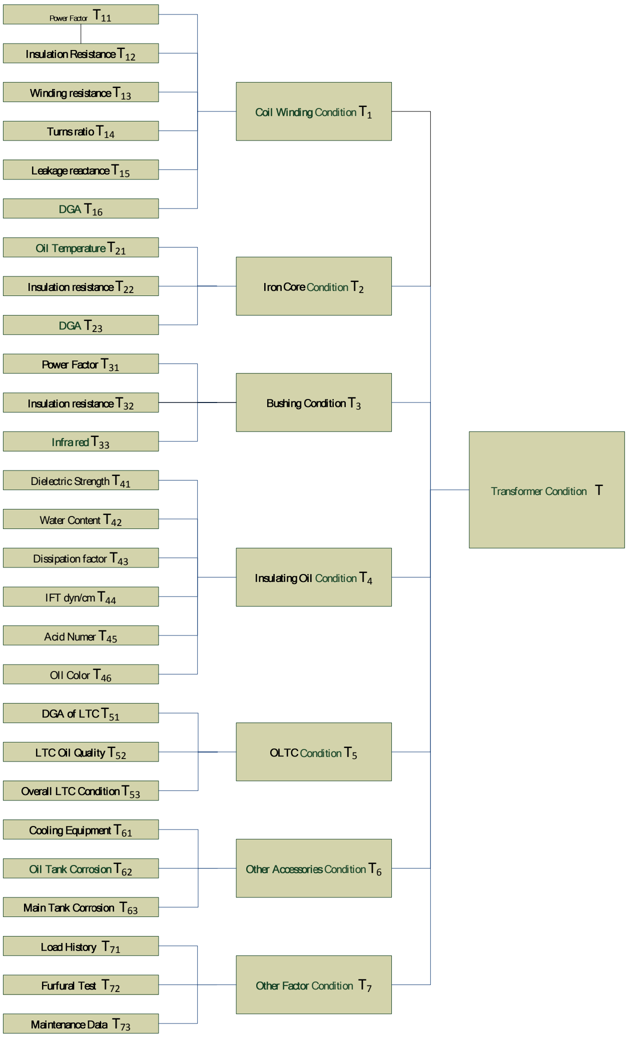

Fig.1 transformer conditions

V. ESTABLISH A COMMENTS SET

After the evaluation factors of a transformer are determined, transformer conditions are classified in order to establish the comments set of each factor for fuzzy comprehensive evaluation. The transformer conditions are classified as good, acceptable, need caution, and poor in this paper, which are expressed as V={good, acceptable, need caution, poor} = {v1 , v2 , v3 , v4}. A good condition means that the test data of transformer operations are normal, and each quantity of condition deviates significantly from the regulated attention value. Fault occurrence probability is low and long term operation is available. An acceptable condition means that the transformer has been operated for a certain time, and the test data are normal or the reliability of certain individual quantity of a condition is slightly reduced. As the data are reliable, its operation can be continued and fault probability is low. A need caution condition means that during the test period, the test data deviate from the normal condition. Some quantities of condition reflect that abnormal phenomenon may exist in the transformer, thus, the probability of fault occurrence is increased, and though the transformer can continue to operate, the maintenance period should be shortened. A poor condition means that the overall operation properties of the transformer are below average. Most of the quantities of conditions obtained by testing and detection exceed the standards, and the probability of fault occurrence is high. A normal condition can be recovered through maintenance. Maintenance with power cuts can be considered to meet the demands of power system operations.

VI. DETERMINE THE SUBORDINATE FUNCTION OF EVALUATION FACTORS

A. Relative degradation degree

The concept of relative degradation is introduced to represent the relative degradation degree between the current transformer condition and the fault condition [8]. It is a quantified index with a value range of “0 to 1”. According to different values, degradation degrees of index conditions can be shown.

For a higher index values, indices such as the insulation resistance are better. The calculation of the index is as follows (1).

$$\mathbf{I_i} = \left[\frac{\mathbf{x_i - x_{min}}}{\mathbf{x_o - x_{min}}}\right]^{\mathbf{k}} \qquad (1)$$

For a lower index value, indices such as the dielectric dissipation are better. The calculation of the index is as follows (2).

$$\mathbf{I_i} = \left[\frac{\mathbf{x_i - x_o}}{\mathbf{x_{max} - x_o}}\right]^{\mathbf{k}} \qquad (2)$$

In the equation: Ii denotes the relative degradation of the i condition index; Xo denotes the allowable value of this index (value of good condition); Xmax or Xmin denotes the limit value of the index; Xi denotes the actual measured value; k denotes the degree of effect of parameter change on equipment condition, and is determined with the value of 1 in this paper.

B. Determine the subordinate function of test index

There are many methods for determining the subordinate function; however, there is no uniform pattern. The common method is the fuzzy distribution method. According to the characteristics of the problems, the existing fuzzy distribution of a certain pattern, and the measured data, the parameters in the distribution can be determined. The subordinate functions can have different shapes, such as triangle or ladder-shaped. As the subordinate function of a triangle has a simple shape and is easy to calculate, and the obtained result has little difference compared to that of other complex subordinate functions, it is widely adopted. This study adopted the triangle distribution function to determine the subordination degree. The subordinate function of each evaluation factor is established according to the standards of the hierarchical system. The subordinate functions distribution is shown in Fig. 2.

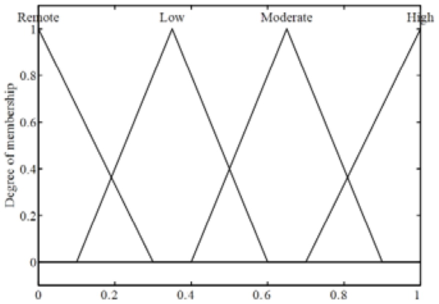

Fig.2 subordinate functions distribution

To determine the subordinate functions of the evaluation factors, the parameters are converted into functions within a range from “0 to 1”. The triangle distribution function is then used to determine the subordination degree. Therefore, the concept of relative degradation is introduced. By calculating the relative degradation degree of evaluation factors, parameters are converted into the functions within a range from “0 to 1”. Finally, the subordination degree of the relative degradation of the four operating conditions in the comments set is calculated. The representation of the relationship between the relative degradation and the transformer operating condition can serve as reference to the semantic definition of the relative degradation degree, as shown in Table I .

TABLE I
SEMANTIC DEFINITION OF RELATIVE DEGRADATION

Numeric area of degradation	Semantic description of transformer condition
0~0.25	The equipment is in good condition and can continue to operate.
0.25~0.5	A low degradation. The equipment is in normal operating condition.
0.5~0.75	A medium degradation. Slight faults occur, observation and detection should be enhanced.
0.75~1.0	The condition has shifted from the degradation condition to the fault condition. Serious faults have occurred.

C. Setting subordinate functions of electric test indices

By relative degradation, the data of electric testing are converted into a numerical value within the range of “0 to 1”, which can represent each input parameter. The input parameters of failure occurrence are described as Good, Acceptable, Need Caution, and Poor. The input values of parameters, fuzzy language definitions, and membership functions are as shown in Table II、Table III、 Table IV and Fig. 3. Subordinate functions of all evaluation factors can be obtained, which will not be detailed here. The output numerical value of each fuzzy estimation, fuzzy language definition, and membership function are as shown in Table V. The present membership function is roughly set and will be revised and adjusted according to future practices and experiences to make the membership function more perfect and objective. [Max-min synthesis] of Mamdani fuzzy model is adopted in this paper for fuzzy estimation [9]–[11].

TABLE II
THE MEMBERSHIP GRADE FUNCTION TABLE OF TURN RATIO DEVIATION AND INSULATING RESISTANCE [12]

Factor / Condition	Turn ratio (TR) deviation of actual to declared [%]	insulating resistance
Good	□TR□0.1%	R > 1000MΩ
Acceptable	0.1% < □TR □0.5%	100 MΩ□R < 1000 MΩ
Need Caution	0.5% < □TR □1%	10 MΩ□R < 100 MΩ
Poor	1% < □TR < 2%	1 MΩ□R < 10 MΩ

TABLE III
THE MEMBERSHIP GRADE FUNCTION TABLE OF WINDING RESISTANCE DEVIATION AND LEAKAGE REACTANCE DEVIATION[12]

Factor / Condition	Winding resistance deviation [%]	Leakage reactance deviation [%]
Good	□R < 1%	□X < 0.5%
Acceptable	1%□□R < 2%	0.5%□□X < 1%
Need Caution	2%□□R < 3%	1%□□X < 2%
Poor	3%□□R < 5%	2%□□X < 3%

TABLE IV
THE MEMBERSHIP GRADE FUNCTION TABLE OF MAXIMUM POWER FACTOR[13]

Factor / Condition	Maximum Power Factor [%]
Good	Maximum Power Factor < 0.5
Acceptable	0.5□Maximum Power Factor < 0.7
Need Caution	0.7□Maximum Power Factor < 1
Poor	1□Maximum Power Factor < 2

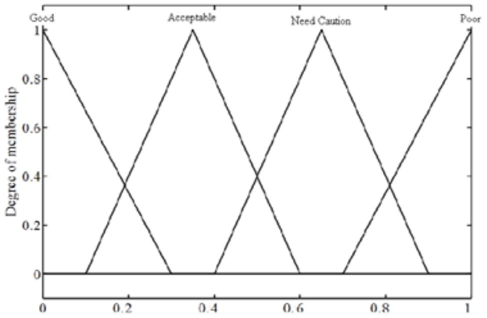

Fig. 3 Membership function figure of fuzzy estimation input

TABLE V
COMPONENT FUZZY ESTIMATION OF OUTPUT SUBORDINATE FUNCTION EXPLANATION

Degree	Explanation	Range
Remote	Normal component function	0 ~ 0.3
Low	Low failure risk of component function	0.1 ~ 0.6
Moderate	Moderate failure risk of component function	0.4 ~ 0. 9
High	High failure risk of component function	0.7 ~ 1.0

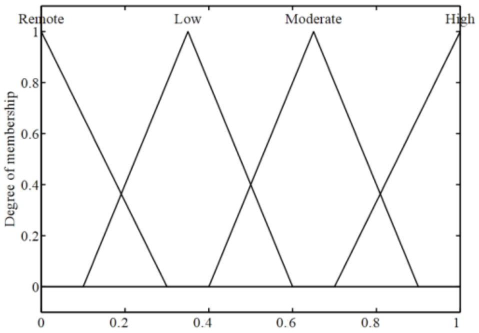

Fig. 4 Membership function figure of fuzzy estimation output

VII. ESTABLISH ESTIMATION FACTORS WEIGHTS

The sources of transformer faults and failures are various, and the probable effect degrees of faults are different, therefore, each factor has different weight. The weights of the probable factors of fault are determined by the expert investigation method, which is a widely used method. The detailed procedures are as follows: experts with relevant experiences grade each element in U= {u1,u2,…un}. with the weight vector Wj=(wj1,wj2,wj3 …wjn) j=1,2,…,m, respectively, according to which they regard as most appropriate. The number of experts is m. Each weight vector is in accordance with the following equation (3):

$$\sum_{j=1}^{m} W_{ji} = 1 \tag{3}$$

A grade matrix can be obtained by normalizing conditions. The following equation (4) can be adopted for the calculation of weights for each factor.

$$W_i = \frac{\sum_{j=1}^{m} W_{ji}}{\sum_{j=1}^{m}\sum_{i=1}^{n} W_{ji}} \tag{4}$$

Weights set is $W=(w_1, w_2, \dots, w_n)$ weight of the sources of transformer component fault and failure, as determined by expert investigation. There are 7 sources of transformer component fault modes, which are $U=\{u_1,u_2,\dots u_7\}$={ coil winding, iron core, bushing, OLTC, insulating oil, other accessories, other factors}, respectively. Their corresponding weights set is $W=(w_1, w_2, \dots, w_7)$, for example, according to the opinions of three experts and the significance of each factor. The following grade matrix of A(7×3) can be established.

$$A = \begin{bmatrix} 0.23 & 0.1 & 0.12 & 0.13 & 0.22 & 0.1 & 0.1 \\ 0.21 & 0.05 & 0.09 & 0.15 & 0.24 & 0.11 & 0.15 \\ 0.25 & 0.09 & 0.09 & 0.17 & 0.17 & 0.06 & 0.17 \end{bmatrix}$$

According to the above equation, weight vector W= (0.23, 0.08, 0.1, 0.15, 0.21, 0.09, 0.14) can be obtained and taken as the weight ratio of the sources of a transformer's component failure models.

VIII. EXAMPLE OF FAILURE PROBABILITY ESTIMATION OF TRANSFORMER'S COMPONENT

This study aimed to establish evaluation indices of comprehensive factors by adopting the fuzzy theory, and create failure probability indices of transformer components, as based on fuzzy comprehensive evaluation. The normal conditions of a transformer are evaluated by the comprehensive failure probability indices of the components. Example of failure probability estimation of transformer's component is shown in Table VI and Fig.5

TABLE VI
EXAMPLE OF FAILURE PROBABILITY ESTIMATION OF TRANSFORMER'S COMPONENT

transformer's component	input parameter	failure probability indices (%)	weights	The weighting is calculated
Coil Winding	$T_{11}=0.2$ $T_{12}=0.25$ $T_{13}=0.25$ $T_{14}=0.2$ $T_{15}=0.3$ $T_{16}=0.2$	30.03%	0.23	6.91%
Iron Core	$T_{21}=0.2$ $T_{22}=0.25$ $T_{23}=0.2$	28.45%	0.08	2.28.%
Bushing	$T_{31}=0.2$ $T_{32}=0.25$ $T_{33}=0.3$	31.62%	0.1	3.162%
Insulating Oil	$T_{41}=0.5$ $T_{42}=0.6$ $T_{43}=0.5$ $T_{44}=0.7$ $T_{45}=0.5$ $T_{46}=0.6$	65%	0.15	9.75%
OLTC	$T_{51}=0.3$ $T_{52}=0.15$ $T_{53}=0.2$	28.45%	0.21	5.975%
Other Components	$T_{61}=0.2$ $T_{62}=0.15$ $T_{63}=0.1$	23.6%	0.09	2.124%
Other Factors	$T_{71}=0.3$ $T_{72}=0.4$ $T_{73}=0.25$	35%	0.14	4.9%
The comprehensive failure probability indices of the transformer(%)	35.09%			

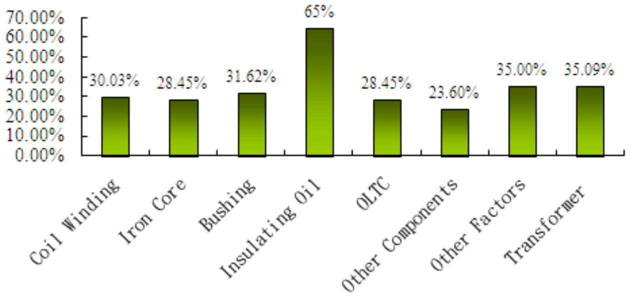

Fig. 5 failure probability indices of transformer

IX. CONCLUSION

The primary analysis of the example found that, the fuzzy evaluation model can obtain correct and objective qualitative estimations of transformer conditions, determine the normal conditions of components of a transformer, and arrange maintenance methods according to the failure index of components. The findings can serve as reference for the CBM of a transformer.

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