Comprehensive Assessment of Transformer Insulation Condition Based on Extension Theory

Qunjing Chen*, Jinding Cai, Rong Ye
College of Electrical Engineering and Automation, Fuzhou University, Fuzhou, Fujian, 350108, China.
*e-mail: 1324225473@qq.com

Abstract. Due to the fuzziness and uncertainty of the transformer’s insulation state by itself, when using the index to evaluate the insulation of oil paper transformers alone, the insulation state of transformers may appear contradictory and incompatible situations. This paper establishes evaluation models of extension theory to comprehensively evaluate the state of the oil-paper insulation transformers. Firstly, it establishes multilevel framework of the transformer and determines the weight coefficient of each index by means of extensive AHP; Then, this paper establishes the classical domain and joint domain of transformer’s four kinds of matter-element models using large amounts of the measured data; Finally, using correlation function to determine the insulation state of transformers to be evaluated, this paper realizes the synthetic evaluation with the qualitative and quantitative combination for the transformer. The validity and feasibility of the method are proved by the example in this paper.

1. Introduction
Time-domain dielectric response method is a non-destructive diagnosis method. It has been widely used in transformer insulation state assessment in recent years because of its rich information, strong anti-interference, no need for hanging core and easy operation. The oil-paper transformer is a complex system which is composed of the insulating paper and the insulating oil[1]. There are many characteristics that can reflect the insulation condition of transformers but those characteristics have great fuzziness and uncertainty. It is difficult to accurately reflect the insulation state of the transformer by a single characteristic variable. Therefore, the multi-time domain characteristic variable can be used to accurately evaluate the insulation state of the transformer by means of mathematical theory. At present, the commonly used evaluation methods of the transformer insulation are cloud theory, fuzzy analysis, gray target theory, gray analytic hierarchy process, Bayesian network, rough set and evidence theory etc. Although these methods can reflect the insulation condition of the transformer to a certain extent, they are difficult to be widely used because of the large amount of calculation and the complicated calculation process. Chen Hancheng points out that the state evaluation of the transformer is a multi-attribute decision-making problem, and evidence theory is applied to the comprehensive evaluation of transformers[2]; Liao Ruijin uses fuzzy mathematics to evaluate the state of transformer, but the determination of membership function has great subjective factors[3]; Huang Wentao uses gray correlation method to diagnose the insulation of power transformers[4]. However, the influence of redundant characteristics on the insulation state of transformers is not fully considered.

In view of the deficiencies of transformer insulation status diagnosis, this paper presents a comprehensive evaluation of transformer insulation states based on extension theory, which can
integrate multi-time domain characteristics and simplify the calculation process. Firstly, a hierarchical multi-level frame model is built according to the characteristic quantities which can reflect the insulation state, and the weight coefficients of each layer index of the transformer are determined by the extension analytic hierarchy process. Then, based on a large number of measured data and the results of calculation and analysis, the classical domain and joint domain of the four insulation states of the transformer are determined; finally, the value of the correlation function about the four insulation states of the transformer to be diagnosed is determined by the correlation function, thereby the insulation state of the transformer to be diagnosed is determined.

2. Extension theory
Extension theory is based on matter-element theory and extension theory as the theoretical framework. It calculates the correlation values of matter-element about each evaluation state level by means of the basic concepts of classical domain, joint domain, correlation function, and extension AHP. Next, we introduce the basic concept of matter-element, classical domain, joint domain, correlation function and extension analytic hierarchy process [6] respectively.

2.1 Matter element
For a given name N, characteristic c, and the corresponding quantity v, an ordered ternary \( R = (N, c, v) \) can be formed as the basic element to describe objects, which are called matter element for short. Among them, v is determined by N and C, and is written as \( v = c(N) \). For a certain object, there are multiple characteristic quantity \( c_1, c_2, \ldots, c_n \) and its corresponding value \( v_1, v_2, \ldots, v_n \), its matter element model is expressed as:

\[
R = \begin{pmatrix}
N & c_1 & v_1 \\
& c_2 & v_2 \\
& \cdots & \cdots \\
& c_n & v_n \\
\end{pmatrix}
\]

(1)

2.2 classical domains and joint domain of matter element
The matter-element state is divided into \( N_1, N_2, \ldots, N_m \). For a matter-element characteristic variable \( c_i \), under certain conditions, the majority of its values fall on the interval \( [\mu_{ij} - 3\sigma_{ij} \leq v_{ij} \leq \mu_{ij} + 3\sigma_{ij}] \), so the classical domain matrix \( R_p \) of matter-element in each state level is determined as follows:

\[
R_p = \begin{pmatrix}
N & N_1 & N_2 & \cdots & N_j & \cdots & N_m \\
c_1 & v_{p11} & v_{p12} & \cdots & v_{p1j} & \cdots & v_{p1m} \\
c_2 & v_{p21} & v_{p22} & \cdots & v_{p2j} & \cdots & v_{p2m} \\
\vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
c_i & v_{pi1} & v_{pi2} & \cdots & v_{pij} & \cdots & v_{pin} \\
\vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
c_n & v_{p11} & v_{p12} & \cdots & v_{pnj} & \cdots & v_{pnm} \\
\end{pmatrix}
\]

(2)

In formula (2), \( v_{p1j} (i=1,2,\ldots,N, j=1,2,\ldots,M) \) denotes the classical domain of the characteristic variable \( C_i \) under the state \( j \); \( v_{p1j} = [\mu_{ij} - 3\sigma_{ij} \leq v_{ij} \leq \mu_{ij} + 3\sigma_{ij}] \), where \( \mu_{ij} \) and \( \sigma_{ij} \) can be obtained from formula (3).

\[
\begin{align*}
\mu_{ij} &= \left( \sum_{k=1}^{N_j} v_{ijk} / t_j \right) \\
\sigma_{ij} &= \sqrt{\frac{1}{t_j} \sum_{k=1}^{N_j} (v_{ik} - \mu_{ij})^2}
\end{align*}
\]

(3)

\( \mu_{ij} \) and \( \sigma_{ij} \) represent the average and standard deviation of the characteristic variable \( C_i \) in the state \( j \) respectively, \( t_j \) is the number of samples whose matter-element state level is \( N_j \).

The joint domain matrix \( R_q \) of each state matter element is determined as follows:
In formula (4), \( v_{qij} (i=1, 2, ..., N, j=1, 2, ..., M) \) represents the joint domain of matter-element feature \( c_i \) in the state \( j \) under the sample data: \( v_{qij} = \langle v_{ijmin}, v_{ijmax} \rangle \). \( v_{ijmin} \) represents the minimum of \( v_{ij} \), \( v_{ijmax} \) represents the maximum of \( v_{ij} \).

### 2.3 Correlation function

The correlation function is used to determine the correlation degree between each condition level and the matter to be evaluated. If the correlation value \( K \) is larger, it suggests that the matter element under test is more likely to be correlated with the certain state level. The correlation function \( K \) is defined as follows:

\[
K = \begin{cases} 
\rho(v_i, v_{pij}) & \rho(v_i, v_{qij}) \neq \rho(v_i, v_{p+ij}) \\
-\rho(v_i, v_{p-ij}) - 1 & \rho(v_i, v_{qij}) = \rho(v_i, v_{p+ij})
\end{cases}
\]

(5)

In the formula (5), \( v_i \) represents the characteristic variable. \( v_{pij} \) is the classical domain; \( v_{qij} \) is the joint domain; and \( \rho(v_i, v_{pij}) \) is the distance of point \( v_i \) about the interval \( v_{pij} = \langle v_{pij1}, v_{pij2} \rangle \) and can be calculated as follows:

\[
\rho(v_i, v_{pij}) = \left| v_i - \frac{(v_{pij1} + v_{pij2})}{2} \right| - \frac{(v_{pij2} - v_{pij1})}{2}
\]

(6)

### 2.4 Extension analytic hierarchy process

In this paper, multi-index is introduced to evaluate the transformer comprehensively, and different indexes play different roles in evaluating the aging state of the transformer. According to the relative importance of each index, it is very important to assign different weights to each index for accurately evaluating the insulation state of the transformer. In this paper, the analytic hierarchy process (AHP) is used to determine the weight of each index of the transformer [7]. The weights of indicators are determined as follows:

The extension judgment matrix is constructed. In the extension judgment matrix \( E = (e_{ij})_{n \times n} \), \( e_{ij} \) needs to satisfy the following conditions, for all \( i,j=1, 2, ..., N \), \( e_{ij} = \langle e_i, e_j \rangle, 1/9 \leq e_{ij} \leq 9 \); \( e_{i1} = 1, e_{ji} = e_{ij}^{-1} = \langle 1/e_i, 1/e_j \rangle, (i,j) = (1,2, ..., n) \).

The steps to satisfy the consistency requirement are as follows:

1) The corresponding eigenvector of the maximum eigenvalues of the left judgment matrix \( E^- = (e_{ij})_{n \times n} \) and the right judgment matrix \( E^+ = (e_{ij}^+)_{n \times n} \) are obtained and normalized to obtain \( X^- = (a^-_i)_{n \times n}, X^+ = (a^+_i)_{n \times n} \).

2) \( \lambda = (\lambda_1, \lambda_2, ..., \lambda_n)^T = rX, sX^+ \) is obtained, where \( r \) and \( s \) are calculated by formula (4).

\[
\begin{align*}
    r &= \sqrt{\sum_{j=1}^{n} 1 / \sum_{i=1}^{n} a_{ij}} \\
    s &= \sqrt{\sum_{j=1}^{n} 1 / \sum_{i=1}^{n} a_{ij}^+}
\end{align*}
\]

(7)

3) the weight of each index is calculated through \( \lambda \).
We can suppose the two interval numbers $e=\langle e^-, e^+ \rangle$, $f=\langle f^-, f^+ \rangle$, then:

$$V(e \geq f) = \frac{2(e^--f^-)}{(e^- - e^+)(f^- - f^+)}$$

(8)

Through the formula (8), we can calculate the following formula:

$$V(\lambda_i \geq \lambda_j) (i = 1, 2, ..., n; \ i \neq j)$$

(9)

If $V(\lambda_i \geq \lambda_j) \geq 0 \ (i=1, 2, ..., n; \ i \neq j)$, then $\omega_j = 1$, $\omega_i = V(\lambda_i \geq \lambda_j)$, ($i = 1, 2, ..., n; \ i \neq j$), $\omega_i$ represents the weight coefficients of each index.

3. Application of extension theory in condition assessment of transformer oil paper insulation

3.1. Establishment of extension evaluation index system for transformers

![Analytic hierarchy diagram of transformer’s evaluation index](image)

Due to the different dimensions of each index, the parameters need to be dimensionless. For the different properties of the indexes in the evaluation index system, formula (10) is used for the maximal index (the bigger the better), formula (11) is used for the miniature index (the smaller the better) [8]-[9].

$$v_i = \frac{v'_i - v'_{i-min}}{v'_{i-max} - v'_{i-min}}$$

(10)

$$v_i = \frac{v'_{i-max} - v'_i}{v'_{i-max} - v'_{i-min}}$$

(11)

3.2. The determination for classical domain matter-element model and joint domain matter-element model of transformer state levels.

We can suppose the insulation state of the transformer is matter element $N$. According to the "Preventive Test Rules for Electric Power Equipment", the transformer insulation state can be divided into four states, $N_1$ means good insulation state, $N_2$ means medium insulation state, $N_3$ means slight aging of insulation, $N_4$ means serious aging of insulation [5]. Then we can determine the classical domain and joint domain of transformers by means of formula(2) and formula(4). The classical domain matrix and joint matrix of each insulation state of transformer are obtained as follows:

$$R_p = \begin{bmatrix}$$

$$R_q = \begin{bmatrix}$$

3.3 establishment for the weights of transformers.

we can obtain the extension interval judgement matrix of the transformer when we consider the experts’ suggestions.
From the extension judgment matrix given by the above experts and the section 2.4, the weights can be obtained as follows: the weights of the first level index are $\omega_1=(0.5772,0.0372,0.3856)$. The weights of each index of the recovery voltage are $\omega_{21}=(0.2599,0.4471,0.2779,0.0152)$. The weights of each index of the Debye model are $\omega_{22}=(0.0829,0.9171)$, the weights of depolarization current are $\omega_{23}=(0.0415,0.9585)$.

In summary, the steps of transformer extension evaluation method are:

A. the classical domain, joint domain and matter element model are determined.
B. extension hierarchy analytic methods is established to determine the weights of each characteristic variable.
C. the correlation values of each characteristic variable with the insulation state levels are calculated.
D. the weight coefficient is combined to determine the correlation degree of the matter-element on each state levels.

$$K_j(N) = \sum_{i=1}^{8} w_i \times K_i(v_j)$$ (12)

In the formula(12), $K_j(N)$ is a comprehensive value considering the weights and it represents the correlation values between the matter element to be evaluated and each state levels. Then, we can choose the maximal values of $K_j(N)$ ($j=1, 2, 3, 4$), and the insulation state of transformer is $N_j$.

4. Example

Nearly 60 transformers were measured by RVM5461 tester. Based on the measured and analyzed statistics of transformers, this paper extracts eight characteristic variables $U_{rmax}$, $t_{cdom}$, $S_r$, $t_{peak}$, $R_g$, $N$, $W_{rmax}$, $t_{rmax}$ which can well reflect the insulation state of transformers. Because of the space limitation, only ten transformers were listed in this paper. The characteristic values are shown in table 1.

| No. | $U_{rmax}/v$ | $t_{cdom}/s$ | $S_r/(v\cdot s^{-1})$ | $t_{peak}/s$ | $R_g/G\Omega$ | $N$ | $W_{rmax}/J$ | $t_{rmax}/s$ | Service years | Insulation condition |
|-----|-------------|-------------|----------------|-------------|--------------|-----|-------------|-------------|---------------|-------------------|
| T1  | 397.9       | 895.3       | 98.5           | 312.0       | 9.56         | 7   | 0.198       | 45.6        | 16            | severely damp and aging |
| T2  | 190.3       | 2226        | 40.7           | 403.4       | 14.2         | 4   | 0.124       | 168.5       | 7             | slightly aging |
| T3  | 269.3       | 1135        | 111            | 401.6       | 5.68         | 6   | 0.156       | 171.1       | 9             | Have aged in the lower voltage side |
| T4  | 172.9       | 2436        | 30.6           | 246.3       | 20.7         | 4   | 0.054       | 192.6       | 4             | Good insulation condition |
| T5  | 387.5       | 902.5       | 189            | 651.2       | 8.79         | 7   | 0.197       | 42.8        | 15            | severely aging |
| T6  | 257.5       | 1057        | 98.6           | 389.4       | 6.87         | 5   | 0.098       | 124.5       | 3             | Have aged in the lower voltage side |
| T7  | 598.3       | 849.5       | 114            | 346.5       | 8.96         | 7   | 0.198       | 42.2        | 11            | severely damp and aging |
| T8  | 162.5       | 2578        | 85.4           | 546.2       | 20.8         | 4   | 0.076       | 204.3       | 2             | Good insulation condition |
| T9  | 409.6       | 865.2       | 169            | 298.7       | 15.6         | 7   | 0.168       | 42.7        | 14            | severely aging |
| T10 | 276.4       | 1242        | 189            | 410.5       | 20.8         | 6   | 0.087       | 115.6       | 2             | Have aged in the higher voltage side |
The formula (5) and (12) is used to calculate the correlation degree. The correlation values of each state level of ten transformers are shown in the table 2.

Table 2: the correlation degree of ten transformers on each state level

| correlation degree | T1  | T2  | T3  | T4  | T5  | T6  | T7  | T8  | T9  | T10 |
|-------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| N1                | -6.38 | -0.99 | -5.22 | -0.33 | -7.98 | -4.40 | -8.20 | 0.68 | -3.42 | -5.14 |
| N2                | -11.9 | -1.22 | 0.18 | -1.76 | -17.34 | 36.3 | -15.04 | -1.65 | -16.66 | 28.4 |
| N3                | -0.16 | -0.69 | -0.65 | -1.29 | -0.83 | 0.11 | -1.91 | -0.39 | -1.04 | -0.63 |
| N4                | 0.95  | -19.7 | -11.24 | -23.4 | 0.86  | -6.95 | -0.33 | -24.6 | -0.11 | -7.6  |

Table 2 shows that the diagnostic insulation state of 10 transformers are basically consistent with the actual insulation condition. Take transformers T1 and T2 as examples to illustrate the diagnostic results. The correlation values of the transformer T1 with four insulation states (N1, N2, N3, N4) are -6.3841, -11.946, -0.168 and 0.9489 respectively. The maximal value is 0.9489, that is, the corresponding state is "serious aging of insulation" (N4), and the diagnostic results are the same as the actual state. In addition, the maximal correlation value of transformer T2 is -0.6935, that is, the corresponding insulation state is "slightly aging insulation" (N3), which is consistent with the actual situation. Due to the limitation of space, the diagnostic results of other transformers will not be covered here.

5. conclusion

This paper applies the extension theory to evaluate the insulation states of oil-paper transformer and gets the following conclusions.

1) Considering the suggestions of many experts, this paper uses the Extension AHP to construct the extension judgment interval and effectively assign the weights to each parameter of the transformer. This paper combines the calculation of the weight vector with the consistency test organically, which can greatly reduce the traditional AHP verification.

2) Matter-element model and correlation function are introduced into the process of transformer insulation state evaluations. The transformer insulation state levels can be calculated quantitatively and multi-feature quantities can be fused to evaluate. Compared with single feature quantity, the method has higher accuracy.

3) The paper applies the theory of normal distribution in probability theory to the process of calculating the classical domain and joint domain and the historical reference database can be used to the greatest extent.

References

[1] SONG, R.J., LIU R.Y. (2017) Application of Grey Fixed Weight Clustering and Variable Weight Model in Transformer Condition Evaluation. Advanced Technology of Electrical Engineering and Energy, 36: 75-80.

[2] CHEN, H.C., CAI J.D. (2017) Synthetic insulation state evaluation based on multiple time-domain characteristic parameters for transformer oil-paper. Electric Power Automation Equipment, 37: 184-190.

[3] LIAO, R. J., WANG Q., LUO S.J., et al. (2008) Condition assessment model for power transformer in service based on fuzzy synthetic evaluation. Automation of Electric Power Systems, 32: 70-75.

[4] HUANG, W.T., ZHAO X.Z., WANG W.J., et al. (2004) Extension Diagnosis Method of Power Transformer Faults Based on Matter-element Model. Automation of Electric Power System, 28: 45-49.

[5] CAI, J.D., HUANG Y.C. (2015) Study on insulation aging of power transformer based on
gray relational diagnostic model. High Voltage Engineering, 41: 3296-3301.

[6] ZOU, Y., CAI J.D. (2015) Experimental analysis on time domain polarization spectrum of oil-paper insulation transformer. Transactions of China Electrotechnical Society, 30: 307-313.

[7] MA, L.Y., DING R.R., LU Z.G., et al. (2016) Comprehensive Evaluation and Sensitivity Analysis for Economic Operation of Distribution Network Based on Extension Cloud Theory. Advanced Technology of Electrical Engineering and Energy, 35: 8-16.

[8] YANG, G.J., JIANG C.H., GUI W.H., et al. (2015) Fuzzy synthesis evaluation method for position state of blast furnace cohesive zone based on entropy weight extension theory. Acta Automatica Sinica, 41: 75-83.

[9] LIAO, R.J., Zhang Y.Y., HUANG F.L., et al. (2012) Power Transformer Condition Assessment Strategy Using Matter Element Analysis. High Voltage Engineering, 38: 521-526.