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Comprehensive Assessment of Transformer Insulation Condition Based on Extension Theory

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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,... ,c_n and its corresponding value v_1, v_2,..., v_n, its matter element model is expressed as:

$$R=\begin{pmatrix} N & c_1 & v_1 \\ & c_2 & v_2 \\ & \cdots & \cdots \\ & c_n & v_n \end{pmatrix} \tag{1}$$

2.2 classical domains and joint domain of matter element

The matter-element state is divided into N_1, N_2, ..., N_m. For a matter-element characteristic variable c_i, under certain conditions, the majority of its values fall on the interval [μ_{ij}-3σ_{ij}≤v_{ij}≤μ_{ij}-3σ_{ij}], so the classical domain matrix R_p of matter-element in each state level is determined as follows:

$$R_{\mathrm{p}}=\begin{pmatrix} N & N_1 & N_2 & \cdots & N_j & \cdots & N_m \\ c_1 & v_{p11} & v_{p12} & \cdots & v_{p1j} & \cdots & v_{p1m} \\ c_2 & v_{p21} & v_{p22} & \cdots & v_{p2j} & \cdots & v_{p2m} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ c_i & v_{pi1} & v_{pi2} & \cdots & v_{pij} & \cdots & v_{pim} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ c_n & v_{pn1} & v_{pn2} & \cdots & v_{pnj} & \cdots & v_{pnm} \end{pmatrix} \tag{2}$$

In formula (2), v_{pij} (i=1,2,... N, j=1,2,..., M) denotes the classical domain of the characteristic variable C_i under the state j; v_{pij} = [μ_{ij}-3σ_{ij}≤v_{ij}≤μ_{ij}+3σ_{ij}], where μ_{ij} and σ_{ij} can be obtained from formula (3).

$$\begin{cases} \mu_{\mathbf{ij}} = (\sum_{k}^{t_j} v_{ijk}) / t_j \\ \sigma_{ij} = \sqrt{\frac{1}{t_j}\sum_{k}^{t_j} (v_i - \mu_{ij})^2} \end{cases} \tag{3}$$

μ_{ij} and σ_{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:

$$R_q = \begin{pmatrix} N & N_1 & N_2 & \cdots & N_j & \cdots & N_m \\ c_1 & v_{q11} & v_{q12} & \cdots & v_{q1j} & \cdots & v_{q1m} \\ c_2 & v_{q21} & v_{q22} & \cdots & v_{q2j} & \cdots & v_{q2m} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ c_i & v_{qi1} & v_{qi2} & \cdots & v_{qij} & \cdots & v_{qim} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ c_n & v_{qn1} & v_{qn2} & \cdots & v_{qnj} & \cdots & v_{qnm} \end{pmatrix} \tag{4}$$

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: $v_{qij} = < v_{ijmin}, v_{ijmax} >$, 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 the 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:

$$K = \begin{cases} \dfrac{\rho(v_i, v_{pij})}{\rho(v_i, v_{qij}) - \rho(v_i, v_{pij})}, & \rho(v_i, v_{qij}) \neq \rho(v_i, v_{pij}) \\ -\rho(v_i, v_{pij}) - 1, & \rho(v_i, v_{qij}) = \rho(v_i, v_{pij}) \end{cases} \tag{5}$$

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 $v_{pij} = < v_{pij1}, v_{pij2} >$ and can be calculated as follows:

$$\rho(v_i, v_{pij}) = \left| v_i - (v_{pij1} + v_{pij2}) / 2 \right| - (v_{pij2} - v_{pij1}) / 2 \tag{6}$$

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 , $e_{ij}=<e^-_{ij}, e^+_{ij}>$, $1/9 \le e^-_{ij} \le 9$; $e_{ii}=1$, $e_{ji}=e^{-1}_{ij}=<1/e^+_{ij}, 1/e^-_{ij}>$, $(i, j=1, 2, ..., n)$.

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 $X^-=(a^-_{ij})_{n\times n}$, $X^+=(a^-_{ij})_{n\times n}$.

2) $\lambda=(\lambda_1, \lambda_2, \ldots, \lambda_n)^T=<r\boldsymbol{X}^-, s\boldsymbol{X}^+>$is obtained, where r and s are calculated by formula (4).

$$\begin{cases} r = \sqrt{\sum_{j=1}^{n} 1 / \sum_{i=1}^{n} a^+_{ij}} \\ s = \sqrt{\sum_{j=1}^{n} 1 / \sum_{i=1}^{n} a^-_{ij}} \end{cases} \tag{7}$$

3) the weight of each index is calculated through λ.

We can suppose the two interval numbers $e=<e^-, e^+>$, $f=<f, f^+>$, then:

$$V(e \geq f)=\frac{2(e^+ - f^-)}{(e^+ - e^-)+(f^+ - f^-)} \quad (8)$$

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

$$V(\lambda_i \geq \lambda_j) \quad (i=1,2,\ldots,n;\; i \neq j) \quad (9)$$

If $V(\lambda_i \geq \lambda_j) \geq 0$ $(i=1,2,\ldots,n;\ i \neq j)$, then $\omega_j=1$, $\omega_i=V(\lambda_i \geq \lambda_j)$, $(i=1,2,\ldots,n;\ i \neq j)$, ω_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

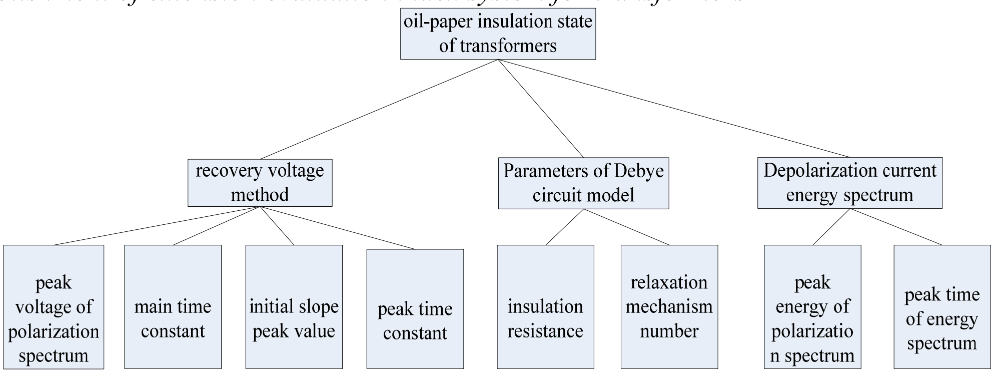

Figure 1. Analytic hierarchy diagram of transformer's evaluation index

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].

$$v_i=\frac{v_i^{'}-v'_{i-\min}}{v'_{i-\max}-v'_{i-\min}} \quad (10)\;;\quad v_i=\frac{v'_{i-\max}-v_i^{'}}{v'_{i-\max}-v'_{i-\min}} \quad (11)$$

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:

$$R_p=\begin{pmatrix} N & N_1 & N_2 & N_3 & N_4 \\ c_1 & <0.0266,0.0824> & <0.2226,0.3258> & <0.0723,0.5403> & <0.3371,1> \\ c_2 & <0,0.1108> & <0.3129,0.8511> & <0.1937,0.9929> & <0.9459,1> \\ c_3 & <0,0.6187> & <0.3908,0.5528> & <0.1868,1> & <0.2987,1> \\ c_4 & <0,0.8517> & <0.34,0.4528> & <0.2802,0.7266> & <0,1> \\ c_5 & <0,0.025> & <0,1> & <0,1> & <0.0119,1> \\ c_6 & <0,0.1034> & <0,0.8496> & <0,1> & <0.4646,1> \\ c_7 & <0,0.4428> & <0,1> & <0.1851,0.9033> & <0.5,1> \\ c_8 & <0,0.1629> & <0,0.8684> & <0,1> & <0.9732,1> \end{pmatrix} R_q=\begin{pmatrix} N & N_1 & N_2 & N_3 & N_4 \\ c_1 & <0.0232,0.1859> & <0.1517,0.3933> & <0.0723,0.5724> & <0.2767,1> \\ c_2 & <0,0.1706> & <0.2122,0.8912> & <0.0024,0.9929> & <0.9243,1> \\ c_3 & <0,0.7284> & <0.2435,0.5743> & <0.1272,1> & <0.2264,1> \\ c_4 & <0,0.9327> & <0.23,0.67> & <0.2607,0.8327> & <0,1> \\ c_5 & <0,0.2432> & <0,1> & <0,1> & <0,1> \\ c_6 & <0,0.2023> & <0,0.9322> & <0,1> & <0.4213,1> \\ c_7 & <0,0.6396> & <0,1> & <0,1> & <0.5,1> \\ c_8 & <0,0.2736> & <0,0.8722> & <0,1> & <0.9439,1> \end{pmatrix}$$

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.

$$A=\begin{pmatrix} <1,1> & <5,7> & <3,4> \\ <\frac{1}{7},\frac{1}{5}> & <1,1> & <\frac{1}{4},\frac{1}{3}> \\ <\frac{1}{4},\frac{1}{3}> & <3,4> & <1,1> \end{pmatrix};B_1=\begin{pmatrix} <1,1> & <\frac{1}{7},\frac{1}{5}> & <3,4> & <5,7> \\ <5,7> & <1,1> & <6,7> & <7,9> \\ <\frac{1}{4},\frac{1}{3}> & <\frac{1}{7},\frac{1}{6}> & <1,1> & <3,4> \\ <\frac{1}{7},\frac{1}{5}> & <\frac{1}{9},\frac{1}{7}> & <\frac{1}{4},\frac{1}{3}> & <1,1> \end{pmatrix};B_2=\begin{pmatrix} <1,1> & <\frac{1}{3},\frac{1}{2}> \\ <2,3> & <1,1> \end{pmatrix};B_3=\begin{pmatrix} <1,1> & <\frac{1}{4},\frac{1}{3}> \\ <3,4> & <1,1> \end{pmatrix}$$

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 ω_1=(0.5772,0.0372,0.3856). The weights of each index of the recovery voltage are ω_{21}=(0.2599,0.4471,0.2779,0.0152). The weights of each index of the Debye model are ω_{22}=(0.0829,0.9171), the weights of depolarization current are ω_{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.

$$K_j(N)=\sum_{i=1}^{8} w_i \times K\ (v_i) \tag{12}$$

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.

Table1. Statistical data of the measured values of ten transformers

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.

Table2 . the correlation degree of ten transformers on each state level

correlation degree	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
N_1	-6.38	-0.99	-5.22	*-0.33*	-7.98	-4.40	-8.20	*0.68*	-3.42	-5.14
N_2	-11.9	-1.22	*0.18*	-1.76	-17.34	*36.3*	-15.04	-1.65	-16.66	*28.4*
N_3	-0.16	*-0.69*	-0.65	-1.29	-0.83	0.11	-1.91	-0.39	-1.04	-0.63
N_4	*0.95*	-19.7	-11.24	-23.4	*0.86*	-6.95	*-0.33*	-24.6	*-0.11*	-7.6
diagnostic results	N_4	N_3	N_2	N_1	N_4	N_2	N_4	N_1	N_4	N_2

Table 2 shows that the diagnostic insulation state of 10 transformers are basically consistent with the actual insulation condition. Take transformers T_1 and T_2 as examples to illustrate the diagnostic results. The correlation values of the transformer T_1 with four insulation states(N_1, N_2, N_3, N_4) 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"(N_4), and the diagnostic results are the same as the actual state. In addition, the maximal correlation value of transformer T_2 is -0.6935, that is, the corresponding insulation state is "slightly aging insulation"(N_3), 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.

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