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Evaluation of transformer insulation condition based on cloud matter element model

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Abstract. The purpose of this paper is to study the insulation state of transformer. Insulation system is an important part of the transformer, and it is the basic condition for the normal operation and operation of the transformer. The insulation condition assessment of transformer is of great significance to guide the condition based maintenance of the transformer, to enhance the life cycle management and to save the cost of operation. Based on the cloud matter element theory, a method for evaluating the insulation state of transformers is proposed. The results show that the transformer insulation state evaluation model can effectively integrate various state parameters, and accurately assess the insulation state of the transformer each insulation parts and the whole part. Based on the above findings, we conclude that the model is suitable for evaluating the insulation state of transformers.

Key words. Transformer, insulation state, cloud model, matter element theory.

1. Introduction

Power transformer is the core of energy-conversion and transmission in the grid network, it is one of the most important equipment in power system, and it is in a pivotal position in power system. Its running state directly affects the security and reliability of the whole power system. For a long time, the maintenance of transformer in China adopts the planned maintenance mode, but planning maintenance has serious limitations and defects, which may lead to "maintenance excesses" and "lack of maintenance", causing the equipment effective time utilization loss and waste of manpower, financial and material resources, and adding new risks. In re-

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cent years, with the gradual improvement of unit condition monitoring technology, the maintenance mode of transformer has changed from planned maintenance to predictive maintenance (condition maintenance) based on condition monitoring. It is to make use of life characteristics of some important parts of the transformer, through the advanced detection means for data acquisition, to compare and analyze the transformer operation history and the operation conditions of the same type of transformer, to evaluate the current operation state of transformers, and to predict its development trend.

A large number of data show that the main reason for the failure of equipment is the deterioration of its insulation performance, and most of the failure of electrical equipment are insulation failure. In consequence, the transformer insulation system is the basic condition for the normal operation and operation of the transformer. Evaluate the transformer insulation system condition, determine the insulation state of the insulation oil, solid insulation and insulation casing and other components. It not only provides theoretical support and reference data for the life prediction of the transformer, and provide scientific basis for effectively realizing the transformer condition maintenance, making reasonable operation, protection, and updating plan. As a result, it has important academic value and practical significance to study the insulation condition assessment of the transformer.

2. State of the art

The cloud model is, based on probability theory and fuzzy set theory these two theories mutually penetrating, by constructing a specific algorithm, to form the transformation model between qualitative concept and quantitative representation, and to reveal the internal relationship between the randomness and the fuzziness.

Let U be set to the quantitative domain composed of accurate numerical values, and A is a qualitative concept on U. For an arbitrary element x on U, there is a random number $\mu(x) \in [0, 1]$ with a stable tendency, which is called the membership of X for A, and the distribution of membership in the domain is referred to as the cloud. Each x is called a cloud.

The numerical characteristics of the cloud are represented by using three values, respectively, the expectation (Ex), the entropy (En) and the hyper entropy (He). The expectation indicates the expectation of the domain spatial distribution of droplet, referring to the value that can most represent the qualitative concept in the domain space, which reflects the gravity position of the cloud [1]. The cloud at this position 100 % belongs to the qualitative concept. Entropy is a measure of the uncertainty of the qualitative concept. In general, the larger the entropy, the vaguer the concept, and the more difficult it is to quantify the concept. The hyper entropy is the entropy of entropy, and it is the uncertainty measure of entropy [2]. It reflects the degree of coherence of all points in the domain space, namely the condensation degree of cloud droplets, the greater the hyper entropy, the greater the randomness of each cloud membership, and the greater the thickness of the cloud.

Cloud generation algorithm is called cloud generator, which establishes the mapping relationship of qualitative and quantitative inter-connection, inter-dependence, and inter-transformation. Cloud generator, according to the calculation direction, can be divided into positive direction cloud generator and reverse cloud generator; according to the different dimensions of the cloud, it can be divided into one-dimension cloud generator and two-dimension cloud generator. The clouds involved in this paper are one-dimension clouds. Normal cloud generator is the most basic cloud generator, with universal applicability. The following will focus on the generation rules and related algorithms of normal cloud.

Positive normal cloud generator is a mapping from qualitative to quantitative, achieving the scope and distribution regular of quantitative data obtained from qualitative information expressed by the language value, which is a forward and direct process, as shown in Fig. 1.

Fig. 1. One-dimensional positive cloud generator

For the one-dimension normal cloud, three digital characteristics (Ex, En, He) of cloud are given, and the generated required cloud drop(x_i, μ_i) algorithm is shown in Fig. 2.

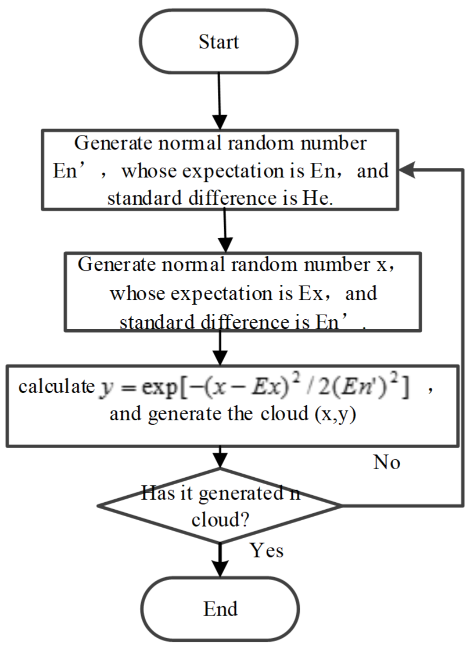

Fig. 2. Algorithm flow of one-dimensional normal positive cloud generating droplet

Reverse normal cloud generator effectively converts a certain number of accurate numerical to the qualitative concept represented by digital features (Ex, En, He), which is a reverse and indirect process, as shown in Fig. 3.

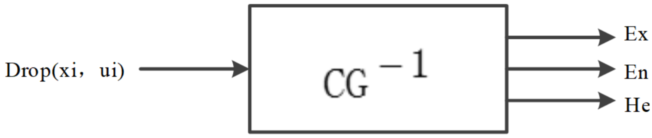

Fig. 3. One-dimensional reverse cloud generator

Reverse normal cloud generator algorithm is based on the principle of statistics, including using the membership information and not using the membership information these two basic algorithms, and the reverse cloud generator by using the membership information is shown in Fig. 4.

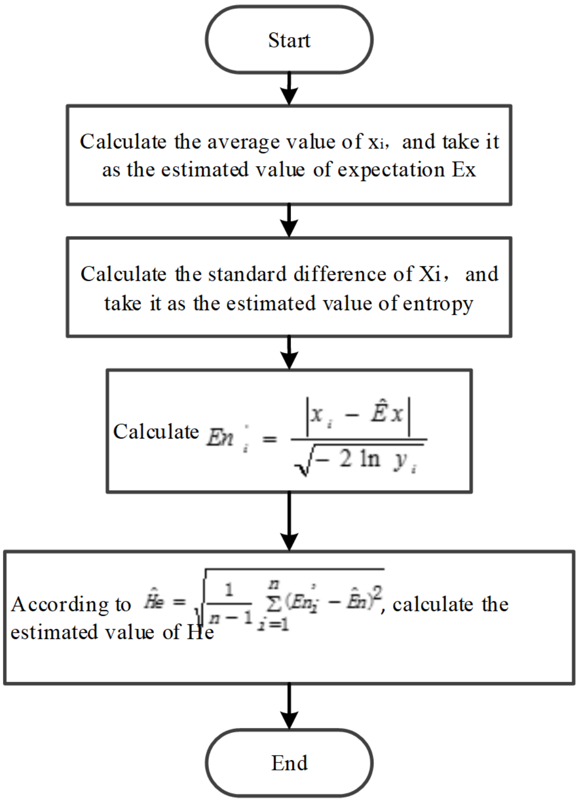

Fig. 4. Algorithm flow of reverse cloud generator by using membership information

For a given thing, represented by the name N, N has the characteristics of c, and its value is v [3]. The names, characteristics and values of things are orderly combined to form $R = (N, c, v)$ as a basic element to describe things, referred to as matter element.

If the matter N has n features $c_1, c_2, \ldots, c_n$, then, using these characteristics and corresponding values of $v_1, v_2, \ldots, v_n$, the description of thing N can be expressed as

$$R = \begin{bmatrix} N, & c_1, & v_1 \\ & c_2 & v_2 \\ & \cdots & \cdots \\ & c_n & v_n \end{bmatrix} = \begin{bmatrix} N, & c_1 & c_1(N) \\ & c_2 & c_2(N) \\ & \cdots & \cdots \\ & c_n & c_n(N) \end{bmatrix}. \tag{1}$$

Here, R is called a multidimensional matter element, in which $R_i = (N, c_i, v_i), (i = 1, 2, ..., n)$ is called the sub matter element of R.

3. Methodology

3.1. Establishment of evaluation index system of transformer insulation

Transformer insulation system is a system composed of insulating oil and solid insulation. There is no standard index system used to evaluate the insulation condition of the transformer [4]. In this paper, according to the different classifications and compositions of insulation, the index hierarchy evaluation system is established, as shown in Table 1.

3.2. Determination of index weight

In the evaluation process, the weight is an objective reflection of the index status and subjective measurement of relative importance of each index. According to the advantages of cloud model in expressing the fuzziness and randomness of natural language, this paper introduces the cloud model into the traditional analytic hierarchy process, and improves the analytic hierarchy process to make the evaluation result more objective.

In the improved analytic hierarchy process, the scale of the element importance is represented by the following 9 cloud models: $C_1(Ex_1, En_1, He_1)$, $C_2(Ex_2, En_2, He_2)$, $C_3(Ex_3, En_3, He_3)$, $C_4(Ex_4, En_4, He_4)$, $C_5(Ex_5, En_5, He_5)$, $C_6(Ex_6, En_6, He_6)$, $C_7(Ex_7, En_7, He_7)$, $C_8(Ex_8, En_8, He_8)$, $C_9(Ex_9, En_9, He_9)$. Among them, the expectations Ex_1 to Ex_9 were 1 to 9. For the cloud model of each scale, use the following assumptions: since that the meaning that 1, 3, 5, 7, and 9 these 5 grades express is relatively clear, expert's judgment about them is relatively clear[5]. While the judgment for other language value is relatively vague, so the cloud model used will not be the same. According to the principle of the golden section method, the entropy and the entropy of each cloud model are obtained in the form

$$En_1 = En_3 = En_5 = En_7 = En_9 = 0.382(\chi_{\max} - \chi_{\min})\alpha/6 = 0.437\,, \tag{2}$$

$$En_2 = En_4 = En_6 = En_8 = En_1/0.618 = 0.707\,, \tag{3}$$

Table 1. Index hierarchy evaluation system

	Item layer	Sub item layer	Index layer
Insulation state of transformer X	Oil insulation state $X1$	Oil chromatographic analysis $X11$	H_2 content $X111$
			C_2H_2 content $X112$
			Total hydrocarbon content $X113$
		Oil test $X12$	Micro water $X121$
			Acid value $X122$
			Breakdown voltage $X123$
			Oil dielectric loss value $X124$
	Solid insulation state $X2$	Aging index $X21$	$CO+CO_2$ content $X211$
			Furfural $X212$
			Polymerization degree $X213$
		Insulation test $X22$	Insulation resistance $X221$
			Absorption ratio $X222$
			Winding leakage current $X223$
			Dielectric loss factor $X224$
	Casing insulation state $X3$	Casing oil chromatographic analysis $X31$	H_2 content
			CH_2 content $X312$
			C_2H total content $X313$
		Casing electrical test $X32$	Capacitance $X321$
			Dielectric loss $X322$
			Main screen insulation resistance $X323$
			End shield to ground insulation resistance $X324$

$$He_1 = He_3 = He_5 = He_7 = He_9 = 0.382(\chi_{\max} - \chi_{\min})\beta/3 = 0.073\,, \qquad (4)$$

$$He_2 = He_4 = He_6 = He_8 = He_1/0.618 = 0.118\,. \tag{5}$$

According to the characteristic number of each cloud model, the cloud model of each scale grade can be obtained by using the generating algorithm of forward normal cloud.

The analytical hierarchy process method based on cloud model scale judgment matrix starts from its determination. The judgment matrix of the comparison of the elements importance in a certain layer after the aggregation of the experts group is as follows:

$$\begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ c_{n1} & c_{n2} & \cdots & c_{nn} \end{bmatrix} =$$

$$= \begin{bmatrix} C_{11}(Ex_{11}, En_{11}, He_{11}) & C_{12}(Ex_{12}, En_{12}, He_{12}) & \cdots & C_{1n} \\ C_{21}(Ex_{21}, En_{21}, He_{21}) & C_{22}(Ex_{22}, En_{22}, He_{22}) & \cdots & C_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ C_{n1}(Ex_{n1}, En_{n1}, He_{n1}) & C_{n2}(Ex_{n2}, En_{n2}, He_{n2} & \cdots & C_{nn} \end{bmatrix}. \tag{6}$$

In the above equation, the entropy and hyperentropy of diagonal elements of the cloud model is equal to 0, that is, $C_{ii}(Ex_{ii}, En_{ii}, He_{ii}) = C(1,0,0)$, element c_{ij} represents the importance degree of element i relative to element j, and for its reciprocal c_{ji}, it is obtained by cloud reciprocal computing method [7].

After obtaining the judgment matrix, according to the multiplication operation of the cloud model, the relative weights $W_i(Ex_i, En_i, He_i)$ of the expectation, fuzziness and randomness of elements in the matrix are obtained.

After getting the weights of each index element, it is necessary to carry out consistency validation of the expectation. When it meets$CR = \frac{CI}{RI} < 0.1$, through consistency validation, $CI = \frac{\lambda_{\max}-n}{n-1}$, RI corresponding random consistency index can be acquired from the table.

According to the different reflections of each item layer and index on the insulation state and performance of transformer, make use of the improved hierarchical analysis method based on cloud model to determine the weight of each factor. The specific method is: invite 5 industry or technical personnel, according to the comparison angle, compare the element of the target layer, that under the same item layer, and the index importance, and build the original $A - U$ judgment matrix. This paper takes the oil test sub project level as an example, the $A - U$ judgment matrix of 5 experts is:

$$W^{(1)} = \begin{bmatrix} 1 & 2 & 1/3 & 1/2 \\ 1/2 & 1 & 1/4 & 1/3 \\ 3 & 4 & 1 & 2 \\ 2 & 3 & 1/2 & 1 \end{bmatrix}, \quad W^{(2)} = \begin{bmatrix} 1 & 1 & 1/3 & 1/2 \\ 1 & 1 & 1/3 & 1/2 \\ 3 & 3 & 1 & 2 \\ 2 & 2 & 1/2 & 1 \end{bmatrix},$$

$$W^{(3)} = \begin{bmatrix} 1 & 1 & 1/4 & 1/2 \\ 1 & 1 & 1/3 & 1/2 \\ 4 & 3 & 1 & 3 \\ 2 & 2 & 1/3 & 1 \end{bmatrix}, \quad W^{(4)} = \begin{bmatrix} 1 & 1 & 1/3 & 1 \\ 1 & 1 & 1/3 & 1/3 \\ 3 & 3 & 1 & 2 \\ 1 & 3 & 1/2 & 1 \end{bmatrix},$$

$$W^{(5)} = \begin{bmatrix} 1 & 2 & 1/3 & 1/2 \\ 1/2 & 1 & 1/3 & 1/3 \\ 3 & 3 & 1 & 1 \\ 2 & 3 & 1 & 1 \end{bmatrix}.$$

For each judgment matrix, the element importance scale is represented by the cloud model, and the judgment matrix of the element importance by the experts is obtained, in which the judgment matrix of expert 1 is shown as follows [8]:

$$W^{(1)} = \begin{bmatrix} (1,0,0) & (2,0.707,0.118) & (1/3,0.049,0.008) & (1/2,0.177,0.030) \\ (1/2,0.177,0.030) & (1,0,0) & (1/4,0.442,0.007) & (1/3,0.049,0.008) \\ (3,0.437,0.073) & (4,0.707,0.118) & (1,0,0) & (2,0.707,0.118) \\ (2,0.707,0.118) & (3,0.437,0.073) & (1/2,0.177,0.030 & (1,0,0) \end{bmatrix}.$$

After getting the expert's cloud model judgment matrix, the clouds in the same position are assembled by using the group decision method, and the comprehensive judgment matrix of the 5 experts is obtained [9]:

$$W = \begin{bmatrix} (1,0,0) & (1.391,0.563,0.094) & (0.320,0.048,0.008) & (0.571,0.209,0.034) \\ (0.718,0.291,0.049) & (1,0,0) & (0.327,0.484,0.008) & (0.356,0.062,0.010) \\ (3.125,0.470,0.079) & (3.063,0.454,0.076) & (1,0,0) & (1.371,0.547,0.088) \\ (1.750,0.640,0.104) & (2.813,0.488,0.079) & (0.730,0.291,0.047) & (1,0,0) \end{bmatrix}$$

The index weight of the sub item of oil test is [10]

$$W^0 = [(0.157,0.161,0.162),(0.119,0.116,0.117),(0.420,0.409,0.409),(0.304,0.313,0.313)] .$$

And then it is necessary to carry out the consistency test of the expectation, as shown in Table 2.

Table 2. Consistency validation results

Name	$\lambda_{\max}$	CI	RI	CR
Value	4.0167	0.0056	0.9	0.0062

From Table 2, we can see that the test result is $CR = 0.0062 < 0.1$, which meets the requirement of consistency. By using the method mentioned above, carry out weight calculation of other indexes in the index system and the item layer, and the index weight distribution is shown in Table 3.

Table 3. The weights distribution chart of each index

	Item layer	Weights	Sub item layer	Weights	Index layer	Weights
Transformer insulation condition	Transformer oil insulation state	0.301	Oil chromatographic analysis	0.364	H_2	0.188
					C_2H_2	0.392
					Total hydrocarbon	0.420
			Oil test	0.636	Micro water	0.157
					Acid value	0.119
					Breakdown voltage	0.420
					Oil dielectric loss	0.304
	Solid insulation state	0.563	Aging index	0.485	Furfural	0.360
					Polymerization degree	0.538
					$CO+CO_2$ content	0.103
			Insulation test	0.515	Insulation resistance	0.139
					Absorption ratio	0.170
					Winding leakage current	0.254
					Dielectric loss factor	0.436
	Casing insulation state	0.136	Casing oil chromatographic analysis	0.381	H_2	0.250
					CH_4	0.222
					C_2H total content	0.528
			Casing electrical test	0.619	Capacitance	0.419
					Dielectric loss	0.297
					Main screen insulation resistance	0.154
					End shield to ground insulation resistance	0.130

4. Result analysis and discussion

4.1. Steps for evaluation of transformer insulation state based on the cloud matter element model

The insulation condition of power transformer is comprehensively reflected by all the indexes in the index system, and different indicators tend to have different magnitude and dimension, cannot adopt a uniform measurement standard for the analysis of all indexes. Therefore, before the evaluation, each characteristic state should be quantified [11]. This paper uses the relative deterioration degree to measure the insulation status degree of deterioration, the range of degree of deterioration of [0, 1], with 0 suggesting insulation in good condition, 1 indicating the insulation in the fault state. The greater the value, the more serious the deterioration.

In this paper, with reference to "Oil immersed transformers (reactors) state assessment guide", considering the state development trend of the transformer, the transformer insulation condition is divided into excellent, good, general, attention, and serious these five state levels, and the deterioration degree of each index partition on the state level is shown in Table 4.

Table 4. Level division of transformer insulation state

Deterioration degree range	0–0.15	0.15–0.35	0.35–0.6	0.6–0.8	0.8–1
State levels	Excellent	Good	General	Attention	Serious

The specific steps for evaluating the insulation of the transformer are shown in Fig. 5.

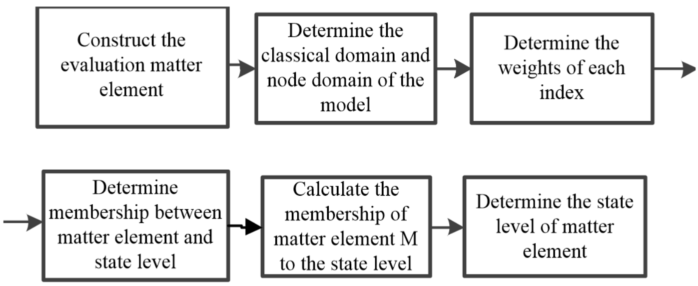

Fig. 5. Specific steps for transformer insulation state evaluation

4.2. Case analysis

Tested was a 240 MVA, 220 kV transformer, model for SFPSZ1-240000/220, in 2014 and 2015. Some parts of the number of preventive test values after its building are as shown in Table 5 [12]. The two spectrum tracking data in 2015 are shown in Table 6.

Using the above information, the concrete steps for evaluating the insulation condition of the transformer are as follows: According to the transformer insulation condition assessment system established in the previous paper, the condition index of each sub item layer constitutes the element to be evaluated [13].

Table 5. Prediction test data

Test items	2014	2015
Absorption ratio	1.48	1.28
Winding leakage current change	23.1	122.7
Winding dielectric loss	0.275 %	0.59 %
Capacitive casing dielectric loss	0.57 %	0.72 %
Capacitance casing	-1.2 %	-1.4 %
Water content in oil	16 mg/l	21mg /l
Oil dielectric loss	1.57 %	2.41 %
Oil breakdown voltage	52 kV	48 kV
Furfural content in oil	0.27 mg/l	0.32 mg/l

Table 6. Oil chromatographic data

Test date	CO	CO_2	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	Total hydro-carbon
2015.5.25	30.6	310	64	7.7	1.1	1.0	2.5	21.3
2015.8.02	197	2481	92.1	28	3.2	73.6	9.1	113.9

Using the above information, the concrete steps for evaluating the insulation condition of the transformer are as follows:

According to the transformer insulation condition assessment system established in the previous paper, the condition index of each sub item layer constitutes the element to be evaluated [13]:

Oil chromatographic analysis of matter element MX11:

$$R_{M_{X11}} = \begin{bmatrix} M_{X11} & c_{X111} & 0.518 \\ & c_{X112} & 0.64 \\ & c_{X113} & 0.722 \end{bmatrix}.$$

Oil chemical test matter element MX12:

$$R_{M_{X12}} = \begin{bmatrix} M_{X12} & c_{X121} & 0.6 \\ & c_{X122} & 0.675 \\ & c_{X124} & 0.47 \end{bmatrix}.$$

Aging index matter element MX21:

$$R_{M_{X21}} = \begin{bmatrix} M_{X21} & c_{X211} & 0.812 \\ c_{X212} & 0.8 & \end{bmatrix}.$$

Insulation test matter element MX22:

$$R_{M_{X22}} = \begin{bmatrix} M_{X22} & c_{X222} & 1 \\ & c_{X223} & 1 \\ & c_{X224} & 0.738 \end{bmatrix}.$$

Casing electrical test matter element MX32:

$$R_{M_{X32}} = \begin{bmatrix} M_{X32} & c_{X321} & 0.68 \\ c_{X322} & 0.9 & \end{bmatrix}.$$

The weights of each index are determined according to the index weights introduced in the previous paper, and the results are shown in Table 7.

Table 7. Weights of each index

Indexes	Objective indexes	Indexes	Objective indexes
X	0.301, 0.563, 0.136	$X12$	0.292, 0.383, 0.325
$X1$	0.364, 0.636	$X21$	0.376, 0.625
$X2$	0.485, 0.515	$X22$	0.163, 0.406, 0.430
$X11$	0.161, 0.345, 0.493	$X31$	0.529, 0.471

The evaluation results show that the insulation index of the transformer is in the "attention" state, the deterioration trend is obvious, especially the winding insulation absorption ratio and leakage current exceed the value of attention. In the face of various insulation parts of the transformer, the insulation oil is in the "attention" state, solid insulation and casing insulation are in the "serious" state [14]. On the whole, the transformer insulation is in the "attention" state, close to the "serious" state, the aging phenomenon is more serious, and the possibility of failure is high, supposed to strengthen the monitoring of the transformer, to pay close attention to the development of insulation condition, to arrange the repair as soon as possible, and to timely process insulating oil degassing and filtration.

In 2015, after 1 month of test running, we examined the transformer. We found that the casing cap did not seal the tank completely. Thus the insulation part of the transformer was damp. The insulation oil was dissolved with large amount of air. The above description fit the evaluation model built in the study.

5. Conclusion

Insulation system is an important part of the transformer, and it is the basic condition for the normal operation and operation of the transformer. The insulation condition assessment of transformer is of great significance to guide the condition based maintenance of the transformer, to enhance the life cycle management and to save the cost of operation. According to the composition and characteristics of transformer insulation system, a state evaluation model based on cloud matter element theory is established. The evaluation results show that the transformer insulation index is in a dangerous state, and the trend of deterioration is obvious. In particular, the insulation absorption rate and leakage current of windings are more than the attention value. On the whole, the insulation aging of transformer is more serious, and the possibility of failure is very high. The government should strengthen the monitoring of transformers, pay close attention to the development of insulation status, arrange maintenance as soon as possible, and timely deal with the degassing and filtration of insulating oil. After a month's pilot work on transformer maintenance, we found that the lid was not sealed, causing insulation to damp. The insulation of the transformer is seriously degraded. It is consistent with the model evaluation conclusion. As a result, the model is proved to be correct and reliable according to the analysis of the case.

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