Fuzzy synthetic method for life assessment of power transformer

Z. Qian and Z. Yan

Abstract: The ageing condition of a power transformer is identified, dividing it into normal ageing and abnormal ageing. Fuzzy theory is applied to assess the degree of ageing and whether it is normal or abnormal. Then a synthetic evaluation model is constructed to identify the ageing condition step by step. The simulation results show that this model is effective for recognising the status of solid insulation, and its result will be helpful to the prediction of residual life.

1 Introduction

It is of great value to evaluate the insulation condition of a power transformer accurately and at the correct time. Especially for a power transformer operated beyond a nominal design life of $25\sim30$ years, it is crucial to evaluate the status of the solid insulation accurately; the results will provide information for the prediction of residual life and the arrangement of a maintainance scheme [1].

Transformer insulation is mainly oil–paper insulation, including insulating oil, insulation paper and pressboards. Usually the degradation of solid insulation such as pressboards is more serious than that of insulating oil because the solid insulation is irreplaceable and its position is very important. However, it is more difficult to assess the status of solid insulation. A number of techniques exist for assessing the insulating condition, several relying on knowledge of the physical mechanism of failure so that tests that accelerate these mechanisms on similar materials can be used [2–6] and corresponding statistical techniques utilised to establish the ageing rule. Others identify the ageing status according to the decomposition product of oil–paper insulation [7–12], and a corresponding identification rule could also be established according to statistical analysis of the concentration of decomposing products.

1.1 Research of ageing rule

Solid insulating materials usually have high dielectric and high tensile strengths. However, these materials are gradually degraded due to the action of thermal stress, electrical stress, etc. Thus several empirical models such as a 10°C rule, an electrical ageing rule, and a multifactor ageing rule have been proposed [2–6]. Most models are established according to the result of accelerated tests. Since the testing condition differs from the operating condition of solid insulation to some extent, the validity and reliability of models is unsatisfactory. Moreover, the ageing of solid insulation under thermal and electrical stress is complex. Exiguous factors such as oxygen and moisture also influence the ageing course but these are usually neglected. Thus the existing ageing rules do not fully reflect the ageing mechanism of solid insulation under multifactorial influences.

1.2 Research of identifying rule

Most solid insulation materials are made of cellulose materials. The degrading mechanism of cellulose is complicated but is likely to be one of the following forms: hydrolytic degradation, oxidative degradation and thermal degradation. The decomposation products are mainly carbon monoxide, carbon dioxide and furfural. At the same time the degree of polymerisation of paper made of cellulose will decrease [7]. Thus the identifying rules according to the concentration of the decomposition products have been proposed [1, 8–12]. However, there are still problems when using these rules. Carbon monoxide and carbon dioxide can also be generated by the oxidative decomposition of oil, thus the accuracy of the identifying rule according to the concentrations of CO_2 and CO will be reduced. The detection of furfural concentration will be influenced by many factors such as load condition, cooling method, and oil disposing times, therefore the reliability of an identifying rule based on furfural concentration will also be affected. The highest accuracy of the identifying rule is in accordance with the degree of polymerisation but it is very difficult to realise the test when the transformer is in operation.

2 Assessment of normal ageing

It is usual that the solid insulation of a transformer will gradually age under normal operation because of the action of electric stress, thermal stress and mechanical stress. Thus it is valuable to assess the ageing degree of solid insulation; the result will be helpful for the prediction of residual life and the substitution of an invalid transformer. Here an evaluation model for normal ageing degree is established. As shown in Section 1, to assess the degree of normal ageing by using the concentration of a single product is insufficient; a better method is to use the concentration of every product synthetically. Thus the original intention is to establish a synthetic assessment of normal ageing. The theoretical basis of the evaluation model is called fuzzy comprehensive assessment.

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2.1 Basic theory of fuzzy assessment

In practice, the basic characteristics of an object could be revealed by the synthetic assessment of many parameters. Since fuzzy comprehensive assessment could give an assessment on the basis of evaluating every parameter, the conclusion could reflect the general characteristic of the object. Thus it is possible to assess the residual life of a transformer using fuzzy comprehensive assessment.

If the sets $U=\{u_1, u_2, \ldots, u_n\}$ and $V=\{v_1, v_2, \ldots, v_m\}$ are the assessing parameter set and assessing result set, respectively, the fuzzy assessing matrix is shown as follows:

$$E = \begin{array}{c c} & \begin{array}{cccc} v_1 & v_2 & \cdots & v_m \end{array} \\ \begin{array}{c} u_1 \\ u_2 \\ \\ u_n \end{array} & \begin{pmatrix} u_{11} & u_{12} & \cdots & u_{1m} \\ u_{21} & u_{22} & \cdots & u_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ u_{n1} & u_{n2} & \cdots & u_{nm} \end{pmatrix} \end{array} \quad (1)$$

And the weight of every parameter can be expressed as a fuzzy set $(x_1/u_1, x_2/u_2, \ldots, x_n/u_n)$, thus the assessing result could be found as $(y_1/v_1, y_2/v_2, \ldots, y_m/v_m)$. Thereinto

$$y_j = \bigcup_{i=1}^{n} (x_i \cap u_{ij}) \quad (i = 1, 2, \cdots, n;\ j = 1, 2, \cdots, m) \quad (2)$$

where, $\cup$-$\cap$ is fuzzy operator, and could be selected smartly according to different conditions. Sometimes many methods can be utilised to assess the condition of an object, thus a synthetic assessment should be studied to integrate their conclusion. Here, a two-step fuzzy comprehensive assessment is put forward and is used to assess the normal ageing condition. The first step is to assess the ageing degree by using the fuzzy assessing matrices E_1 and E_2. The fuzzy assessing matrices E_1 and E_2 consider the concentration information of oxycarbide (CO and CO_2) and furfural, respectively. The second step could synthesise the evaluation results of the first step. As the merits of each method could perhaps be sufficiently utilised in a synthetic assessment, the result would possess better accuracy and higher reliability.

2.2 Normal ageing model

2.2.1 Constitution of assessing parameter set and assessing result set:

It is possible to assess the ageing condition of a transformer according to the decomposing products. Thus the assessing parameter set is made of oxycarbide and furfural information. And since it is very difficult to give the exact age of a transformer, the concept of insulating age and ageing level is introduced [1, 13]. The ageing level consists of five conditions which are the elements of the assessing result set. The constituents of the two sets are shown in Tables 1 and 2.

The triangle function is adopted to construct the membership function of an element in the assessing parameter set. The triangle function equations are expressed as follows:

$$\mu_{Low}(x) = \begin{cases} 1 & x < x_1 \\ \frac{x-x_1}{x_1-x_2} + 1 & x_1 \le x < x_2 \\ 0 & x \ge x_2 \end{cases} \quad (3)$$

$$\mu_{Middle}(x) = \begin{cases} 0 & x < x_1 \\ \frac{x-x_1}{x_2-x_1} & x_1 \le x < x_2 \\ \frac{x-x_2}{x_2-x_3} + 1 & x_2 \le x < x_3 \\ 0 & x \ge x_3 \end{cases} \quad (4)$$

$$\mu_{High}(x) = \begin{cases} 0 & x < x_2 \\ \frac{x-x_2}{x_3-x_2} & x_2 \le x < x_3 \\ 1 & x \ge x_3 \end{cases} \quad (5)$$

where x_1, x_2 and x_3 are the adjustment coefficients of the triangle function. In accordance with the statistical results of collected transformer samples, the value of the adjustment coefficient for each element in the assessing parameter set is shown in Table 3.

2.2.2 Configuration of fuzzy assessing matrix:

The fuzzy assessing matrix could give the relation between the assessing parameter and assessing result; it is the key part when making a fuzzy assessment. In the ageing

Table 1: Assessing result set

Level	A	B	C	D	E
Condition	excellent (<15years)	good (15∼20years)	normal (20∼30years)	worse (30∼40years)	worst (>40years)

Table 2: Assessing parameter set

Furfural concentration			Furfural growth rate			($CO+CO_2$) concentration			($CO+CO_2$) growth rate		
low	middle	high	low	middle	high	low	middle	high	low	middle	high

Table 3: Value of adjustment coefficients

	Furfural concentration mg/l	Furfural growth rate mg/l	($CO+CO_2$) concentration $\times 10^{-6}$	($CO+CO_2$) growth rate $\times 10^{-6}$ pa.
x_1	0	0	0	0
x_2	0.5	0.1	5700	1450
x_3	4	0.3	24550	6300

model, the fuzzy assessing matrix includes two submatrices. One considers the relationship between oxycarbide (CO and CO_2) and ageing level, the other considers the relationship of furfural and ageing level. Based on the statistical results from collected transformers, and the recommended values from some references, the practical configuration of the assessing matrix is shown in Table 4.

It should be mentioned that the parameters of the membership function and the value of the assessing matrix are mainly determined by statistical results. Since this method is an open model, these parameters and values may be changed with increased understanding of the ageing mechanism and the collection of more data from suspected transformers. In other words, the parameter rationality, could be gradually improved.

2.2.3 Fuzzy comprehensive assessment:

When starting the assessment of normal ageing level, the first step is to assess the ageing level by using matrices E_1 and E_2; and then the fuzzy comprehensive assessment is adopted to synthesise the merits of the two methods of assessing the ageing level, thus the evaluation results are more accurate and reliable.

Suppose that the evaluation results of E_1 and E_2 are (y_{1A}, y_{1B}, …, y_{1E}) and (y_{2A}, y_{2B}, …,y_{2E}), respectively, and the weights of E_1 and E_2 are 0.60 and 0.40, then the final evaluation result is as follows:

$$(y_A, y_B, y_C, y_D, y_E) = (0.60, 0.40) \circ \begin{pmatrix} y_{1A}, y_{1B}, y_{1C}, y_{1D}, y_{1E} \\ y_{2A}, y_{2B}, y_{2C}, y_{2D}, y_{2E} \end{pmatrix} \qquad (6)$$

where, $\circ$ is the fuzzy operator, and $y_A \sim y_E$ is the ageing level. The selection of weightings is very important when making a comprehensive assessment. The foregoing selection considers the reliability of the furfural analysis method is better than that of oxycarbide, thus the weighting comes from experience, as a result of an insufficient number of samples. However, it is reasonable to utilise a statistical method to calculate the weightings. In other words, since the accuracy of assessing results varies with different weightings, the value corresponding to the highest accuracy is the best one.

3 Establishment of abnormal ageing

Sometimes the solid insulation of a power transformer will age rapidly because of the action of a fault such as a winding overheating, or a treeing discharge on an insulating barrier. This is abnormal ageing. If the fault diagnosis is timely, the loss will be reduced. This is the original intention of establishing an abnormal ageing model. To solve the problem of fuzziness during the course of diagnosis, the fuzzy equation is utilised.

3.1 Basic theory of fuzzy equation

Suppose that $\tilde{A}$ is the set of causal events, $\tilde{B}$ is the set of resulting events, and $\tilde{R}$ is the matrix of the fuzzy equation between the causal and resulting events; the fuzzy equation could be established first as:

$$\tilde{A} \circ \tilde{R} = \tilde{B} \qquad (7)$$

Then according to $\tilde{B}$ and $\tilde{R}$, $\tilde{A}$ could be calculated as the solution of this equation. Usually the number of solutions is greater than one, such as $\{\tilde{A}_1, \tilde{A}_2, \cdots \tilde{A}_k\}$. The following method could be adopted to find the optimal solution and the possible cause.

First, define the degree of fuzzy closeness

$$\sigma = \sum (x_k \wedge y_k) / \sum (x_k \vee y_k) \qquad (8)$$

Table 4: Configuration of fuzzy assessing matrix

Assessing submatrix		Assessing result *A*	*B*	*C*	*D*	*E*
E_1	furfural concentration high			0.20	0.35	0.45
	furfural concentration middle	0.05	0.10	0.50	0.25	0.10
	furfural concentration low	0.60	0.40			
	furfural growth rate high	0.10	0.05	0.15	0.30	0.40
	furfural growth rate middle	0.20	0.10	0.40	0.20	0.10
	furfural growth rate low	0.40	0.50	0.10		
E_2	($CO+CO_2$) concentration high		0.05	0.20	0.30	0.45
	($CO+CO_2$) concentration middle	0.10	0.10	0.40	0.25	0.15
	($CO+CO_2$) concentration low	0.50	0.40	0.10		
	($CO+CO_2$) growth rate high	0.05		0.15	0.30	0.50
	($CO+CO_2$) growth rate middle	0.10	0.10	0.40	0.30	0.10
	($CO+CO_2$) growth rate low	0.45	0.50	0.05		

Table 5: Set of abnormal ageing causes A

Number	a_1	a_2	a_3	a_4	a_5
Fault	bad connections of winding leads	flashover of leads	short-circuit between interturns	winding overheating	treeing discharge on insulating barrier

Table 6: Set of abnormal ageing symptoms B

Number	b_1	b_2	b_3	b_4	B_5	b_6	b_7	b_8
Symptom	overheating judged by triple ratio	discharge judged by triple ratio	correlation between CO and H_2	correlation between CO and CH_4	imbalance of three phases	variant of transformer ratio	quantity of partial discharge	content of water in oil

Table 7: Fuzzy equation matrix between ageing cause and ageing symptom R

Cause	Symptom							
	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
a_1	0.70	0.20		0.60	0.80			
a_2	0.10	0.80	0.90				0.80	0.30
a_3	0.30	0.60	0.80		0.60	0.80	0.70	
a_4	0.80			0.90	0.60			
a_5	0.10	0.80	0.80				0.70	0.40

where σ is the degree of closeness, x, y represent two different fuzzy vectors, x_k and y_k represent the value of the k segment in the fuzzy vector. Then calculate the $\tilde{B}_i$ of every $\tilde{A}_i$ according to $\tilde{A}_i \circ \tilde{R} = \tilde{B}_i$. Subsequently the degree of closeness between $\tilde{B}_i$ and $\tilde{B}$ could be calculated. Finally, rank all the degrees of closeness, and search $\tilde{B}_i$ for the corresponding maximum degree of closeness. The relevant $\tilde{A}_i$ is the optimal solution. The causal event corresponding to the maximum membership degree in $\tilde{A}_i$ is the possible cause.

3.2 Abnormal ageing model

According to the statistical results of collected transformer samples, $\tilde{A}$, $\tilde{B}$ and $\tilde{R}$ are shown in Tables 5–7.

According to the basic fuzzy equation theory shown in Section 3.1, the abnormal ageing model can be established. And the abnormal ageing cause could also be achieved through the equation solution and searching the optimal all-in-one solution.

4 Constitution of synthetic evaluating model

During the assessing course for solid insulation, whether it is ageing or not should be identified first, and then the ageing cause should be recognised: the abnormal ageing or the normal ageing model should be utilised according to the recognised result. If it is abnormal ageing, the cause could be found by using the abnormal ageing model. This result will provide useful information for the maintenance of the transformer. If it is normal ageing, the level will be obtained. It will be helpful in predicting the life of the transformer.

The block diagram of operating flow of synthetic evaluating model is shown in Fig. 1, and the assessing steps are expressed as follows. The identifying rule is selected carefully in accordance with the recommended values in some papers and statistical analysis of collected transformers.

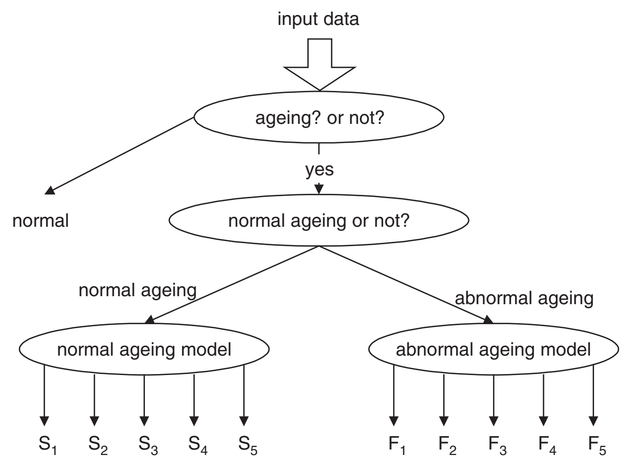

Fig. 1 *Block diagram of synthetic evaluating model*

(i) The detection results of furfural, CO and CO_2 are the input data of the synthetic evaluating model.

(ii) Whether the solid insulation is ageing or not: If the CO concentration is greater than 400×10^{-6}, or the CO_2 concentration is greater than 5300×10^{-6}, or the ratio of CO to CO_2 is lower than 0.09 or greater than 0.33 ($\Delta CO/\Delta CO_2 < 0.09$ or $\Delta CO/\Delta CO_2 > 0.33$), or the furfural concentration is greater than 0.5 mg/l, the solid insulation is in an ageing condition.

(iii) Ageing identified: If the growth rate of CO_2 is greater than 1042×10^{-6} per year, or the growth rate of CO is greater than $(407 \times 10^{-6}/2x^{1/2})$ per year, or the furfural concentration is greater than $\exp(-1.29 + 0.058x)$ where x is the operating years, the ageing is fault induced. Otherwise the solid insulation is in normal ageing.

(iv) According to the ageing cause deduced in (iii), the normal or abnormal ageing model is utilised. If it is normal ageing, the ageing level could be determined; this is useful for life prediction. If it is abnormal ageing, the fault could be diagnosed; this is helpful in the arrangement of a maintaining scheme.

(v) If fuzzy membership degree of fault diagnosed by abnormal ageing model is lower than specified threshold, the ageing is not abnormal ageing. It is normal ageing, and the ageing level should be achieved by using normal ageing model.

5 Example analysis

5.1 Example 1

The chromatogram data of CO and CO_2 of a transformer is 1590×10^{-6} and 26395×10^{-6}, respectively, and the furfural concentration is 2.04 mg/l. Operating life is 35 years. By using the synthetic model, normal ageing is first identified. Then the normal ageing model is utilised, the assessing result of matrix E_1 and E_2 is (0.05, 0.10, 0.44, 0.35, 0.45) and (0, 0.05, 0.20, 0, 0.45), respectively, and the assessing result of the second step is (0.003, 0.062, 0.344, 0.330, 0.450). Since the fifth value is the greatest, one can deduce the ageing level; it is E. In other words, the ageing degree of this transformer (>40 years) is greater than the normal operating years. The measured result of the polymerisation degree of insulating paper demonstrates this result simultaneously (the value of polymerisation degree is 212). Thus this transformer is abandoned. It shows that the synthetic model gives the correct conclusion.

5.2 Example 2

The dissolved gas analysis data and the furfural concentration of a transformer, in operation since 1981, are shown in Table 8.

The growth of CO and CO_2 is rapid between the two testing dates. Thus further testing is carried out. The imbalance factor of three phases is 2.4%, which shows that this transformer probably has some problems.

By using the synthetic assessing model, abnormal ageing is identified at first. Then the abnormal ageing model is utilised: the diagnostic solution is [0, 0.2], [0, 0.3], [0, 0.6], [0.9, 1.0],[0, 0.4] according to the symptom set and fuzzy equation. Since the fourth value is the greatest, one can conclude that according to the maximum membership degree, it is winding overheating. The factual condition is the serious degradation of interturn insulation of low-voltage winding following a jam in the oil channel. The diagnostic conclusion coincides well with the factual condition; the synthetic model gives the right conclusion.

Thirty-two abnormal-ageing transformers were selected as diagnosis samples with and the results shown in Table 9.

The total accuracy is 87.5%. It demonstrates that the validity of the synthetic model is satisfied. Statistical results for normal ageing could not be achieved since there were insufficient samples.

6 Conclusions

The assessment of ageing condition for solid insulation in transformers was the main object of this paper. In accordance with the broad investigation and statistic, the cause of ageing in solid insulation is divided into normal ageing and abnormal ageing, which is induced by transformer fault. A corresponding diagnostic model is set up by using fuzzy theory. A synthetic evaluation model has been presented in which the identification of the ageing condition could be processed step by step. If it is caused by a fault, the abnormal ageing model can be used to recognise the fault. Otherwise, the normal ageing model is adopted to identify the ageing level. The diagnostic conclusion provides information for the arrangement of maintenance schemes. Examples demonstrate the efficiency of the synthetic model.

The synthesis is the basic characteristic of the proposed method. Sometimes, monitoring the results of one parameter could not give more useful information. However, the synthetic identification of more monitoring information will gives a correct conclusion. With a better understanding of the ageing mechanism, collection of more data of suspected transformers and the appearance of more effective markers, this model could be improved gradually, with a consequent increase in efficiency.

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Table 8: Measuring results of suspected transformer (DGA unit $\times 10^{-6}$)

Testing date	H_2	CO_2	CO	CH_4	C_2H_6	C_2H_4	C_2H_2	Testing date	Furfural concentration
1992.4.1	24	26395	1590	27.8	24.4	30	0	1992	1.79 mg/l
1992.5.19	33.9	47201	2412	36.5	31.5	39.3	0		

Table 9: Simulation results of abnormal-ageing transformers

	Fault				
	a_1	a_2	a_3	a_4	a_5
Examples	7	4	7	12	2
Right members	6	4	6	10	2
Accuracy(%)	85.7	100	85.7	83.3	100
Total accuracy(%)			87.5		

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