

The Transformer Condition Assessment Model is Based on The Fuzzy Calculation

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Abstract—This paper proposed a more accurate assessment model for the transformer which in the loss fault period. Firstly, we established the transformer fault tree model, then calculated the Probability importance of each event in fault tree, and get the weighting of each event in fault tree. Secondly, we determined the membership function of each event in fault tree, and give the different membership function for transformer running on accidental failure period and loss fault period. And thus it can be more accurately determine the operational status for the transformers which in the loss fault period. Finally, we combined with the weight of each end of the event indicators to derive the status of transformer. The examples show that this method is reasonable and effective.

Keywords- Transformer; fault tree; accidental failure period; loss fault period; membership function

I. INTRODUCTION

With the rapid development of power grid, we have more and more high level to the power system in security, stability and economic operation [1]. Since the transformer is an important part in the whole power system, it is a great significance that the operating condition assessment of transformer for the safe operation of the power system.

In recent years, many scholars have carried out many work for the operating condition assessment of transformer. Literature 2 studied a multi-level evaluation method which combine with fuzzy theory to fuzzy evaluation of transformer running state, and establish a hierarchical assessment index system for transformer, and introduction of the relative degree of deterioration judging by the actual status of each indicator to the degree of deterioration of the fault state transition. Literature 3 proposed the method of fault tree to identify weak links in the power transformer, and put forward the proportional sharing principle and unreliability tracing algorithm for fault tree analysis (FTA). Literature 4 proposed the analysis of the life of the transformer which based on the reliability to determine the best time of repair the transformer. Then it will prolong the life of the transformer.

But in real life, the operating time of most transformers are about 20 years, and some of the transformer's running time is very long, such as remote rural areas, the running time of the transformer even reached 30 years. The actual data show that the transformer will enter into a loss of failure when they running more than 15 years, then the probability of failure of transformer is more larger. For the operating condition assessment of transformer, The traditional analysis does not take into account the problem of running time, it

could lead to the evaluation results are not accurate. This paper will discuss it and given algorithm.

II. THE TRANSFORMER'S BOTTOM EVENT PROBABILITY IMPORTANCE CALCULATION IS BASED ON THE FAULT TREE

A. The construction of fault tree and the algorithm process of this paper

In this paper, transformer can be divided into seven categories which are lead failure, and the failure of winding and iron core fault, casing failure, oil pillow failure, tap-changer fault and other failure. These categories are respectively to remember as A, B, C, D, E, F, G. According to the structure characteristics of the major components, we could differentiate various failure modes for each componentsalutation remember as bottom event. For example, Winding fault can be divided into insulation falling B1, abnormal dc resistance B2, discharge fault B3, overload B4, poor manufacturing process B5 and short circuit fault B6, then we analysis the logical relationship of each event which in fault tree, and we could get that fault tree diagram. Because of limited space. This article only listed the fault tree graph which seven categories of transformer, the other events are shown in table 1, and the logic of relations between bottom events and top events is and relations. Namely that the occurrence of any of the bottom events are cause the top event.

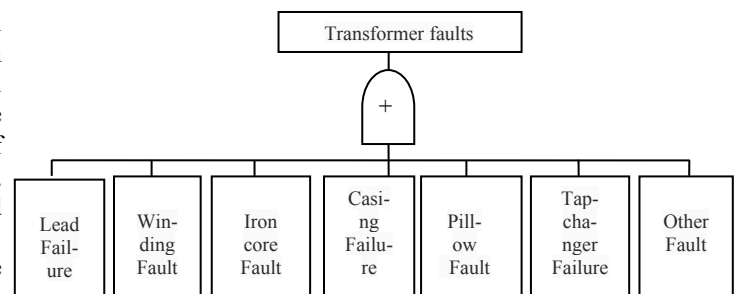


Figure 1. The fault tree model of Power transformer

B. The determination of the fault tree bottom event weights

After found the fault tree, we need to determine the weights of each bottom event in fault tree, namely that the size of the impact to the top event when the bottom events occurred. This paper will mainly using the method of calculating probability importance degrees of bottom events for judgment, using the probability importance take the place of the weight of each bottom event. This method can

avoid the error of subjective factor which caused by the traditional Analytic Hierarchy Process (AHP) to determine the weight. And it also can avoid the cumbersome process of AHP consistency test.

Firstly, we calculate the minimum cut sets of fault tree, Then according to the descending method, We concluded that the minimum cut set of fault tree is $C = \{A, B1, B3, B2, B3, B4, B5, C1, C2, C3, C4 \text{ and } D1, D2, D3, D4, E1 \text{ and } E2, F1, F2, F3 \text{ and } F4, G\}$, it include 21 minimum cut sets

TABLE 1 The probability importance of each bottom event

<i>Fault components</i>	<i>number</i>	<i>bottom event</i>	<i>The probability of Failure</i>
Lead	A	lead failure	0.09
Winding fault	B1	insulation resistance drop	0.09
	B2	dc resistance abnormal	0.061
	B3	discharge fault	0.055
	B4	overload	0.054
	B5	Short circuit fault	0.038
Iron core fault	C1	Multipoint earthing	0.064
	C2	Insulation falling	0.053
	C3	Local overheating	0.024
	C4	over-excitation	0.050
Casing failure	D1	sealed	0.036
	D2	Casing overheating	0.039
	D3	Casing aging	0.057
	D4	breakdown	0.044
pillow fault	E1	Oil level anomalies	0.050
	E2	jam	0.016
Tap-changerfailure	F1	Bad connection	0.027
	F2	Insulation falling	0.030
	F3	Pressure is not enough	0.014
	F4	Chromatography is abnormal	0.024
Other fault	G	Other fault	0.084

After that we calculate the probability importance of each bottom events, probability importance is usually defined as: if $Q_i(t)$ represents the i th a failure probability of bottom events in t time, $g(Q(t))$ represents the failure probability of top event in t time. Then the probability importance I_i is defined as:

$$I_i = \frac{\partial g[Q_i(t)]}{\partial Q_i(t)} \quad (1)$$

And we have the following theorem:

$$\frac{\partial g[Q_i(t)]}{\partial Q_i(t)} = g[1_i, Q(t)] - g[0_i, Q(t)] \quad (2)$$

Which $g[1_i, Q(t)]$ expression that in time t , the probability of top event failure when the bottom events is fails, $g[0_i, Q(t)]$ expression that in time t , the probability of top event failure when the bottom events is normal. And we can get the following normalized probability importance, which is the weight of each bottom event, is shown in table 1.

III. THE DETERMINATION OF MEMBERSHIP FUNCTION AND MEMBERSHIP DEGREE OF EACH BOTTOM EVENTS

Generally speaking, transformers will in a relatively good condition when their working years is less than 15 years, then the occasional failure is less. But when their working years is greater than 15 years, transformers will enter in loss stage [6]. According to everyday experience, when the transformers enter in loss stage, although some indicators of the bottom events in the normal state, it is more prone to failure at this moment which compare with the accidental failure period. For this two cases, this paper design two different membership functions for the same bottom events, in order to more accurately judgment for the operating state of transformer .

A. The determination of the quantitative indicators of bottom events' membership function when it in the accidental failure period.

According to the minimum fuzzy method [7], we are using ridge type distribution of membership functions to describe the fault feature index. Because the membership function of device degradation in the transformer is not a linear change, compared with the traditional triangle - trapezoid membership function, ridge type membership function can more accurately describe the index changes of fault characteristics.

In this paper, we as an example for the casing failure of the insulation resistance down B1 to determine the insulation resistance of subordinate function. According to the regulations, for transformer of 220kv and below its, the insulation resistance should not be less than $800 M \Omega$ at $20^\circ C$, and according to the practical experience, the insulation resistance is in good condition when it is greater than $1600 M \Omega$. Therefore, we can use the bigger the better type of ridge type membership function for the insulation resistance of subordinate function. Then we establish a set of evaluation for the operation condition of transformer insulation resistance. Respectively remember as {" good " " general" " warning " " damaged"}, then the insulation resistance of B1 ridge type membership function change into a comment set membership function. And through expert experience and the related regulations, we determine the fuzzy state level of each evaluation set, specific as follows.

Belong to the membership function of damaged state is :

$$f(x) = \begin{cases} 1, & x \leq 800 \\ \frac{1}{2} - \frac{1}{2} \sin \frac{\pi}{150} (x - \frac{1750}{2}) & 800 < x \leq 950 \\ 0 & x > 950 \end{cases} \quad (5)$$

Belong to the membership function of warning state is:

$$f(x) = \begin{cases} 0, & x \leq 850 \\ \frac{1}{2} + \frac{1}{2} \sin \frac{\pi}{200} (x - \frac{1900}{2}) & 850 < x \leq 1050 \\ \frac{1}{2} - \frac{1}{2} \sin \frac{\pi}{200} (x - \frac{2300}{2}) & 1050 < x \leq 1250 \\ 0 & x > 1250 \end{cases} \quad (6)$$

Belong to the membership function of general state is:

$$f(x) = \begin{cases} 0, & x \leq 1150 \\ \frac{1}{2} + \frac{1}{2} \sin \frac{\pi}{200} (x - \frac{2500}{2}) & 1150 < x \leq 1350 \\ \frac{1}{2} - \frac{1}{2} \sin \frac{\pi}{200} (x - \frac{2900}{2}) & 1350 < x \leq 1550 \\ 0 & x > 1550 \end{cases} \quad (7)$$

Belong to the membership function of good state is:

$$f(x) = \begin{cases} 0, & x \leq 1450 \\ \frac{1}{2} + \frac{1}{2} \sin \frac{\pi}{150} (x - \frac{3050}{2}) & 1450 < x \leq 1600 \\ 1 & x > 1600 \end{cases} \quad (8)$$

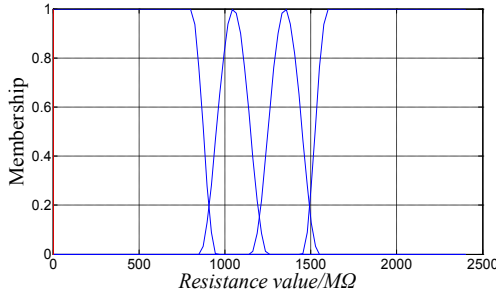


Figure 2. The membership function diagram of insulation resistance which in accidental failure period

Through the simulation of matlab, we can get the figure of the membership function is shown as figure2.

Similarly, we can get the other quantitative indicators' membership function which in the accidental failure period.

B. The determination of the quantitative indicators of bottom events' membership function which in the loss fault period.

For the transformer which using time is more than 15 years, because the probability failure of the transformer will change as the growth of the time of rendering index changing [5]. So the membership function of the bottom events is also changed. According to the literature [6], we can get the relationship of the transformer's operation failure probability and time is shown below:

$$f(t) = \begin{cases} 0.0619 & t \leq 15 \\ \frac{4.551}{28.1719} \times (\frac{t}{28.1719})^{3.551} & t > 15 \end{cases} \quad (9)$$

Then we can see when the operation of the transformer time is in 15 years ago, the probability of failure is in a

relatively stable value, but when the time is more than 15 years, the transformer's probability of failure present an index changes. On the basis of this function, this paper studies after 15 years, membership function will change as a function of run time, and with the increase of operation time, the transformer in the damaged membership will become more and more higher.

Because the relationship of the time of the operation of the power transformer and the probability of failure is in line with weibull distribution [5], in this paper, the relationship of the membership function of the transformer's bottom events and the transformer operating time is also in line with weibull distribution. The simplified form of weibull distribution is shown as follows:

$$\lambda(t) = \alpha \cdot t^{\beta-1} \quad (10)$$

Let's also take the insulation resistance for example. The membership functions is formula 3, because the transformer will be damage if the insulation resistance is less than 800 MΩ, we are set a1 to 800, a2 will changes with the running time, so the simplified form of weibull distribution is Change to formula 11:

$$a_2(t) = \alpha \cdot t^{\beta-1} \quad (11)$$

Then determine the parameters of α and β , according to many literatures and historical data record, the power transformer's life cycle is generally for 25 to 30 years, there is few transformer's using time is exceed 30years, so this article will be seen $t = 30$, $a_2 = 1450$ as a limit value, the initial value for $t = 15$, $a_2 = 950$, in this way, we can get $\alpha=182.1$ $\beta=1.61$, which is in formula11, $a_2(t)=182.1 \cdot t^{0.61}$, so the damaged state of membership functions of power transformer's insulation resistance which using time is more than 15 years is shown as follows:

$$f(x) = \begin{cases} 1, & x \leq 800 \\ \frac{1}{2} - \frac{1}{2} \sin \frac{\pi}{182.1 \cdot t^{0.61} - 800} (x - \frac{182.1 \cdot t^{0.61} + 800}{2}) & 800 < x \leq 182.1 \cdot t^{0.61} \\ 0 & x > 182.1 \cdot t^{0.61} \end{cases} \quad t \in \mathbb{Z} \text{ and } t \geq 15 \quad (12)$$

Similarly, we can get the other state of membership functions of the power transformer's insulation resistance, which using time is more than 15 years.

$$f(x) = \begin{cases} 0, & x \leq 450.5 \cdot t^{0.23} \\ \frac{1}{2} + \frac{1}{2} \sin \frac{\pi}{623.2 \cdot t^{0.19} - 450.5 \cdot t^{0.23}} (x - \frac{450.5 \cdot t^{0.23} + 623.2 \cdot t^{0.19}}{2}) & 450.5 \cdot t^{0.23} < x \leq 623.2 \cdot t^{0.19} \\ \frac{1}{2} - \frac{1}{2} \sin \frac{\pi}{802.8 \cdot t^{0.16} - 623.2 \cdot t^{0.19}} (x - \frac{802.8 \cdot t^{0.16} + 623.2 \cdot t^{0.19}}{2}) & 623.2 \cdot t^{0.19} < x \leq 802.8 \cdot t^{0.16} \\ 0 & x > 802.8 \cdot t^{0.16} \end{cases} \quad t \in \mathbb{Z} \text{ and } t \geq 15 \quad (13)$$

$$f(x) = \begin{cases} 0, & x \leq 712.3 \cdot t^{0.18} \\ \frac{1}{2} + \frac{1}{2} \sin \frac{\pi}{1021 \cdot t^{0.1} - 712.3 \cdot t^{0.18}} \left(x - \frac{1021 \cdot t^{0.1} + 712.3 \cdot t^{0.18}}{2} \right), & 712.3 \cdot t^{0.18} < x \leq 1021 \cdot t^{0.1} \\ \frac{1}{2} - \frac{1}{2} \sin \frac{\pi}{1369.2 \cdot t^{0.05} - 1021 \cdot t^{0.1}} \left(x - \frac{1369.2 \cdot t^{0.05} + 1021 \cdot t^{0.1}}{2} \right), & 1021 \cdot t^{0.1} < x \leq 1369.2 \cdot t^{0.05} \\ 0, & x > 1369.2 \cdot t^{0.05} \end{cases} \quad (14)$$

$$f(x) = \begin{cases} 0, & x \leq 1270.1 \cdot t^{0.05} \\ \frac{1}{2} + \frac{1}{2} \sin \frac{\pi}{1418.8 \cdot t^{0.04} - 1270.1 \cdot t^{0.05}} \left(x - \frac{1418.8 \cdot t^{0.04} + 1270.1 \cdot t^{0.05}}{2} \right), & 1270.1 \cdot t^{0.05} < x \leq 1418.8 \cdot t^{0.04} \\ 1, & x > 1418.8 \cdot t^{0.04} \end{cases} \quad (15)$$

If a transformer running time is 25 years, through the matlab simulation, we can get the membership function's curve as shown in figure 3:

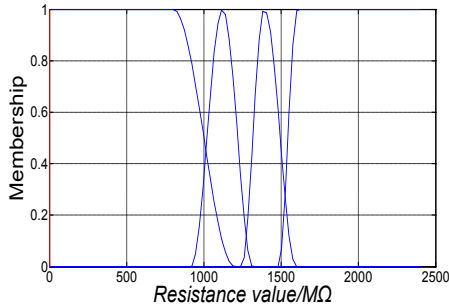


Figure 3. The membership function diagram of insulation resistance which in loss fault period

From the figure, we can see the difference of the transformer insulation resistance's membership function which using time is 25 years and 15 years.

C. The determination of the qualitative indicators of bottom events' membership function

For some of the qualitative indexes, such as discharge fault, and poor sealing etc, we adopt the fuzzy statistical test method, through the survey of experts, making the questionnaires and distribute to each expert, in order to determine each factor's membership degree. The expression is like this:

$$\text{membership} = \frac{\text{the number of experts who think factors } i \text{ belong to comments } j}{\text{the number of experts who participate in evaluation}} \quad (16)$$

D. The treatment of evaluation index

Based on the literature [2], for the management of evaluation indicators, we use the comprehensive evaluation of weighted average model.

$$B_j = A_j \circ R_j = \sum_{i=1}^m A_i R_i \quad (17)$$

When we get the B_j after calculation, we take the maximum membership degree principle, namely that we take the evaluation value element which is correspond with $B_{\max} = \max\{B_j | j=1,2,3,4\}$ for the final evaluation results.

IV. EXPERIMENTS

A transformer's model is SZ10-40000/110, running time is about 20 years. The experimental data are as follows: the gas volume which in the oil are shown in table 3, the pressure test for insulation resistance is needed, and the test is continued 15S and 60S in 27°C, then we get the value is $R_{15}=770M\Omega$ and $R_{60}=1460M\Omega$, absorption ratio is 1.90, dielectric loss rate and capacitance measurement are $\tan\delta=0.6\%$ and $C=280PF$, the biggest imbalance rate is 1.22%, the current of Core grounding is 33.26mA.

TABLE 2. The volume ratio of gas oil

gas composition	content (ug/L)
H ₂	178
CH ₄	42
C ₂ H ₂	0
C ₂ H ₄	13.6
C ₂ H ₆	9
Total hydrocarbon	58.4

First, the experimental data will be divided into quantitative index and qualitative index. For the quantitative indicators, because the transformer of this article selected has been running for 20 years, so it have entered the phase loss, therefore, the second kind of membership function is adopted to determine the membership degree. For example, we make a pressure test which is last 60S for insulation resistance in 27°C, we get the data is $R_{60}=1460M\Omega$, then get into the formula of membership function, we can get the judgment matrix of $R_1 = [0 \ 0, 0.92, 0.92]$.

$$R_{21} = \begin{bmatrix} 0 & 0.24 & 0.65 & 0.11 \\ 0 & 0 & 0.92 & 0.08 \\ 0 & 0.18 & 0.72 & 0.1 \\ 0 & 0.35 & 0.55 & 0.1 \\ 0 & 0.25 & 0.5 & 0.25 \\ 0 & 0.2 & 0.7 & 0.1 \\ 0 & 0.4 & 0.6 & 0 \\ 0 & 0.12 & 0.88 & 0 \\ 0 & 0.5 & 0.5 & 0 \\ 0 & 0.3 & 0.6 & 0.1 \\ 0 & 0.26 & 0.74 & 0 \\ 0 & 0.2 & 0.8 & 0 \\ 0 & 0.2 & 0.8 & 0 \\ 0 & 0.6 & 0.4 & 0 \\ 0 & 0.3 & 0.6 & 0.1 \\ 0 & 0.25 & 0.75 & 0 \\ 0 & 0.15 & 0.85 & 0 \\ 0 & 0 & 0.82 & 0.18 \\ 0 & 0.2 & 0.6 & 0.2 \\ 0 & 0.38 & 0.62 & 0 \\ 0 & 0.35 & 0.65 & 0 \end{bmatrix}$$

For some qualitative indexes such as short circuit fault, according to the expert survey, we can get the judgment matrix of $R_2 = [0 \ 0.2 \ 0.7 \ 0.1]$, and so on, we get the judgment matrix of the whole bottom events.

Then Combining with the allocation of weights and formula 17, we can get $B_{21} = A_{21} \circ R_{21} = [0 \ 0.251 \ 0.685 \ 0.062]$. By the calculation results, we know that the membership degree of the transformer in the damaged state is 0; the membership degree in the good state is only 0.06; the membership degree in the warning state is 0.25; the membership degree in the general state is 0.685. According to the maximum membership degree principle, we can presume that the operating state of transformer is most likely in the general state. And according to the actual data of transformer, the transformer has been a major overhaul, so the transformer's each index is roughly at a normal state and it can continue to run, but at this point the staff need to be timely tracking it, in order to master the real-time running status of transformer and to avoid accidents.

V. CONCLUSIONS

In this paper we use the theory of fuzzy comprehensive evaluation to establish the evaluation model of the transformer's operating state, and for the long running time transformer, proposed a more accurate way to determine its running state. First of all, we establish the fault tree model of the transformer, and then use the probability importance of the fault tree bottom event to determine the weight of each bottom event. Secondly, using the knowledge of the fuzzy comprehensive evaluation to determine the indicators

of each event's membership function, and give two different membership functions for the transformer respectively in accidental failure period and failure loss period. Lastly, the example results show that this method is more accurate assessment for the transformer which running time is long. Certainly, this model also needs more examples to verify.

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