Aging Assessment of Power Transformer Using Multi-parameters

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Abstract: As the population of transformers in service increases and their operating time extends, much attention has been focused on their availability and reliability. However, insufficient research work concentrates on how to evaluate transformer's aging condition, although huge progress has been made on the techniques of fault diagnosis and condition assessment of transformer in past decades. This paper presents the concept of Aging Index (AI), which is a practical tool that combines the results of routine inspections, and site and laboratory testing to estimate the aging condition of oil-immersed transformers. Further, frequency domain spectroscopy (FDS) as a novel non-destructive testing technique to estimate remained life expectancy is included in aging evaluation system. Moreover, a software system based on transformer's electrical and thermal parameters is developed correspondingly, by using a multi-parameters analytic approach. This system would dedicate to decision-making and replacement planning and has good application prospects.

Keywords: aging assessment, power transformer, aging index, hot spot temperature, dielectric response, life expectancy.

1. Introduction

As the most expensive and important equipment in electric power system [1-2], power transformer plays a vital role in maintaining reliable and efficient electricity supply. However, as the population of transformers in service is increasing and growing older, much and much attention has been paid on their aging condition and life assessment than ever. Since a transformer is continuously subjected to thermal, electrical, mechanical and chemical stresses *etc* during its operation [3], it is necessary to include comprehensive parameters while establishing an aging assessment system.

Recently, condition assessment and asset management are both promising technologies for grid enterprises to manage their power equipment. However, assessing whether a transformer is aged or not based on only one kind of test technology or some kinds of combined test results may be an impossible mission yet, since aging process and intrinsic mechanism are very complicated and still opaque up to now [2-4]. A possible optional way may be selecting parameters which are most closely related to insulation aging, then optimizing hierarchy between them and scoring or ranking. In this paper, the concept of Aging Index (AI) is proposed, which represents a practical tool to combine the results of routine inspections, site and laboratory testing to estimate the aging condition of transformer. According to long-term field engineers' experience and some standard recommendation [5-7], this Aging Index calculation considers not only typical electrical and oil quality testing results and hot spot temperature estimation, but also dielectric response tests, as a kind of novel non-destructive testing techniques are also included to estimate the remained cellulose degree of polymerization (DP).

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2. Parameters and Tests

Almost every electric power company has its own test items for transformer, however, the typical testing items employed as well-accepted diagnostic methods are similar all over the world [8]. In this paper, the authors categorize the routine inspections, site and laboratory testing into three groups: typical electrical testing, oil quality testing and hot spot temperature estimation, *etc*.

A. Electrical testing

A.1 Insulation resistance

Insulation resistance measurement may be the simplest on-site testing but also useful one that could determine whether tested object is integrally moistened or inter-connectively deteriorated. Generally, the insulation resistance R_{60} after applying voltage for 60 seconds is required for analysis; additionally absorptance (K_a) and polarization index (PI) are also needed to have an overall judge. It is worth noting that temperature translation is necessary before ranking to get normalized values.

A.2 Leakage current

Leakage current measurement is with the same testing circuit as insulation resistance measurement, but with much higher applied voltage and higher sensitivity which are easier to detect insulating defects and deterioration. Table 1 lists a scoring method based on the recommended threshold value from "Regulations of Condition-Based Maintenance & Test for Electric Equipment" (Q/GDW168-2008) issued by China State Grid Company [9]. Besides, in practical operation, a fault may also occur even when the test result does not exceed the thresholds but only displays a quick increase, so the variation ratio is considered. This table is just a baseline and it can be adjusted with the utility practice, if necessary.

Table 1. Scoring method based on leakage current factor

Condition	Ranking
$L_C \leq 100\mu A$ and ($\lvert Var_L \rvert \leq 30\%$)	100
$L_C \leq 100\mu A$ and ($30\% < \lvert Var_L \rvert < 50\%$)	80
$L_C \leq 100\mu A$ and ($\lvert Var_L \rvert \geq 50\%$)	60
$L_C > 100\mu A$	40

NOTE: In Table 1 the L_C means leakage current and Var_L presents variation ratio of leakage current.

A.3 Dissipation factor

Dissipation factor or power factor is an important data source to monitor the condition of a transformer and its bushing. This test is performed to determine the condition of capacitive insulation between different winding and compartments [10]. A similar ranking method with leakage current is introduced based on recommended threshold value, as shown in Table 2.

Table 2. Scoring method based on dissipation factor

Condition	Ranking
$\tan\delta \leq 0.8\%$ and ($\lvert Var_D \rvert \leq 30\%$)	100
$\tan\delta \leq 0.8\%$ and ($30\% < \lvert Var_D \rvert < 50\%$)	80
$0.8\% < \tan\delta \leq 1\%$ and ($\lvert Var_D \rvert \geq 50\%$)	60
$\tan\delta > 1\%$	40

NOTE: In Table 2 the Var_D presents variation ratio of dissipation factor.

B. Oil Testing

B.1 Dissolved gas analysis (DGA)

DGA of insulating oil is universally used and considered as an important indicator of a transformer's overall condition all over the world. References [5-6,8] provide guidance for the interpretation of DGA results in service. Based on the statistics of more than 6000 groups of DGA data, Chinese guidelines of test and maintenance regulate the alert concentrations of fault indicator gases [11], as listed in Table 3. When the concentration of any gas exceeds the alert value, the related diagnostic module will be triggered. Several kinds of diagnostic methods are available to identify the type of fault involved (e.g., arcing, partial discharges or overheating), such as T-D (Thermal-Discharge) or Cube Graphic method [11], Duval Triangle method [11], etc, as shown in Figure 1.

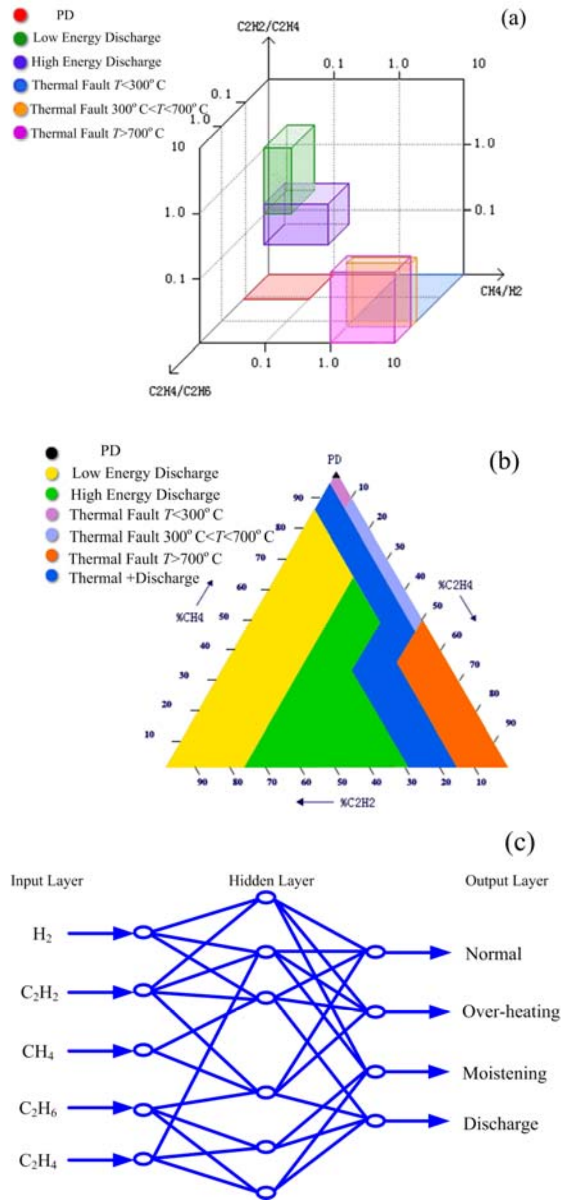


Figure 1. Different diagnostic methods based on DGA data
(a) Cube Graphic method; (b) Duval Triangle method; (c) ANN method

Table 3. Alert Value of fault indicator gases /ppm

H_2	C_2H_2	$\sum C_1+C_2$ (CH_4,C_2H_6,C_2H_4,C_2H_2)
150	5 (U<500kV) 1 (U>=500kV)	150

The principals of Cube Graphic and Duval Triangle are all based on ratio of fault indicator gases. Accordingly, there are possible cases that on the boundary of ratio threshold a miscarriage of diagnosis would occur for Cube Graphic. However Duval triangle always gives a diagnostic result which could solve the above-mentioned problem in cube graphic. So, the system utilizes cube graphic for initial diagnosis, and Duval triangle for checking. Further, advanced method based on artificial neural network (ANN) with back-propagation (BP) algorithm is also introduced. More than 830 instances of typical on-site DGA data are collected to train an ANN to adjust each weight factor. While trainings are finished, the weights are fixed and imbedded into the software system to form an expert-subsystem.

B.2 Carbon contents of oil

Besides key gas components dissolved in oil, carbon content is also a significant indicator of aging since main decomposition byproducts of cellulose are CO and CO_2. The formation of CO_2 and CO from oil-impregnated paper insulation increases rapidly with temperature.

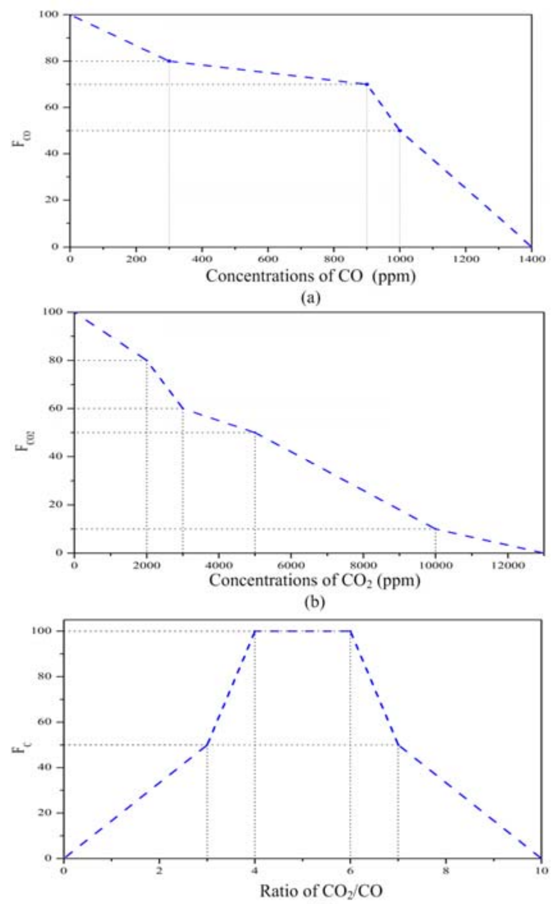


Figure 2. Scoring method based on carbon contents factor
(a) CO (b) CO_2 (c) CO_2/CO

CO_2/CO ratio less than 3 is generally considered as an indication of probable paper involvement in a fault, with some degree of carbonization. Therefore, the concentration of CO and CO_2 and CO_2/CO are used in scoring and ranking. To obtain a flexible scoring, piecewise functions are employed to describe the variation of score with gas concentrations, as shown in

Considering the different recommendations above, carbon content factor is calculated according to

$$F_{C,O} = \sum_{i=1}^{3} \omega_i \cdot F_{C,O}(i) \tag{1}$$

Where i=1, 2, or 3, and ω_i is the assigned weight. An initial value for ω_i is allocated to be 1/3 for three parameters, respectively. Each weight can be optimized in practice.

B.3 Oil quality testing

Subjected to electrical, thermal and chemical stress in runtime operation, transformer oil would gradually get deteriorated, therefore a combination of electrical, physical and chemical tests is performed to establish condition maintenance procedures. Considering the recommendations [5], dielectric strength, acidity, interface tension (IFT), power factor and oil color are chosen to be key factors of oil quality. Table 4 suggests a scoring method similar with Table 2, and the recommended weights are listed in the system diagram.

Table 4. Scoring method based on different oil parameters

Category	U≤66kV	66<U≤220kV	U>220kV	Ranking
Dielectric Strength /kV	≥40	≥47	≥50	100
	35-40	42-47	45-50	80
	30-35	35-42	40-45	60
	<30	<35	<40	40
Acidity /mg(KOH)·g^{-1}	≤0.05	≤0.04	≤0.03	100
	0.05-0.1	0.004-0.1	0.03-0.07	80
	0.1-0.2	0.1-0.15	0.07-0.1	60
	≥0.2	≥0.15	≥0.1	40
IFT(25°C) /mN·m^{-1}	≥25	≥30	≥35	100
	20-25	23-30	25-35	80
	15-20	19-23	20-25	60
	<15	<19	<20	40
tanδ (%) (90°C)	<1.5	<1	<0.5	100
	1.5-3	1-1.5	0.5-1	80
	3-4	1.5-3	1-2	60
	≥4	≥3	≥2	40
Color	light yellow			100
	yellow			80
	dark yellow			60
	chocolate brown			40

B.4 Others parameters

Besides above-mentioned parameters, furan and water content are also included in the assessment system. However, a furan test is not a routine or periodic testing item for power transformer; it is usually employed as a post-diagnostic technique [4, 13]. It should be pointed out that it is difficult to derive an exact DP value correlation from the furan content. It is only an adjuvant measurement and only the sum of different procedures (DGA, humidity in oil and paper, *etc*) with fingerprint and trend analysis would enable the life assessment [2]. Figure 3 depicts a scoring method based on furan contents. A corresponding diagnostic strategy may be given by ranking A, B, C, D and E. Moreover, water content is also chosen as a factor to influence transformer's condition.

C. Temperature and aging

The hot spot temperature inside winding is usually the principal factor limiting the load ability and accelerating the aging of a power transformer. Higher hot spot temperature causes degradation of insulation material and can result in the formation of gas bubbles which could cause dielectric breakdown of a transformer [7].

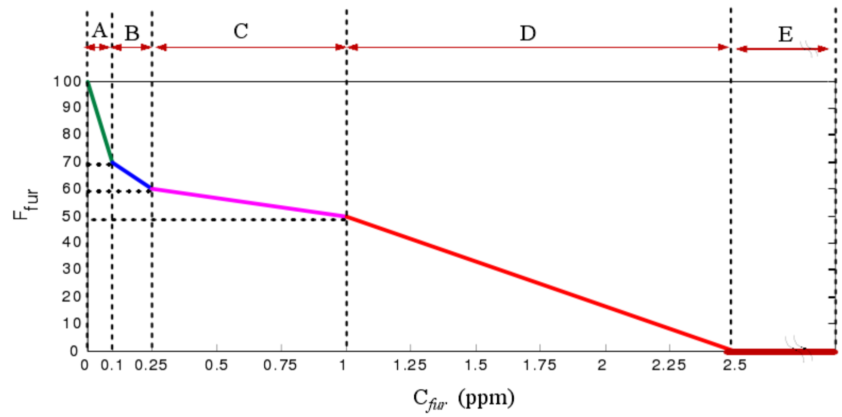


Figure 3. Scoring method based on furan contents

Generally, hot spot temperature can be measured by installing optical fiber device. If the temperature sensor is not available, we can calculate hot spot temperature with ambient temperature and top oil temperature, considering the cooling manner of transformer. Take the natural oil circulation (ON) cooling as example, the calculation of hot spot temperature could be simplified as following

$$\theta_h = t_2 + Hg_r K^y \tag{2}$$

Where θ_h and t_2 denote hot spot temperature and top oil temperature, respectively, Hg_r is the hot spot temperature rise over top oil temperature, the empirical value is 23°C for ON transformer and 38°C for OFF transformer; K is the ratio of actual load current to rated load current, and y is windings' temperature index, the empirical value is 1.6.

Reference [7] points out that the rate of deterioration of mechanical properties could be accelerated twice for 5-10°C increase. Actually the thermal aging factor is not a constant, however, IEC standard simplifies it as 6°C law. Then the cellulose aging rate, v, can be estimated by the following term

$$v = 2^{(\theta_h - 98)/6} \tag{3}$$

Then remaining life of transformer can be estimated through integrating of aging rate between the intervals of service time. It is worthy noted that, even the daily load is readily available, it is really a labor-demanding work using to achieve the remaining life, therefore an average load rate for a week or a month is proposed to simplify the calculation in practice.
Dielectric Response to Estimate Cellulose's Degree of Polymerization

3. Dielectric Response to Estimate Cellulose's Degree of Polymerization

Dielectric response is a non-invasive diagnostic method with a potential to give information about the status of solid insulation in a power transformer. The dielectric response characteristics can be recorded in time or frequency domain. Generally, a time domain current measurement records the charging and discharging currents, also known as Polarization and Depolarization Currents (PDC) [14]. The frequency domain measurements are derived from the well-known tanδ measurements with a scanning frequency range (*e.g.* 0.1mHz~5kHz), called as frequency domain spectroscopy (FDS) [15]. The combination of PDC with FDS drastically reduces the test duration compared to the separate measurement techniques [16].

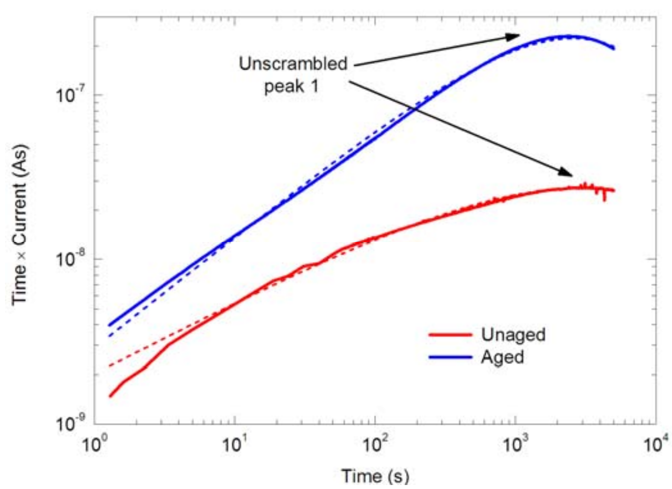
In this paper, PDC and FDS unscrambling algorithms are both proposed and employed to estimate the DP of pressboard cellulose and remaining life through fitting experimental data. Generally, two types of relaxation polarization mechanisms are observed, *i.e.*, the interfacial polarization between oil and paper insulation, and that inside pressboard. Take FDS unscrambling process for example, FDS test can be used to measure the dissipation factor tanδ, real capacitance *C*' and imaginary capacitance *C*'' of oil-paper insulation at different frequencies. The mathematic model can be expressed as following

$$\chi^*(\omega) = \sum_{i=1}^{M} \chi^*_{DS\_i}(\omega) + \sum_{j=1}^{N} \chi^*_{CCS\_j}(\omega) \tag{4}$$

Where $\chi^*_{DS\_i}$ and $\chi^*_{CCS\_j}$ denote dipolar system's (DS) and charge carrier system's (CSS) complex polarizability, respectively; *M* is number of DS polarization and *N* is number of CSS polarization. The real part $C'(\omega)$ of complex capacitance represents capacitance component of insulation material, and the imaginary part $C''(\omega)$ represents the losses component. The fitting results show good identification with real data, as shown in Figure 5.

4. Aging Index Calculation

Figure 6 provides the processing flowchart of main condition parameters and summary of scoring system for aging condition assessment of transformers. The total scores are used for calculating the final AI. For each factor, its weighting coefficient is described in the system diagram. In our present paper, the weight of each component is decided mainly by the more than 15 field engineers and experts in different grid companies of China. The final score is a number from 0 (severely degraded condition) to 100 (perfect condition), as shown in Table 5.



— Measured, --- Unscrambled

Figure 5. tanδ_{min} at different temperatures

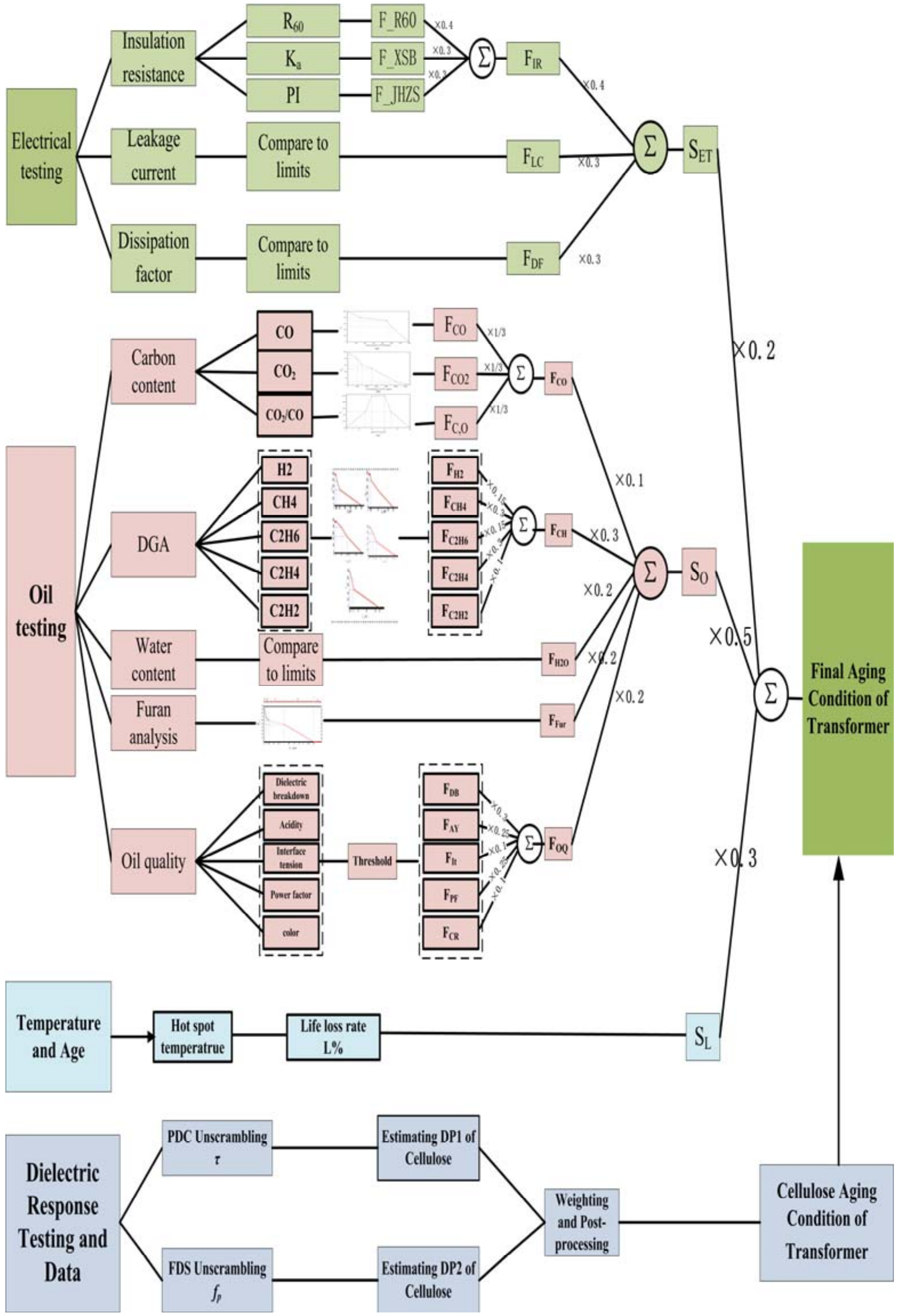


Figure 6. System diagram of aging assessment of transformer using multi-parameters

Table 5. Aging condition ranking based on Aging Index

Aging Condition	Scores
Very Good	[80,100]
Slightly Aged	[60,80)
Fairly Aged	[40,60)
Very Aged	(0,40)

An Example Analysis based on Aging Index

Here an actual example is presented using above-mentioned aging assessment method. The objective is a 110kV power transformer (SFPSZ9-31500/110) which has been commissioning since June, 1997. For aging assessment, its testing data is collected as complete as possible, as shown in Tables 6-8.

Table 6. Leakage current in recent years /μA

Date	Leakage current (different windings to ground)
May 5, 2010	35 (HV) 42 (MV) 50 (LV)
March 5, 2011	38 (HV) 45 (MV) 123 (LV)

Table 7. Most recent key gas concentration /$\mu L \cdot L^{-1}$

H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2
217.5	40	4.9	51.8	67.5	464.7	126.4

Table 8. Most recently tested oil quality /$\mu L \cdot L^{-1}$

Dielectric Strength /kV	Acidity /$mg(KOH) \cdot g^{-1}$	IFT(25°C) /$mN \cdot m^{-1}$	tanδ(90°C) /%	Color
39.5	0.195	20	1.75	yellow

According to Table 1, Figure 2 and Table 4, the score of leakage current item, carbon content and oil quality item are 40, 91 and 57, respectively. The DGA diagnostic results show that the most likely fault is high energy discharge using expert subsystem, and the score of DGA is 54. Additionally, full scores are assigned to those unavailable testing data or item, as statistically evidence is absence. Therefore, the final AI is 74, indicating the transformer is in slightly aged status, but the severe discharge fault needs a preferential maintenance arrangement.

Conclusions

In this paper, an approach to evaluate transformer's aging condition is introduced based on multi-parameters analysis. Aging Index as a useful tool combines the electrical testing, oil quality testing, hot spot temperature and dielectric response characteristics to estimate a transformer's aging rate. FDS and PDC testing, as a novel non-destructive testing technique, are included in the system to estimate remained cellulose's life expectancy through unscramble, extracting and fitting characterization parameters. A corresponding software system is developed to make condition-based maintenance plan of transformers. Currently the weighting factors are based on the experience of field engineers and think-tank, which make the diagnostic system practicable but somewhat subjective. More self adaptive methods based on intelligent algorithm are still needed to be explored in our future work.

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