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Grey Relational Analysis for Insulation Condition Assessment of Power Transformers Based Upon Conventional Dielectric Response Measurement

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Abstract: Conventional dielectric response measurement techniques, for instance, recovery voltage measurement (RVM), frequency domain spectroscopy (FDS) and polarization–depolarization current (PDC) are effective nondestructive insulation monitoring techniques for oil-impregnated power transformers. Previous studies have focused mainly on some single type of dielectric measurement method. However, the condition of oil paper insulation in transformer is affected by many factors, so it is difficult to predict the insulation status by means of a single method. In this paper, the insulation condition assessment is performed by grey relational analysis (GRA) technique after carefully investigating different dielectric response measurement data. The insulation condition sensitive parameters of samples with unknown insulation status are extracted from different dielectric response measurement data and then these are used to contrast with the standard insulation state vector models established in controlled laboratory conditions by using GRA technique for predicting insulation condition. The performance of the proposed approach is tested using both the laboratory samples and a power transformer to demonstrate that it can provide reliable and effective insulation diagnosis.

Keywords: recovery voltage measurement; polarization–depolarization current; frequency domain spectroscopy; grey relational analysis; oil-impregnated transformers

1. Introduction

An oil-impregnated transformer is commonly considered as one of the most crucial pieces of equipment in the electric power transmission and distribution systems [1–3]. Unfortunately, it is a fact that the electrical and mechanical properties of the transformer oil-paper insulation system become aging gradually due to the combination stresses of the mechanical vibration, thermal, electrical, oxygen, water and other factors, in the long-term service process [4–8]. Historically, the applications of oil sample analysis (OSA) in terms of equilibrium relationships between insulating oil and cellulose insulation, dissolved gas analysis (DGA), dielectric loss factor (DLF) and insulation resistance (IR) have been commonly used for performing non-destructive condition monitoring of transformer insulation [9–12]. However, the OSA technique only presents limited knowledge about the aging status of transformer solid insulation. In addition, results obtained using IR and DLF measurements may not diagnose the transformer insulation effectively [13]. With regard to the DGA technique, the interpretation of DGA results is often very difficult due to the gas fluctuation and migration between mineral oil and cellulose paper [14–16].

In order to predict the transformer insulation conditions nondestructively and reliably, a large amount of insulation information of transformers needs to be provided. Therefore, the development of dielectric response diagnostic techniques, for instance, polarization and depolarization current (PDC) [17,18], recovery voltage measurement (RVM) [19–21] and frequency domain spectroscopy (FDS) [22–25] has greatly been promoted in the past several years.

The interfacial polarization spectrum obtained from the RVM, the polarization and depolarization currents obtained from the PDC measurement and the dielectric loss factor spectrum obtained from FDS measurement are believed to be related to the aging status and moisture content of transformer oil-paper insulation system. However, it is complicated to predict the actual state of the insulation and perform the estimation of transformer performance by using any one type of dielectric response measurement data. Meanwhile experienced artificial intelligent algorithm (AIA) will be necessary. To employ a reliable AIA technique in transformer insulation condition prediction is believed to be a good alternative approach. The application of AIA for insulation diagnosis of the transformer oil-paper insulation system has already been reported by some researchers [26–29]. These AIA techniques are based on the principle of the transmission of human expert knowledge into the system and using it with the same results as consulting the human experts.

Authors in [13] reported that an expert system (ES) was used for determining the condition of the oil-paper insulation. The performance of the ES as an in-built routine is capable of estimating the value of oil-moisture content at any specific temperature. Unfortunately, the oil-moisture content at 38 °C obtained from this value of paper moisture content may give rise to misleading conclusions due to the fact that the equilibrium curve is unreliable. Saha and Purkait [2] reported an ES tool for transformer insulation condition assessment based upon the RVM and PDC techniques. However, the database should be strengthened due to the data insufficiency of RVM and PDC in field. Otherwise, the performance of the ES as an in-built routine capable of estimating the value of oil moisture content at any specific temperature may be affected. Sarkar et al. [30] reported a method to combine the PDC and RVM data to obtain optimized insulation models of a number of in-situ power transformers and these optimized insulation models are then used to obtain the relationship of moisture content between oil and paper. The authors believe that the oil-moisture content can be obtained from the values of branch capacitance on the lowest time constant branch in Debye model. Unfortunately, the oil-moisture content is unreliable because of the insulation geometry dependent in branch capacitance. In addition, due to the temperature dependent of central time constant (CTC), the oil-moisture content obtained from the CTC technique is also unreliable. Authors in [31] proposed a support vector machine (SVM) algorithm to provide an effective tool for quantifying the insulation condition of transformers based on PDC measurement. The SVM algorithm used the parameters of resistance and capacitance with the smallest time constant branches and the largest time constant branches as the difference features for insulation liquid and insulation paper, respectively. These parameters were calculated from the measured PDC data. However, quantifying the insulation conditions of transformers is very difficult due to the insulation geometry dependent in branch resistances and capacitances.

The insulation system of a transformer is a typical complex system (i.e., a grey system [32] defined as GRA). The GRA technique is an analysis of the geometric proximity between different discrete sequences of systems. The basic concept of GRA is based on the similarity of the geometry of sequence curves [33–35]. Generally, the closer the curves, the bigger the associated degree between the corresponding sequences. If the two relative changes in the development process are basically consistent, their relevance is great; on the contrary, their correlation is small.

The aim of this paper is to investigate GRA technique for insulation condition assessment of transformers based upon comparative calculations of insulation condition sensitive parameters derived from conventional dielectric response measurement data. The proposed GRA technique aims at obtaining reliable and quick decision on insulation condition prediction using the PDC, RVM and FDS data, which can provide valuable information for the arrangement of transformer maintenance schemes. In this study, oil-impregnated pressboards with different thermal aging degrees and moisture contents are firstly prepared under well-controlled laboratory conditions. Then, the physical and chemical parameters and the PDC, RVM and FDS of the pressboard samples are tested and analyzed. After that, the key idea of the GRA technique and the extraction method of insulation condition sensitive parameters are also presented. Finally, the GRA technique is applied to both the laboratory samples and the field transformers to demonstrate that it can provide reliable and effective insulation diagnosis.

2. Preparation of Experimental Samples

In order to obtain insulation condition sensitive information derived from conventional dielectric response measurement data such as PDC, RVM and FDS in laboratory, it must prepare experimental pressboard samples. The test materials utilized for our experimental activities are Karamay No. 25 naphthenic mineral oil and conventional cellulose pressboards with the diameter of 80 mm and thicknesses of 2 mm. These commercial grade mineral oil specimens have very good electrical and physicochemical properties, which perfectly satisfy ASTM D3487-2000(II). We employ a three-electrode test apparatus to perform the PDC and FDS measurements of oil-impregnated cellulose samples. This test instrument contains three electrodes manufactured with brass material (a voltage electrode, a measuring electrode and a guard electrode). The oil-impregnated cellulose samples are placed in the three-electrode test cell filled with dried and degassed insulation oil and fixed by a spring. Before testing of PDC and FDS, the three-electrode test cell was placed in a constant humidity and temperature chamber to insure temperature equalization between pressboard samples and insulation oil. The PDC and FDS measurements are executed with DIRANA (Chinese version, OMICRON electronics GmbH, Klaus, Austria) made by the widely known corporation in Austria. This test equipment is directly connected to the three-electrode test cell located in the chamber.

2.1. Preprocessing Activities of Pressboard Samples

In order to control the initial moisture content and reliably prepare oil-impregnated pressboard samples with different moisture contents and aging degrees, it is necessary to preprocess the pressboard samples. The detailed preprocessing activities are as follows. Firstly, the pressboard samples are dried in a vacuum tank at 105 °C/50 Pa for 48 h. Secondly, the dried and degassed insulation oil is heated to 40 °C/50 Pa. Then, these dried mineral oil and pressboard samples are placed into the vacuum tank with vacuum impregnation for 48 h. Finally, the oil-impregnated pressboards are randomly sampled to determine the initial moisture content by using a Karl Fischer titration method according to IEC 60814. The three measurement objects of oil-impregnated pressboards are the center, edge and the middle part between the center and edge of the oil-impregnated pressboards. Each measurement part is repeatedly measured three times in the same procedure to eliminate measuring errors caused by a personal factor. From the measurement results, the amount of initial moisture content in oil-impregnated pressboard is 1.11%.

2.2. Preparation of Pressboard Samples with Different Aging Degrees

In this study, the accelerated thermal aging experiments of samples are implemented to prepare the oil-impregnated pressboards with different aging status. Firstly, the insulation oil and oil-impregnated pressboard samples preprocessed in Section 2.1 are taken out from the vacuum chamber and then placed into five thermal aging cans named as No. 1, No. 2, No. 3, No. 4 and No. 5, respectively. Secondly, the can of No. 1 is used to conserve unaged samples and the other four are vacuumed and filled up with both pure nitrogen and a given amount of coppers. Thirdly, the four cans are placed into an aging oven to perform an accelerated thermal experiment at 130 °C. Then, the four cans (aged for 8 days, 21 days, 32 days and 42 days, respectively) are conserved successively for 48 h at room temperature and after that the pressboard samples are taken out of the cans. Finally, the pressboard samples with five aging conditions are measured for obtaining the physicochemical parameters in laboratory.

2.3. Preparation of Pressboard Samples with Different Moisture Contents

The pressboard samples with same aging degrees will also lead to different dielectric response test results due to different moisture contents. Therefore, the moisture absorption experiment of pressboard samples with same aging degrees is performed to prepare four different expected moisture content levels (1%, 2%, 3% and 4%), which serves our studies on influences of the moisture contents on the PDC and FDS results. The moisture absorption experiment is implemented at the following steps. In each test, three pieces of pressboards are taken from the samples at the corresponding aging stages. The insulation oil on the surface of the pressboards is cleaned for easy absorption of moisture. Then, the pressboards are placed on the precise electronic balance to record the initial weights. The required weights of the samples after absorbing the target moisture are calculated. After reaching target weights, the pressboards are rapidly put in the three-electrode test cell and stood for 48 h under 45 °C.

3. Analysis of Experimental Results

3.1. Moisture Contents and DP (Degree of Polymerization) of Pressboards

The moisture contents and DP values of the pressboard samples during the aging process are measured by a Karl Fischer moisture meter (English version, Metrohm, Greifensee, Switzerland) and an automatic viscosity tester (Chinese version, Shanghai S.R.D. Scientific Instrument Inc., Shanghai, China). The measured results are shown in Table 1. It can be seen that the moisture contents varied in the range of 1.11~1.26%. And the DP values are recommended as a reliable characterization of paper aging. In order to value aging degrees of oil paper insulation, the DP values of oil-impregnated pressboards are measured in the laboratory. From Table 1, it is obvious that the DP values decrease with the increasing aging time.

Table 1. Moisture contents and DP of pressboards during the aging process.

Pressboard Samples	0 Day	8 Days	21 Days	32 Days	42 Days
DP values	1285	994	841	550	415
Moisture contents (%)	1.11	1.02	1.26	1.06	1.17

The fluctuation phenomenon of moisture contents can be interpreted as follows. The high temperature results in the pyrolysis of celluloses and then some by-products of them are moisture. Firstly, the high aging temperature causes the moisture in pressboards to move into the oil. When the relative humidity of oil is greater than the nitrogen above the oil-paper insulation, the moisture would migrate from oil to the nitrogen. At last, the moisture transfers among the nitrogen, pressboards and insulating oil. It is worth noting that the moisture may be kept in the shape of water vapor in the nitrogen and later escaped from the environment during sampling [36,37].

3.2. PDC Results and Analysis

Figure 1 showed the test results of polarization current of the oil-paper insulation samples with different moisture gradients at the same expected aging condition under 45 °C. Except for the abnormal results from the samples with the moisture content of 2.82% which have been aging for 8 days, it could be seen that the polarization current curve of the oil-paper insulation sample with different moisture gradients moved to the upper left as moisture content increases and the tail of the polarization current increased gradually. It is indicated that the conductivity of insulation transformer oil and pressboards increased gradually.

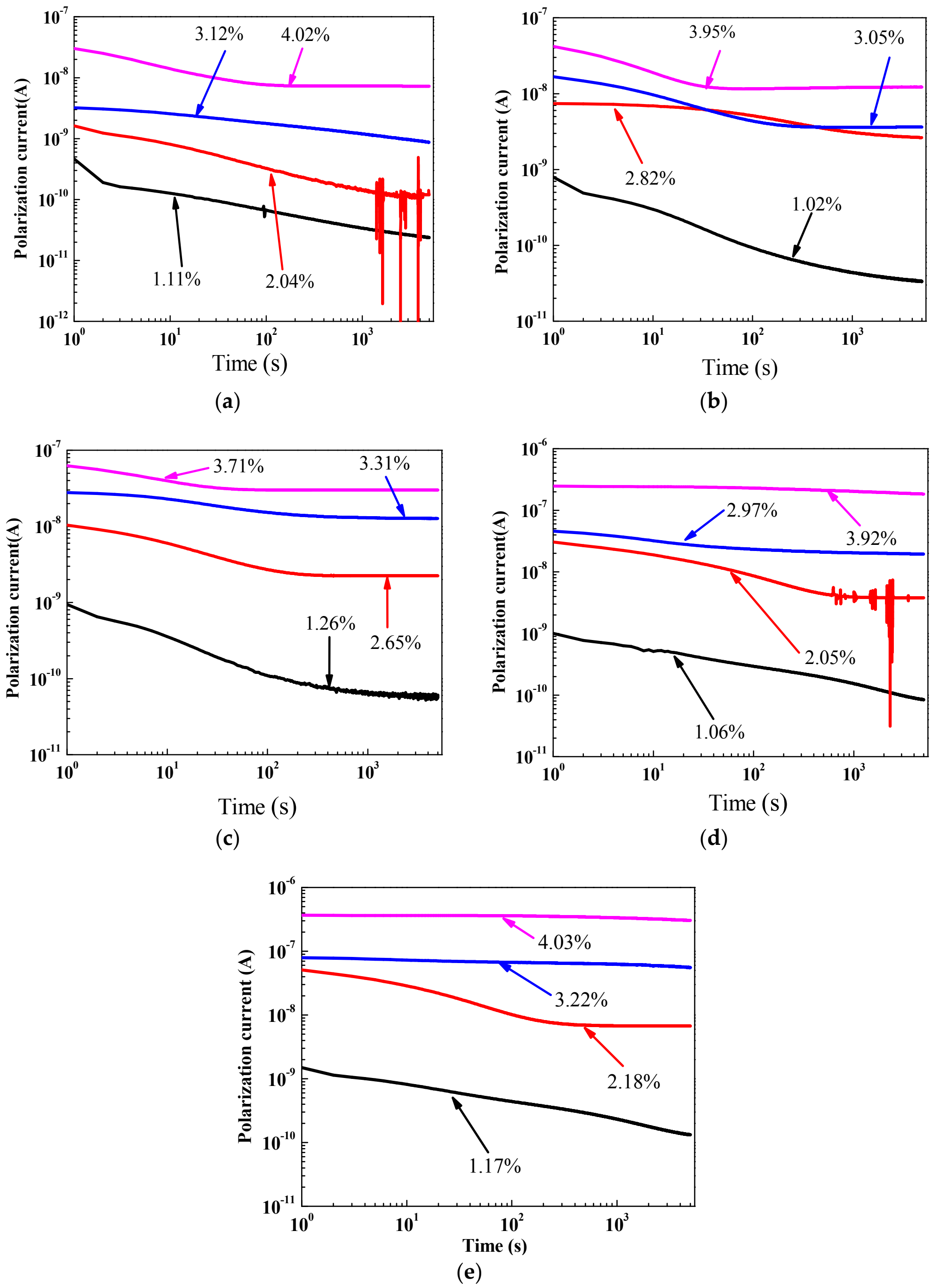


Figure 1. Polarization current results of oil-impregnated pressboards. (**a**) Aged 0 day; (**b**) Aged 8 days; (**c**) Aged 21 days; (**d**) Aged 32 days; and (**e**) Aged 42 days.

Figure 2 showed the test results of depolarization current of oil-paper insulation samples with different moisture gradients at the same expected aging condition under 45 °C. It is obvious that with increasing of moisture contents, the depolarization current curves moved to the top left overall. Moreover, the tail of the depolarization current curves increased gradually under different moisture contents.

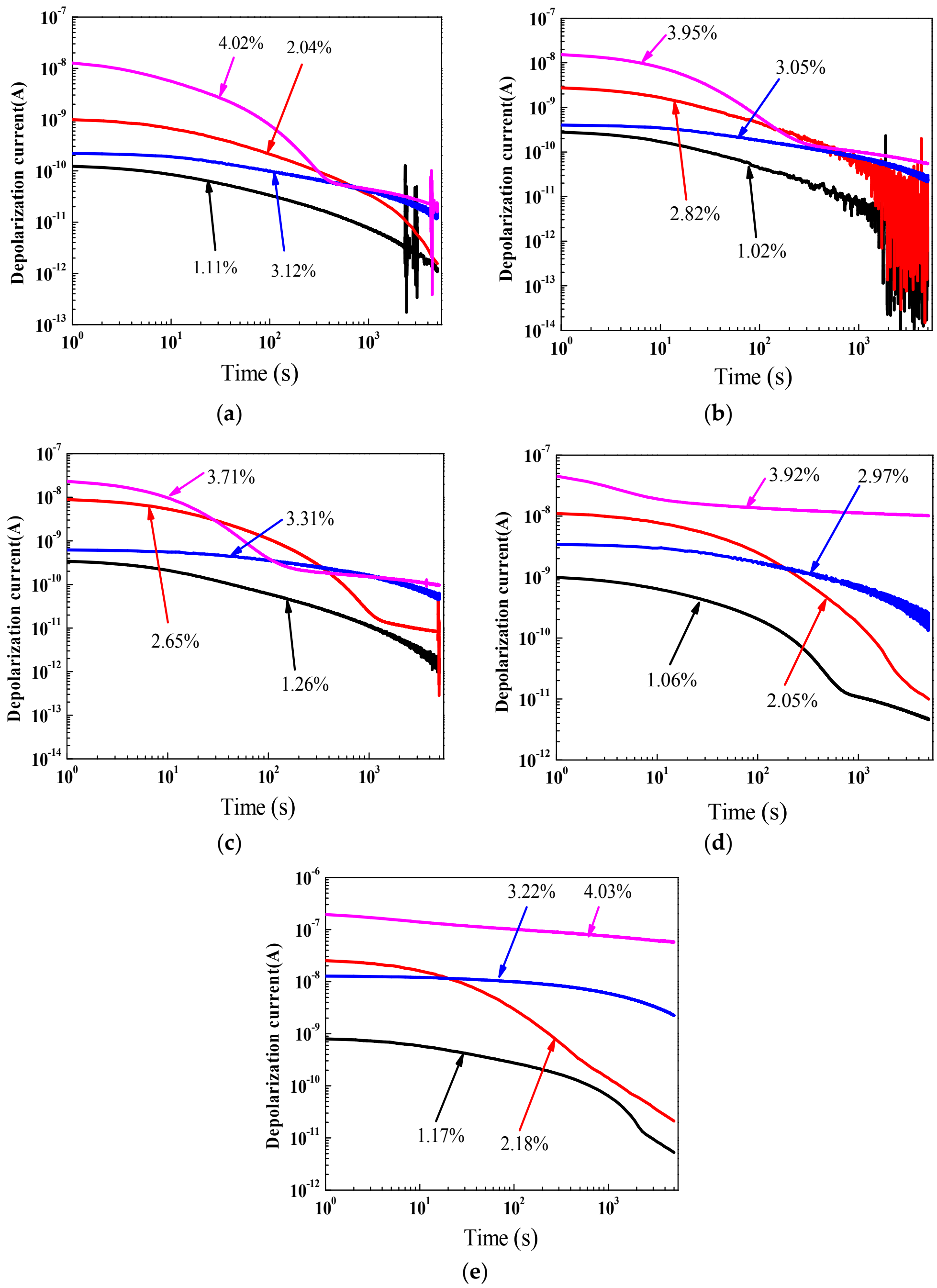


Figure 2. Depolarization current results of oil-impregnated pressboards. (**a**) Aged 0 day; (**b**) Aged 8 days; (**c**) Aged 21 days; (**d**) Aged 32 days; and (**e**) Aged 42 days.

3.3. FDS Results and Analysis

Figure 3 shows the tan δ curves of oil-impregnated pressboards with different moisture gradients at the same expected aging condition under 45 °C. It is obvious that tan δ values of the pressboard samples increases gradually with increasing of the moisture contents in almost all frequency regions. This observed phenomenon can be interpreted by that the water is a strong polar substance and can increase the amount of molecules per unit volume in the pressboards. However, it is found that the tan δ values remain essentially unchanged in the high frequency area.

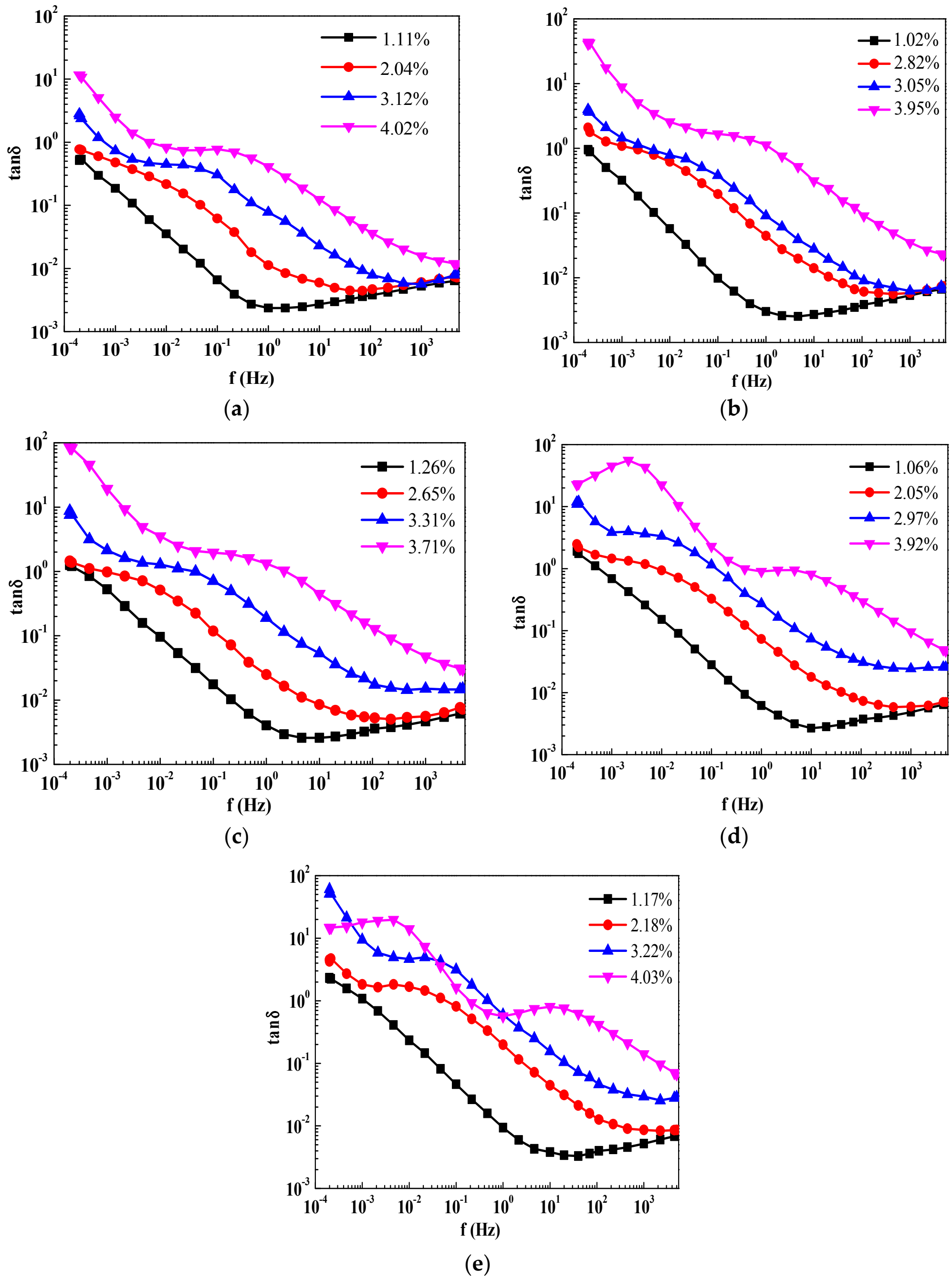


Figure 3. FDS results of oil-impregnated pressboards. (**a**) Aged 0 day; (**b**) Aged 8 days; (**c**) Aged 21 days; (**d**) Aged 32 days; and (**e**) Aged 42 days.

4. Introduction of GRA Technique and Extraction of Insulation Condition Sensitive Parameters

4.1. Introduction of GRA Technique

The insulation system of transformer can be deemed to a typical gray system. The theory of grey system determines the correlation degree between known and unknown objects according to the similarities or differences of different factors [32,38,39]. The advantage of GRA technique is that it does not require a large number of test samples. The grey related algorithm can be depicted as follows.

Setting X_i is the insulation condition (i = 1, 2, ..., m) and the insulation condition includes k observed objects (k = 1, 2, ..., n). $x_i(k)$ is the observed object of the sequence number k ($x_i(k)$ is represented for the characteristic parameter of insulation condition in a transformer), the X_i can be written as:

$$X_i = (x_i(1), \ldots, x_i(k), \ldots, x_i(n)) \tag{1}$$

The Equation (1) can be named as the insulation state sequence of X_i.

Before analyzing the insulation state, it is necessary to eliminate the dimensional effect by using an average operator defined as d_1, which can be written as:

$$\begin{cases} x_i(k)d_1 = \frac{x_i(k)}{\overline{X_i}} \\ \overline{X_i} = \frac{1}{n}\sum\limits_{k=1}^{n} x_i(k) \end{cases} \tag{2}$$

The insulation state sequence can be written as:

$$\begin{cases} X_0 = (x_0(1), \ldots, x_0(k), \ldots, x_0(n)) \\ X_1 = (x_1(1), \ldots, x_1(k), \ldots, x_1(n)) \\ \quad \cdots\cdots \\ X_i = (x_i(1), \ldots, x_i(k), \ldots, x_i(n)) \\ \quad \cdots\cdots \\ X_m = (x_m(1), \ldots, x_m(k), \ldots, x_m(n)) \end{cases} \tag{3}$$

Such that, the grey relational coefficient $\gamma(x_0(k), x_i(k))$ between X_0 and X_i can be written as:

$$\gamma(x_0(k), x_i(k)) = \frac{\min\limits_i \min\limits_k |x_0(k) - x_i(k)| + \xi \max\limits_i \max\limits_k |x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \xi \max\limits_i \max\limits_k |x_0(k) - x_i(k)|} \tag{4}$$

In Equation (4), $\min\limits_i \min\limits_k |x_0(k) - x_i(k)|$ is the largest difference between X_0 and X_i while $\max\limits_i \max\limits_k |x_0(k) - x_i(k)|$ is the smallest difference between X_0 and X_i. $\xi(\xi \in (0,1))$ is called the resolution coefficient, and it is usually selected as 0.5.

Finally, the grey relational degree $\gamma(X_0,X_i)$ between X_0 and X_i can be written as:

$$\gamma(X_0, X_i) = \frac{1}{n}\sum_{k=1}^{n} \gamma(x_0(k), x_i(k)) \tag{5}$$

4.2. Extraction of Insulation Condition Sensitive Parameters

Recently, several published papers have commonly reported the technique that the insulation condition sensitive parameters can extract from PDC, RVM and FDS [36,37,40]. In this study, the oil conductivity, paper conductivity, insulation resistance, absorption ratio, polarization index, maximum value of RVM, initial slope of RVM, CTC value of RVM, dielectric dissipation factor at $f = 10^{-1}$, dielectric dissipation factor at $f = 10^{0}$ and dielectric dissipation factor at $f = 10^{1}$ are selected as the characteristic parameters.

According to the calculation results of insulation condition sensitive parameters obtained from dielectric test data shown in Figures 1–3, it is presented that the oil conductivity (σ_{oil}) and paper conductivity (σ_{paper}) strengthen obviously with the increase of thermal aging duration time and moisture contents. By contrast, insulation resistance (R_{60sec}), maximum value of RVM (U_{rmax}) and CTC value of RVM (t_{cdom}) decreased with different aging times. In addition, it is observed that the variation rules of absorption ratio (K), polarization index (*P.I.*) and initial slope of RVM are unobvious. Finally, it is found that the characteristic parameters obtained from FDS obviously at the same characteristic frequency point strengthened with the increase of thermal aging times and moisture contents. This contribution reveals that the dielectric dissipation factor at $f = 10^{-1}$ ($tan\ \delta_{f=10^{-1}}$), dielectric dissipation factor at $f = 10^0$ ($tan\ \delta_{f=10^0}$) and dielectric dissipation factor at $f = 10^1$ ($tan\ \delta_{f=10^1}$) could be utilized to indicate the insulation condition of transformer oil paper insulation.

5. Selection of Standard Insulation State Model and Standard State Vector Model

It is an accepted fact that there is no accurate standard to define the aging condition and dampness degree of transformer oil-paper insulation system. In this paper, the dampness degree is defined as: dry (moisture content < 1.5%), wet (1.5% ≤ moisture content < 2.5%) and serious wet (moisture content ≥ 2.5%) in accordance with the Prevent Test Code for Electric Power Equipment of China (DT/L 596-2005) while the aging degree is defined as: good (DP ≥ 800), aging (400 < DP < 800) and serious aging (0 < DP ≤ 400) in accordance with the Guide for the Diagnosis of Insulation Aging in Oil-immersed Power Transformer of China (DL/T 984-2005). Table 2 presents the standard insulation state model of oil-paper insulation system.

Table 2. Standard insulation state model of oil-paper insulation system.

Aging Degree (DP Value)	Moisture Content (%)	State Sequence
DP ≥ 800, good	<1.5, dry	X_1
	1.5~2.5, wet	X_2
	≥2.5, serious wet	X_3
400 < DP < 800, aging	<1.5, dry	X_4
	1.5~2.5, wet	X_5
	≥2.5, serious wet	X_6
0 < DP ≤ 400, serious aging	<1.5, dry	X_7
	1.5~2.5, wet	X_8
	≥2.5, serious wet	X_9

According to the analysis of Section 4.2, the oil conductivity (σ_{oil}), paper conductivity (σ_{paper}), insulation resistance (R_{60sec}), maximum value of RVM (U_{rmax}), CTC value of RVM (t_{cdom}), dielectric dissipation factor at $f = 10^{-1}$ ($tan\ \delta_{f=10^{-1}}$), dielectric dissipation factor at $f = 10^0$ ($tan\ \delta_{f=10^0}$) and dielectric dissipation factor at $f = 10^1$ ($tan\ \delta_{f=10^1}$) can be used to represent the insulation condition of transformer oil-paper insulation. Therefore, the eight selected parameters can be utilized for performing the standard insulation state vector model, which can be written as:

$$X = (X(1), X(2), X(3), X(4), X(5), X(6), X(7), X(8)) \tag{6}$$

It should be mentioned here that the oil-impregnated pressboards of four moisture gradients are tested in this paper. According to Table 2, the pressboards of expected moisture levels (3% and 4%) are assigned to "serious wet" while the pressboards of aging 0 day and 8 days are assigned to the "good". In this study, the insulation condition sensitive parameters with the combination of expected moisture levels (1%, 2% and 4%) and expected aging levels (0 day, 21 days and 42 days) are used to establish the standard state vector model of pressboards, which is shown in Table 3.

Table 3. Standard state vector model of oil-paper insulation samples.

State Sequence	σ_{oil} (pS/m)	σ_{paper} (pS/m)	R_{60} (10^{12} Ω)	U_{rmax} (V)	t_{cdom} (s)	$tan\ \delta_{f=10^{-1}}$	$tan\ \delta_{f=10^0}$	$tan\ \delta_{f=10^1}$
X_1	0.113	0.027	2.030	27.640	1256.0	0.0066	0.0024	0.0027
X_2	0.583	0.103	0.500	25.910	415.0	0.0623	0.0113	0.0060
X_3	10.300	7.210	0.024	0.630	248.0	0.7769	0.4116	0.1246
X_4	0.231	0.032	1.710	25.750	1093.0	0.0176	0.0041	0.0026
X_5	2.450	1.590	0.599	0.150	109.0	0.1180	0.0249	0.0085
X_6	22.200	30.000	0.007	0.070	62.0	1.9595	1.3292	0.4480
X_7	0.534	0.121	0.402	20.820	483.0	0.0464	0.0094	0.0038
X_8	18.200	6.130	0.015	6.220	202.0	0.8130	0.1985	0.0446
X_9	106.700	302.900	0.001	1.700	3.7	1.6286	0.5643	0.8036

6. Insulation Condition Evaluation on Laboratory Samples and a Power Transformer in Service

6.1. Laboratory Samples

In order to verify that GRA technique can provide effective insulation diagnosis for oil-immersed transformers, the laboratory samples with unknown status are used to perform the application. The test samples are obtained by using the same accelerated thermal aging procedure. The PDC and FDS test results are shown in Figures 4 and 5, respectively.

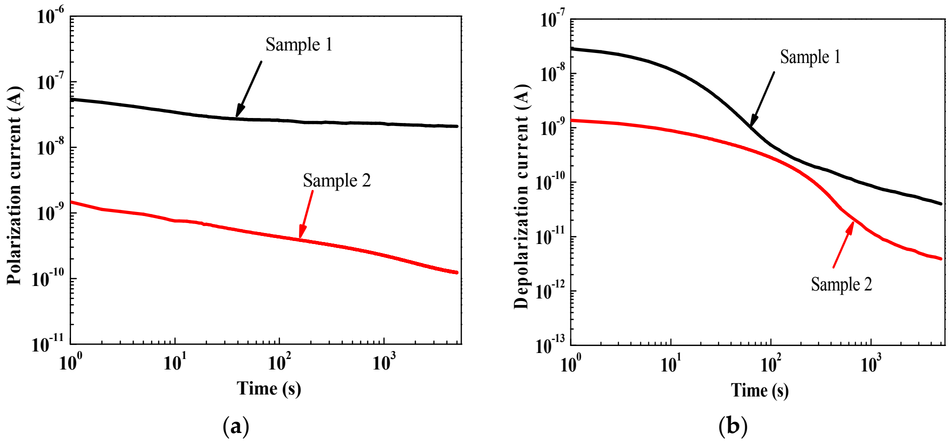


Figure 4. Polarization and depolarization current results of (**a**) Sample 1 and (**b**) Sample 2.

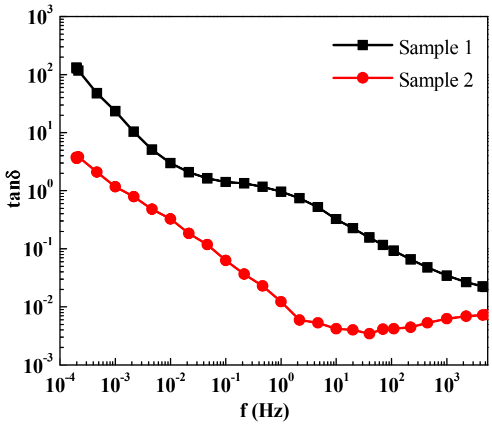


Figure 5. FDS results of Sample 1 and Sample 2.

The standard state vector of the two pressboards is shown in Table 4. Then the degree of association, which can be calculated according to Equation (5), is presented in Table 5. According to Table 5, there exists the maximum degree of association between Sample 1 and X6, while there exists the maximum degree of association between Sample 2 and X7. To further verify the reliability of the evaluation result, the moisture contents and DP values of two pressboards are tested. The DP values of Samples 1 and 2 are 755 and 377, respectively, and the paper moisture contents are 3.62% and 1.09%, respectively. From Table 2, we can draw the evaluation result that Sample 1 is the condition with aging and serious wet and Sample 2 is the condition with serious aging and dry. It preliminarily verifies effectiveness of GRA analysis for the laboratory samples.

Table 4. State vector of test samples.

State Sequence	σ_{oil} (pS/m)	σ_{paper} (pS/m)	R_{60} (10^{12} Ω)	U_{rmax} (V)	t_{cdom} (s)	tan $\delta_{f=10^{-1}}$	tan $\delta_{f=10^{0}}$	tan $\delta_{f=10^{1}}$
$X_{\text{sample 1}}$	21.2	29.2	0.0061	0.0725	62	1.4180	0.9619	0.3242
$X_{\text{sample 2}}$	0.622	0.324	0.329	18.6312	475	0.0489	0.011	0.004

Table 5. Degree of association between standard state and insulation state of test samples.

Test Sample	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9
Sample 1	0.268	0.339	0.583	0.276	0.560	0.765	0.346	0.481	0.512
Sample 2	0.732	0.886	0.524	0.754	0.726	0.352	0.954	0.646	0.276

6.2. A Power Transformer in Service

In this Section, a power transformer in service is employed to verify the GRA analysis based upon conventional dielectric response measurement. Generally, the oil-paper insulation system between high and low voltage windings of a power transformer includes barriers, spacers and oil ducts. To improve the understanding of dielectric behavior, it should simplify the principal arrangement of barriers, spacers and oil ducts presented in [22,25] by establishment of a reliable mathematical model based upon FDS data. In previous studies, a simplified model named as XY model was presented. It is a widely recognized that the XY model can obtain the correlation of FDS data among insulation oil, insulation paper/pressboard and the whole insulation of a transformer. Moreover, this typical mathematical model can also take account of the affection of temperature and insulation geometry. The XY model of the oil paper insulation can be described as [23,41]:

$$\varepsilon^*_{tot}(\omega) = \frac{1-Y}{\frac{1-X}{\varepsilon^*_{oil}(\omega)} + \frac{X}{\varepsilon^*_{PB}(\omega)}} + Y * \varepsilon^*_{PB}(\omega) \tag{7}$$

$$\varepsilon^*_{oil}(\omega) = 2.2 - j\frac{\sigma(T)}{\varepsilon_0 \omega} \tag{8}$$

where $\varepsilon^*{}_{tot}(\omega)$, $\varepsilon^*{}_{oil}(\omega)$, $\varepsilon^*{}_{PB}(\omega)$, $\sigma(T)$ and ε_0 are the complex effective relative permittivity of the whole transformer insulation, complex relative permittivity of liquid insulation, complex relative permittivity of solid insulation, direct current conductivity of liquid insulation at the temperature T and the permittivity of free space, respectively.

Figure 6 shows a detailed flow chart of insulation condition evaluation by DIRANA. To begin with, the DIRANA is used to measure the data of complex capacitance of a field transformer. After that, the data of real part and imaginary part of the complex relative permittivity of transformer insulation are determined according to geometrical capacitance and the complex capacitance. According to the measurement results of on-site oil sample at test temperature T, the complex relative permittivity of insulation oil can be obtained by the direct current conductivity in terms of Equation (8). Then, the correlation of complex relative permittivity spectroscopy among the whole transformer insulation, insulation oil and insulation paper can be derived by Equation (7). The master curve technique was used to correct the temperature effect on FDS curves. After that, the PDC and FDS curves of cellulose insulation are accurately determined. Finally, the evaluation result of insulation condition of transformer cellulose insulation can be obtained by using the proposed grey relational algorithm.

In order to demonstrate the feasibility of the GRA technique and evaluation process, numbers of insulation assessments on real power transformers should be performed. However, it is a shame that the test time of FDS measurement is also very limited due to the power-cut scheme. Moreover, the power outage of a transformer is not allowed. Therefore, it is very infeasible to perform such a large number of assessments on transformers. It is a fact that, the X and Y values are also geometry-dependent and it is very difficult to obtain the X and Y values from transformer enterprises. In view of above challenges, a typical power transformer is offered to perform FDS measurements under field condition and the operation information of the transformer is as follows. The rated voltages are 220 kV, 110 kV and 35 kV with the frequency in 50 Hz, respectively. The rated currents are 524 A, 904 A and 1485 A, respectively. The rated capacities are 180,000 kVA, 180,000 kVA and 90,000 kVA, respectively. The type of connections of the transformer is YYD. In this section, a detailed assessment result of the transformer is to demonstrate the feasibility of evaluation process shown in Figure 6.

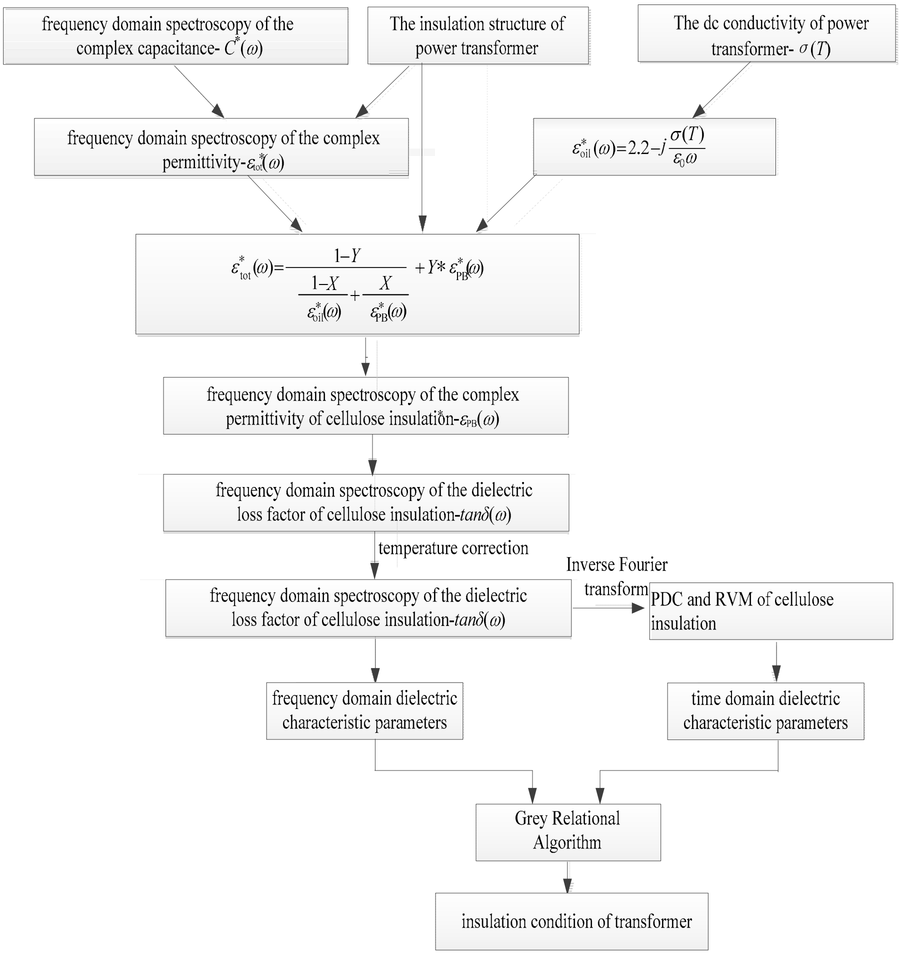


Figure 6. Flow chart of transformer insulation condition evaluation. PDC: polarization-depolarization current; RVM: recovery voltage measurement.

Figure 7 presented the $\varepsilon^*_{tot}(\omega)$ spectroscopy of the transformer main insulation system. Figure 8 showed the calculation results of PDC and FDS results of transformer cellulose insulation. According to these measurement data, the state vector of the transformer cellulose insulation and degree of association between standard state and transformer cellulose insulation are shown in Tables 6 and 7.

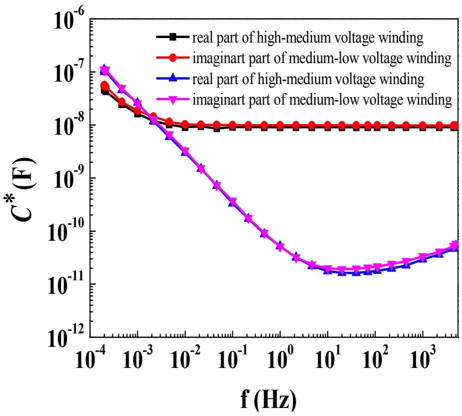
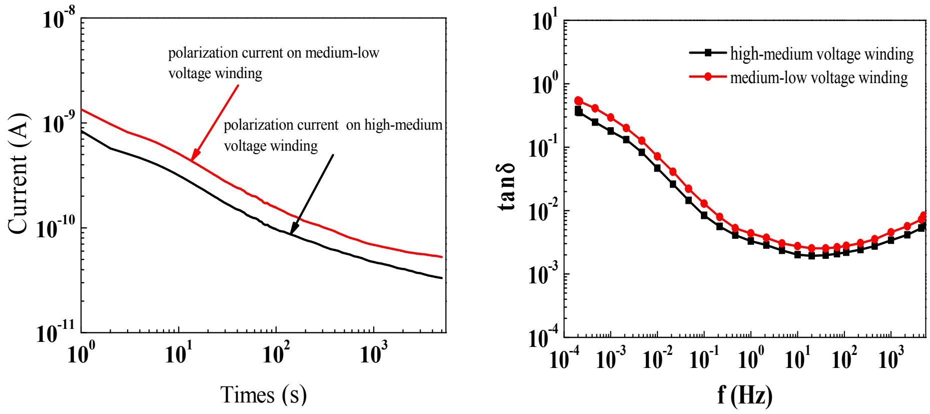


Figure 7. The $\varepsilon^{*}_{tot}(\omega)$ spectroscopy of the transformer main insulation.



(**a**) (**b**)

Figure 8. The time and frequency domain spectroscopy of the transformer cellulose insulation. (**a**) polarization current; (**b**) tan δ.

Table 6. State vector of the transformer cellulose insulation.

Condition	σ_{oil} (pS/m)	σ_{paper} (pS/m)	R_{60} (10^{12} Ω)	U_{rmax} (V)	t_{cdom} (s)	$tan\ \delta_{f=10^{-1}}$	$tan\ \delta_{f=10^{0}}$	$tan\ \delta_{f=10^{1}}$
$X_{\text{high-medium voltage}}$	0.212	0.022	1.61	27.2872	1123	0.0084	0.0033	0.0020
$X_{\text{medium-low voltage}}$	0.261	0.029	1.02	22.8236	1025	0.0129	0.0044	0.0027

Table 7. Degree of association between standard state and the transformer cellulose insulation.

Test Sample	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9
$X_{\text{high-medium voltage}}$	0.896	0.785	0.423	0.937	0.623	0.270	0.759	0.529	0.196
$X_{\text{medium-low voltage}}$	0.816	0.799	0.442	0.869	0.643	0.287	0.813	0.553	0.214

In the present work, it is observed that there existed the maximum degree of association between $X_{\text{high-medium voltage}}$ (insulation condition of high-medium voltage winding) and X_4, and there also existed the maximum degree of association between $X_{\text{medium-low voltage}}$ (insulation condition of medium–low voltage winding) and X_4. In terms of the evaluation results, it is presented that the insulation of high–medium voltage winding and medium–low voltage winding belongs to the condition with aging and dry.

We investigated the operation information of the transformer which was put into operation in 2000 A.D. The transformer is in the early-middle period of the life which indicates that the transformer main insulation is aging (400 < DP < 800). Therefore, the evaluation result of aging degree on the transformer insulation is reasonable (It is worth noting that DP value cannot be obtained due to the fact that obtaining the paper sample from a transformer in service is unpractical). This is in agreement with the standard insulation state defined in Table 2. Besides, the moisture contents of high–medium voltage winding and medium–low voltage winding are both 1.2% tested by DIRANA. It indicates that the transformer main insulation is the dry (<1.5%), which is also in agreement with the standard insulation state defined in Table 2.

7. Conclusions

This paper investigates GRA technique for insulation condition assessment of power transformers based upon conventional dielectric response measurement such as PDC, RVM and FDS. By means of FDS measurement and fitting curve method in PDC data, the insulation condition sensitive parameters from these data are extracted and then used to perform the grey relational calculation to predict the transformer insulation condition.

For two laboratory pressboard samples, according to GRA we draw the evaluation result that Sample 1 is the condition with aging and serious wet while Sample 2 is the condition with serious aging and dry, which are in agreement with the tested results by moisture contents and DP values. In addition, a power transformer in service is employed to verify the GRA analysis based upon conventional dielectric response measurement. A flow chart of evaluation procedure is proposed as an effective tool for transformer insulation diagnosis. According to analysis of Section 6.2, the aging degrees and moisture contents of the transformer insulation are perfectly in agreement with the standard insulation state defined in Table 2. Thus, the laboratory samples and a power transformer of unknown state preliminarily demonstrate that the GRA technique can provide reliable and effective diagnosis of transformer insulation.

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Nomenclature

σ_{oil}	Oil conductivity, S/m
σ_{paper}	Paper conductivity, S/m
R_{60sec}	Insulation resistance, Ω
K	Absorption ratio
$P.I.$	Polarization index
U_{rmax}	Maximum value of RVM, V
S_i	Initial slope of RVM
t_{cdom}	CTC value of RVM, s
$tan\ \delta_{f=10^{-1}}$	Dielectric dissipation factor at $f = 10^{-1}$
$tan\ \delta_{f=10^{0}}$	Dielectric dissipation factor at $f = 10^{0}$
$tan\ \delta_{f=10^{1}}$	Dielectric dissipation factor at $f = 10^{1}$

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