IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received December 7, 2021, accepted January 18, 2022, date of publication January 28, 2022, date of current version February 10, 2022.
Digital Object Identifier 10.1109/ACCESS.2022.3147463

Moisture Assessment of Oil-Immersed Paper Based on Dynamic Characteristics of Frequency Domain Spectroscopy

QINGCHUAN XU, SHENGKANG WANG, FUCHANG LIN, (Senior Member, IEEE), AND HUA LI, (Senior Member, IEEE)
State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
Corresponding author: Fuchang Lin (fclin@mail.hust.edu.cn)

ABSTRACT In on-site measurement, as the transformer's structure is often unknown, the application of frequency domain spectroscopy (FDS) is greatly limited in moisture assessment of transformer. This paper proposes a moisture assessment method for oil-immersed paper based on the dynamic characteristic frequency even for an unknown transformer structure. FDS tests are performed on the oil-paper insulation, corresponding oil-immersed paper, and mineral oil under different moisture conditions. The moisture criterion of oil-immersed paper and the influence of the structural parameters on the calculated frequency spectroscopy at different frequencies are discussed. It is concluded that the moisture criterion's effectiveness, which indicates the sensitivity of assessed moisture content to the error of the tanδ, changes at different frequencies. Moreover, there are some frequencies at which tanδ is not influenced by structural parameters and is close to the measured value, which are regarded as "characteristic frequencies." Based on the characteristic frequency, the moisture content of oil-immersed paper is assessed according to the frequency spectroscopy of oil-paper insulation without the structural parameters. The result shows that the assessing frequency changes under different moisture conditions, and the error of the assessed moisture content is less than 0.1%.

INDEX TERMS Frequency domain spectroscopy (FDS), oil-paper insulation, oil-immersed paper, moisture assessment, dynamic characteristic.

I. INTRODUCTION

The oil-immersed transformer is the crucial equipment in power system. The major insulation of oil-immersed transformer is oil-paper insulation, and undergoes degradation by several factors, such as thermal, electrical stresses, and especially water content [1], [2]. Water content can not only reduce the dielectric properties of transformer, but also accelerate the aging process and significantly shorten the transformer life [3], [4]. Therefore, it is essential to evaluate the moisture content of the transformer.

The dielectric response diagnostic method due to non-destructive property, are widely used in the field of moisture assessment of oil-impregnated electrical equipment, especially power transformers [5]–[7]. In time domain, the dielectric response diagnostic methods include polarization/depolarization current (PDC) [8] and recovery voltage measurement (RVM) [9]. In frequency domain, the dielectric response diagnostic method mainly is frequency domain spectroscopy (FDS) [10]. Due to the limitation of measuring instruments, PDC and RVM can only indicate the dielectric response of transformer below 1Hz [11]. Besides, RVM is inevitably influenced by leakage and surface currents, according to the CIGRE brochure [12], [13]. Compared with the two dielectric response diagnostic technique performed in time domain, FDS has the advantage of more abundant dielectric response information and robustness against electronic interference, while taking more time for measuring (50 minutes when the measuring frequency is 1mHz$\sim$10kHz) [14]. Therefore, FDS is a better dielectric response diagnostic method when the measuring time is unstinted.

Using FDS, the frequency spectroscopy of a transformer's major insulation is measured. Then, the frequency

The associate editor coordinating the review of this manuscript and approving it for publication was Mira Naftaly.

spectroscopy of oil-immersed paper can be calculated by the transformer's structural parameters [15]–[17]. Based on the frequency spectroscopy of oil-immersed paper, the transformer's moisture content can be evaluated [18]–[24]. Though a lot of researchers have conducted extensive research and proposed significant conclusions about the moisture assessment, most of the research is moisture analysis based on the frequency spectroscopy of oil-immersed paper. Few studies have been done on the extraction of oil-immersed paper's frequency spectroscopy and the moisture evaluation of transformer with unknown insulation construction, which is common in the on-site measurement. Therefore, the moisture content of transformer cannot be evaluated based on the frequency spectroscopy of transformer, which greatly limits the application of FDS in the field of moisture assessment.

This paper proposes a moisture assessment method for oil-immersed paper based on the dynamic characteristic frequency to evaluate the moisture content with the unknown structure of the transformer. The derivation of oil-immersed paper's frequency spectroscopy from oil-paper insulation is introduced first. FDS tests are then performed on the oil-paper insulation, corresponding oil-immersed paper, and mineral oil under different moisture conditions. Then, the moisture criterion of oil-immersed paper at different frequencies is discussed. With the unknown structure of the transformer, the influence of the structural parameters used in the calculation on oil-immersed paper's calculated frequency spectroscopy is analysed. Finally, the moisture content is assessed according to the frequency spectroscopy of oil-paper insulation without the structural parameters.

II. DERIVATIONOF OIL-IMMERSED PAPER'S FREQUENCY SPECTROSCOPY FROM OIL-PAPER INSULATION

For most oil-immersed transformers, the major insulation consists of insulating oil, oil-immersed paper, and spacers used for propping the barriers and forming oil ducts, as shown in Fig. 1(a) [25]. By concentrating the oil, oil-immersed paper, and spacers, which are in different locations, the major insulation of transformers can be further simplified as the XY model [26], [27], which is shown in Fig. 1(b). X represents the ratio of the thickness of oil-immersed paper to oil, and Y represents the ratio of the width of the spacers to oil. For most oil-immersed transformers, X is limited within the range of 0.2-0.5, and Y is limited within 0.15-0.25.

The material of spacers is normally regarded as insulation paper. Therefore, the XY model represents a typical kind of oil-paper insulation. The relationship between the complex permittivity of oil-paper insulation, mineral oil and oil-immersed paper is as follows:

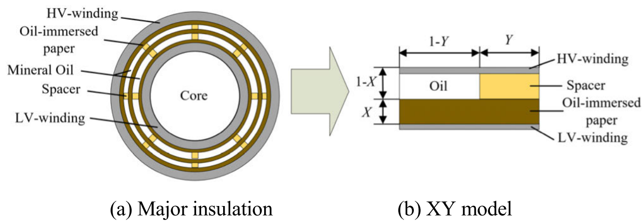


FIGURE 1. Major insulation and XY model of oil-immersed transformer.

$$\varepsilon^*_{whole} = \frac{1-Y}{\frac{1-X}{\varepsilon^*_{oil}} + \frac{X}{\varepsilon^*_{paper}}} + Y\varepsilon^*_{paper} \tag{1}$$

where:
ε^*_{whole} = complex permittivity of oil-paper insulation
ε^*_{oil} = complex permittivity of mineral oil
ε^*_{paper} = complex permittivity of oil-immersed paper.

Equation (1) can be expressed in the form of the quadratic equation whose unknown is ε^*_{paper}:

$$\frac{(1-X)Y}{\varepsilon^*_{oil}}\varepsilon^{*2}_{paper} + (1-X+XY-\frac{1-X}{\varepsilon^*_{oil}}\varepsilon^*_{whole})\varepsilon^*_{paper} - X\varepsilon^*_{whole} = 0 \tag{2}$$

After measuring ε^*_{whole} and ε^*_{oil}, ε^*_{paper} can be calculated as (3), shown at the bottom of the page.

As seen in (3), there are two solutions of ε^*_{paper}, but only one is reasonable, as it meets the condition that ε'_{paper} and ε''_{paper} are both positive. The proof goes as follows.

Define $\varepsilon^*_{paper} = a(R_1 \pm R_2)$.
where:

$$a = \frac{1}{4(1-X)Y} \tag{4}$$

$$R_1 = (1-X)\varepsilon^*_{whole} - (1-Y+XY)\varepsilon^*_{oil} \tag{5}$$

$$R_2 = \sqrt{R_1^2 + 4a\varepsilon^*_{whole}\varepsilon^*_{oil}} \tag{6}$$

The relationship of R_1 and R_2 can be written as follows:

$$R_1^2 - R_2^2 = R_1^2 - (R_1^2 + 4a\varepsilon^*_{whole}\varepsilon^*_{oil}) = -4a\varepsilon^*_{whole}\varepsilon^*_{oil} \tag{7}$$

Define $\varepsilon^*_{whole} = m_1 - \mathrm{j}n_1$, $\varepsilon^*_{oil} = m_2 - \mathrm{j}n_2 (m_i, n_i > 0, i = 1, 2)$. Equation (7) can be written as follows:

$$\begin{aligned} R_1^2 - R_2^2 &= 4a\varepsilon^*_{whole}\varepsilon^*_{oil} = -4a(m_1 - \mathrm{j}n_1)(m_2 - \mathrm{j}n_2) \\ &= -4a(m_1m_2 - n_1n_2 - \mathrm{j}(n_1m_2 + n_2m_1)) \end{aligned} \tag{8}$$

As $0 < X < 1$, $0 < Y < 1$, a is positive; therefore:

$$\mathrm{imag}(R_1^2 - R_2^2) > 0 \tag{9}$$

Define the two solutions of ε^*_{paper}:
$U_1 = a(R_1 + R_2)$, $U_2 = a(R_1 - R_2)$. By reduction to absurdity, the following proves that there is only one of

$$\begin{aligned} \varepsilon^*_{paper} = (&\pm\sqrt{((1-Y+XY)\varepsilon^*_{oil} - (1-X)\varepsilon^*_{whole})^2 + 4(1-X)YX\varepsilon^*_{whole}\varepsilon^*_{oil}} \\ &+ (1-X)\varepsilon^*_{whole} - (1-Y+XY)\varepsilon^*_{oil}))/(2(1-X)Y) \end{aligned} \tag{3}$$

U_1 and U_2 that meets the condition that real(U_i) > 0, imag(U_i) < 0, ($i = 1, 2$).

Assuming real(U_i) > 0, imag(U_i) < 0, as a is positive, according to (9), the relationship of R_1 and R_2 can be written as follows:

$$\mathrm{real}(R_1 + R_2) > 0 \tag{10}$$
$$\mathrm{real}(R_1 - R_2) > 0 \tag{11}$$
$$\mathrm{imag}(R_1 + R_2) < 0 \tag{12}$$
$$\mathrm{imag}(R_1 - R_2) < 0 \tag{13}$$
$$\mathrm{imag}(R_1^2 - R_2^2) > 0 \tag{14}$$

Define $R_1 = s_1 - \mathrm{j}t_1, R_2 = s_2 - \mathrm{j}t_2$. According to (10-14):

$$s_1 + s_2 > 0 \tag{15}$$
$$s_1 - s_2 > 0 \tag{16}$$
$$t_1 - t_2 > 0 \tag{17}$$
$$t_1 + t_2 > 0 \tag{18}$$
$$s_2t_2 - s_1t_1 > 0 \tag{19}$$

According to (15, 17):

$$s_1t_1 - s_2t_2 + s_2t_1 - s_1t_2 > 0 \tag{20}$$

According to (16, 18):

$$s_1t_1 - s_2t_2 + s_1t_2 - s_2t_1 > 0 \tag{21}$$

According to (20, 21), it is shown that $s_1t_1 > s_2t_2$, which contradicts (19). Therefore, there is only one of U_1 and U_2 that meets the condition that real(U_i) > 0, imag(U_i) < 0 ($i = 1, 2$).

As a result, according to (3), $\varepsilon^*_{\mathrm{paper}}$ can be calculated by $\varepsilon^*_{\mathrm{whole}}$ and $\varepsilon^*_{\mathrm{oil}}$. As $\varepsilon'_{\mathrm{paper}}$ and $\varepsilon''_{\mathrm{paper}}$ are both positive in only one of the two solutions, the correct one can be easily chosen.

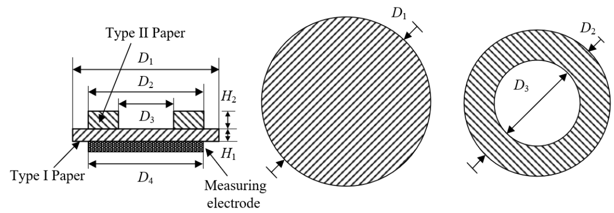
III. EXPERIMENTS

A. SPECIMEN PREPARATION

The mineral oil used in our experiments is 25# KARAMAY oil, a widely used transformer oil. The insulation paper is a kind of kraft paper provided by the transformer factory. The material was dried first. Then, the mineral oil and insulation paper were placed in a vacuum oven for 72h at 90°C/ 50 Pa [28]. Afterwards, the moisture of the dried oil is 8 ppm, and the moisture of the paper is 1.2%.

Following this, the insulation paper was placed in a temperature humidity chamber to absorb moisture. The temperature is 45°C, and the relative humidity is 80%. The weight of the paper was constantly monitored to achieve the desired moisture content. Five kinds of paper with different moisture contents were made for experimental purposes.

Lastly, various types of oil-paper insulation with different moisture conditions were made. The oil-paper insulation comprised mineral oil and two types of insulation paper, as seen in Fig. 2. The Type I paper was round and served as the oil-immersed paper in the oil-paper insulation, while the Type II paper was toroidal and served as the spacer.



(a) Oil-paper insulation (b) Type I paper (c) Type II paper

FIGURE 2. Insulation paper in oil-paper insulation.

TABLE 1. Insulation paper parameters.

Type I paper		Type II paper			Structural parameters	
D_1(mm)	H_1(mm)	D_2(mm)	D_3(mm)	H_2(mm)	X	Y
200	1	150	135	3	0.25	0.19

The diameter and thickness of these two paper types determined the structural parameters X and Y of the oil-paper insulation, as shown in Table 1. The effective diameter of the Type I paper should be the diameter of the measuring electrode D_4, which was 150 mm. The structural parameters X and Y can be calculated as follows:

$$X = \frac{H_1}{H_2} \tag{22}$$
$$Y = \frac{D_2^2 - D_3^2}{D_4^2} \tag{23}$$

The insulation paper with different moisture contents and the dried mineral oil were put into a sealed plate sample electrode system at 45°C for moisture equilibrium. The moisture equilibrium time for the oil-paper insulation sample is shown in Table 2.

After the moisture equilibrium was reached, the moisture content of oil and oil-immersed paper was measured, as seen in Table 2. According to IEC 60814 standards [29], [30], the measurement was performed by a Karl Fischer coulometric titrator (METTLER TOLEDO C10s & DO308), as seen in Fig. 3.

The moisture content of oil can be directly measured by putting 2ml oil sample into the titration vessel cell. The moisture content of oil-immersed paper was measured by putting 1g paper sample into the drying oven and heat the sample to 100°C. The heating drives off all the moisture from the sample to the titration vessel cell.

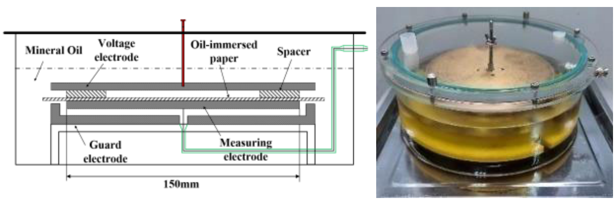
B. ELECTRODE SYSTEM

Two types of electrode systems were used in the experiments. The plate sample electrode system was used to measure the dielectric response of the oil-immersed paper and oil-paper insulation. The liquid sample electrode system was used to measure the dielectric response of the mineral oil. Both electrode systems were comprised of three electrodes:

TABLE 2. Moisture content of oil and oil-immersed paper in the oil-paper insulation with different moisture conditions.

Sample Code	A	B	C	D	E
Moisture equilibrium time	6h	24h	2d	4d	7d
Moisture content of paper (%)	1.1	2.1	3.4	4.5	5.5
Moisture content of oil (ppm)	10	15	22	30	42

FIGURE 3. Karl Fischer coulometric titrator.



(a) Sectional drawing (b) Actual photograph

FIGURE 4. Plate sample electrode system.

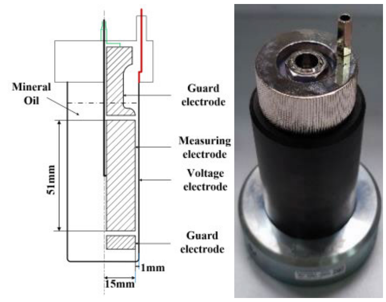
voltage electrode, measuring electrode, and guard electrode. The electrode material was copper.

The plate sample electrode system is shown in Fig. 4. The diameter of the measuring electrode was 150 mm. The gap between the voltage and measuring electrodes depended on the thickness of the oil-immersed paper and spacer, which was 4mm.

The liquid sample electrode system (HIOKI SME-8330) is shown in Fig. 5. The width of the oil gap is 1mm, the radius of the measuring electrode was 15mm, and the height of the measuring electrode was 51mm.

C. FDS TEST

The FDS test system of the oil-immersed paper, mineral oil, and oil-paper insulation employing a frequency domain dielectric response tester (Megger IDAX 300) is shown in Fig. 6. The HI port of the IDAX 300 connected to the voltage electrode of the plate or liquid sample electrode system. The ground port and LO port of the IDAX 300 connected



(a) Sectional drawing (b) Actual photograph

FIGURE 5. Liquid sample electrode system.

to the guard and measuring electrodes, respectively, by a coaxial line. The black part of the FDS test system had the equipotential connection with the LO port of the IDAX 300. This part was vulnerable to electromagnetic interference of the test system. Thus, it was fully protected by the guard electrode and shield layer of the coaxial line, which effectively prevented electromagnetic interference and guarantee the accuracy of measurement. The maximum amplitude of the applied voltage was set at 200 V, and the frequency range of the test was from 1 mHz to 1 kHz.

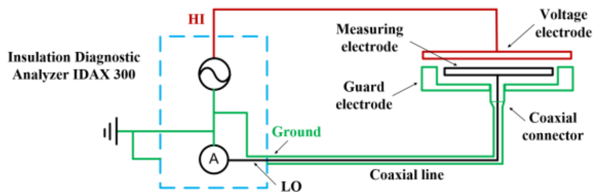


FIGURE 6. FDS test system.

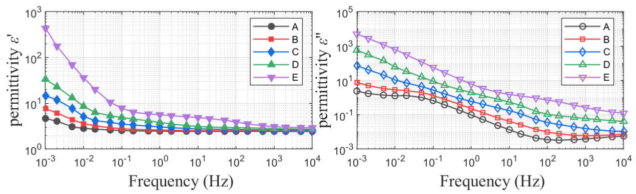
For every oil-paper insulation sample with different moisture contents, the FDS of the oil-paper insulation, oil-immersed paper, and mineral oil were measured at 45°C. After measuring the FDS of the oil-paper insulation using the plate sample electrode system, the spacer of the oil-paper insulation was removed, and the oil-immersed paper's spectroscopy was measured. Next, a 25-ml mineral oil sample was taken from the plate sample electrode system and measured by the liquid sample electrode system.

IV. EXPERIMENTAL RESULTS AND MOISTURE CRITERION DISCUSSION

A. EXPERIMENTAL RESULTS AND VERIFICATION OF XY MODEL

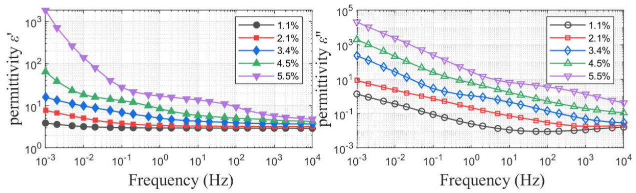
The frequency spectroscopy of the oil-paper insulation samples with five different moisture contents (Samples A-E) is shown in Fig. 7. The frequency spectroscopy of the corresponding oil-immersed paper and mineral oil is shown in Fig. 8 and Fig. 9.

According to the XY model and (3), with the known insulation structural parameters X and Y, oil-immersed paper's frequency spectroscopy can be calculated by the frequency



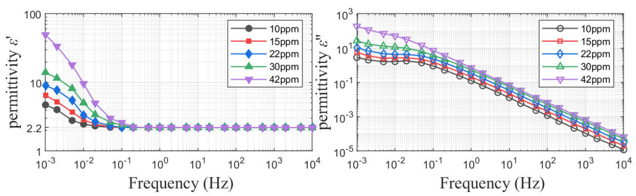
(a) Real part of complex permittivity(b) Imaginary part of complex permittivity

FIGURE 7. Frequency spectroscopy of oil-paper insulation sample with different moisture contents.



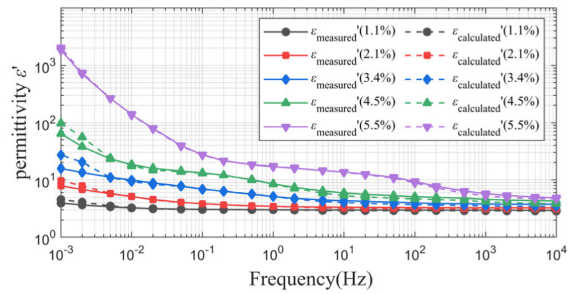
(a) Real part of complex permittivity (b) Imaginary part of complex permittivity

FIGURE 8. Frequency spectroscopy of oil-immersed paper in oil-paper insulation with different moisture contents.

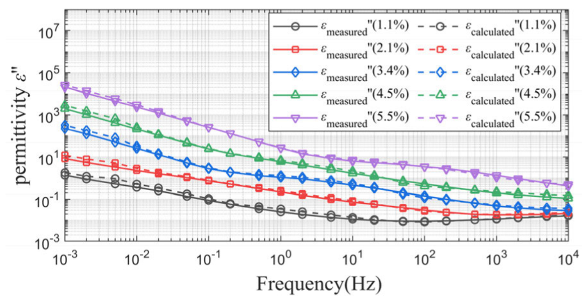


(a) Real part of complex permittivity (b) Imaginary part of complex permittivity

FIGURE 9. Frequency spectroscopy of mineral oil in oil-paper insulation with different moisture contents.

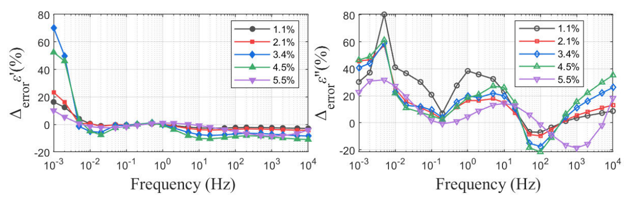


(a) Real part of complex permittivity



(b) Imaginary part of complex permittivity

FIGURE 10. Comparison of calculated and measured frequency spectroscopy of oil-immersed paper.



(a) Error of real part of complex permittivity (b) Error of imaginary part of complex permittivity

FIGURE 11. Relative error of oil-immersed paper's calculated frequency spectroscopy compared with measured value.

spectroscopy of the corresponding oil-paper insulation and mineral oil. The comparison of the calculated and measured frequency spectroscopy of oil-immersed paper is shown in Fig. 10. The solid and dotted lines indicate the measured and calculated frequency spectroscopy of oil-immersed paper, respectively.

R_{cal} and R_{mea} are defined as the calculated and measured frequency spectroscopy of oil-immersed paper, respectively. The relative error of the calculated frequency spectroscopy compared with the measured value can be written as follows:

$$\Delta_{error} = \frac{R_{\text{cal}} - R_{\text{mea}}}{R_{\text{mea}}} \tag{24}$$

Fig. 11 shows the relative error of oil-immersed paper's calculated frequency spectroscopy compared with the measured value. In most moisture and frequency conditions, the relative error of the calculated frequency spectroscopy is less than 20%. The relative error increases at low frequency and high moisture content, but oil-immersed paper's calculated frequency spectroscopy generally agrees with the measured value.

Therefore, with the known insulation structural parameters X and Y, according to the XY model, oil-immersed paper's frequency spectroscopy can be calculated from the oil-paper insulation with minor deviation.

B. MOISTURE CRITERION OF OIL-IMMERSED PAPER

Fig. 8 shows that oil-immersed paper's frequency spectroscopy with different moisture contents varies at different frequencies. According to the frequency domain dielectric response, the moisture content of oil-immersed paper can be assessed. The moisture criterion is based on the dielectric dissipation factor (tanδ) to avoid the influence of the size of oil-immersed paper.

Fig. 12 depicts the measured tanδ of oil-immersed paper with different moisture contents. It is seen that except for the tanδ curve with 5.5% moisture content at low frequency, the tanδ increases monotonously with the increase of the moisture content. Therefore, the moisture content can be assessed by the tanδ of oil-immersed paper.

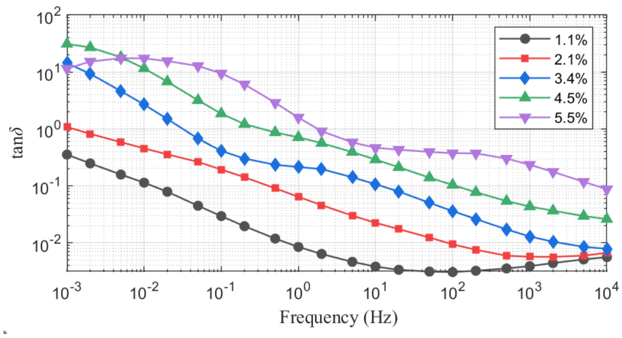


FIGURE 12. tanδ curves of oil-immersed paper with different moisture contents.

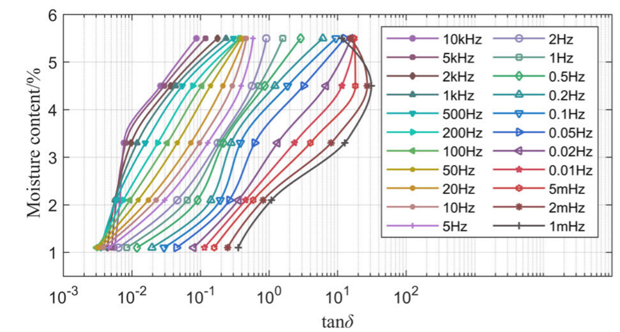


FIGURE 13. Relationship between moisture content of oil-immersed paper and tanδ at different frequencies.

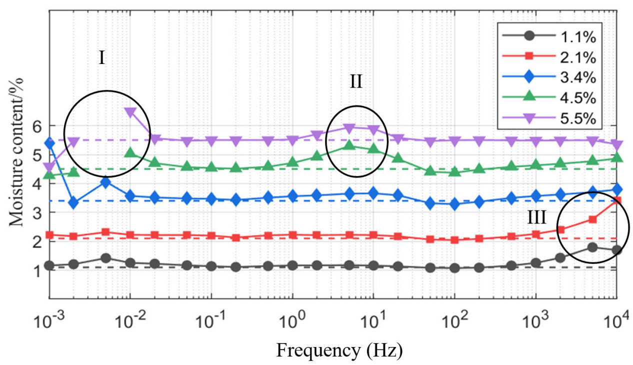


FIGURE 14. Moisture assessment of calculated oil-immersed paper frequency spectroscopy at different frequencies.

Fig. 13 shows the relationship between the moisture content of oil-immersed paper and tan δ at different frequencies, which is also the moisture criterion. According to the calculated frequency spectroscopy of oil-immersed paper in Fig. 10, the assessed moisture contents based on the moisture criterion at different frequencies are shown in Fig. 14. Compared with the measured moisture content, oil-immersed paper's assessed moisture content error is small under most moisture and frequency conditions.

There are three types of moisture-frequency conditions in which the moisture assessment is not good enough. In Condition I, where the moisture content is higher than 4.5%, and the frequency is lower than 0.01Hz, the moisture content cannot be assessed because the tanδ of oil-immersed paper does not increase monotonously with the increase of the moisture content, as seen in Fig.12. In Conditions II and III, where the moisture content is higher than 4.5%, and the frequency is between 2Hz and 20Hz, or the moisture content is lower than 3.4%, and the frequency is higher than 200Hz, the moisture assessment error is larger than those in the other conditions because the tanδ of oil-immersed paper is not sensitive to the moisture content. A slight change of tanδ may greatly influence the moisture assessment. The effectiveness of the moisture criterion depends on the slope of tanδ to the moisture content, which is defined as follows:

$$\chi = \frac{\partial \log_{10}(\tan\delta)}{\partial m} \tag{25}$$

where m is oil-immersed paper's moisture content.

Fig. 15 intuitively shows the relationship between χ and oil-immersed paper's moisture content at different frequencies. In Condition I, the color is pure white, which indicates that χ is negative, and the moisture content cannot be evaluated. In Condition II, III, and IV, the color is lighter than those in the other conditions, which indicates that χ is smaller and the moisture assessment is more susceptible to the relative error of the tanδ of oil-immersed paper. In other conditions, the tanδ is sensitive to moisture content, and the moisture content can be assessed with small error. The best frequency band to evaluate the moisture content of paper is [20, 100] Hz, as the tanδ of oil-immersed paper is always sensitive to the moisture content under all moisture condition.

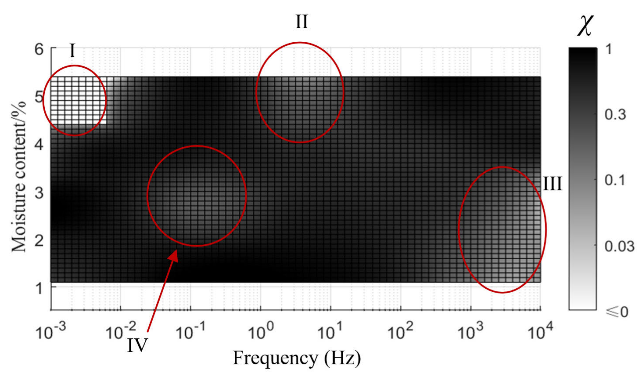


FIGURE 15. Relationship between χ and moisture content of oil-immersed paper at different frequencies.

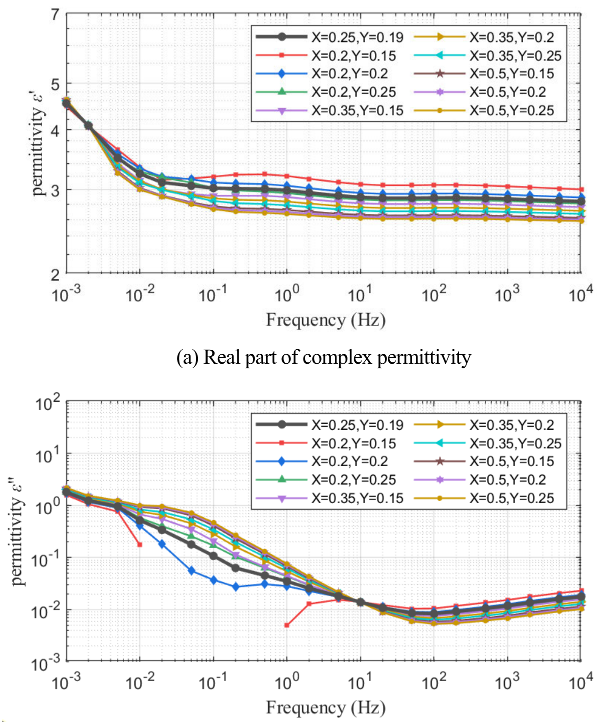
Therefore, according to the moisture criterion proposed, under most moisture and frequency conditions, the moisture content of oil-immersed paper can be assessed by the tanδ of oil-immersed paper at any frequency.

V. MOISTURE ASSESSMENT OF OIL-IMMERSED PAPER BASED ON DYNAMIC CHARACTERISTIC FREQUENCY

A. INFLUENCE OF STRUCTURAL PARAMETERS ON OIL-IMMERSED PAPER'S CALCULATED FREQUENCY SPECTROSCOPY

Section A of IV shows that with the known insulation structural parameters X and Y, oil-immersed paper's frequency spectroscopy can be calculated from the oil-paper insulation with minor deviation. However, in on-site measurement, due to the unknown structure of the transformer, X and Y cannot be determined and may not be the actual structural parameters. This section discusses the influence of X and Y on oil-immersed paper's calculated frequency spectroscopy for the given frequency spectroscopy of oil-paper insulation.

For the measured frequency spectroscopy of oil-paper insulation in Fig. 7, according to (3), oil-immersed paper's calculated frequency spectroscopy using different X and Y is shown in Fig. 16 and 17. Fig. 16 shows the influence of X and Y with low moisture content, while Fig. 17 shows the influence of X and Y with high moisture content. $X = 0.25$, $Y = 0.19$ are the actual structural parameters of the given oil-paper insulation.

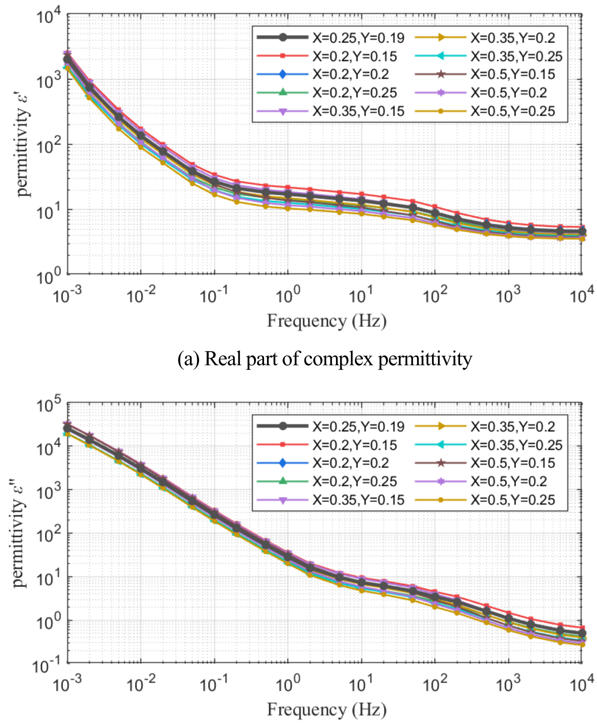


(a) Real part of complex permittivity

(b) Imaginary part of complex permittivity

FIGURE 16. Calculated frequency spectroscopy of oil-immersed paper with 1.1% moisture content using different *X* and *Y*.

As seen in Fig. 16, under the 1.1% moisture content condition, at 10^{-3}-10^{-2}Hz and around 10 Hz, X and Y have little influence on oil-immersed paper's calculated frequency spectroscopy. At other frequencies, the error of the calculated frequency spectroscopy increases with the deviation of X and Y compared with the actual structural parameters. When $X = 0.2$, $Y = 0.15$, the calculated frequency spectroscopy is even negative at 10^{-2}-10^{0}Hz and cannot be represented in log-log coordinates. Under the high moisture condition seen in Fig. 17, different X and Y increase or decrease oil-immersed paper's whole calculated frequency spectroscopy.



(a) Real part of complex permittivity

(b) Imaginary part of complex permittivity

FIGURE 17. Calculated frequency spectroscopy of oil-immersed paper with 5.5% moisture content using different *X* and *Y*.

Fig. 18 shows the tanδ curves of oil-immersed paper's calculated frequency spectroscopy using different X and Y under different moisture conditions.

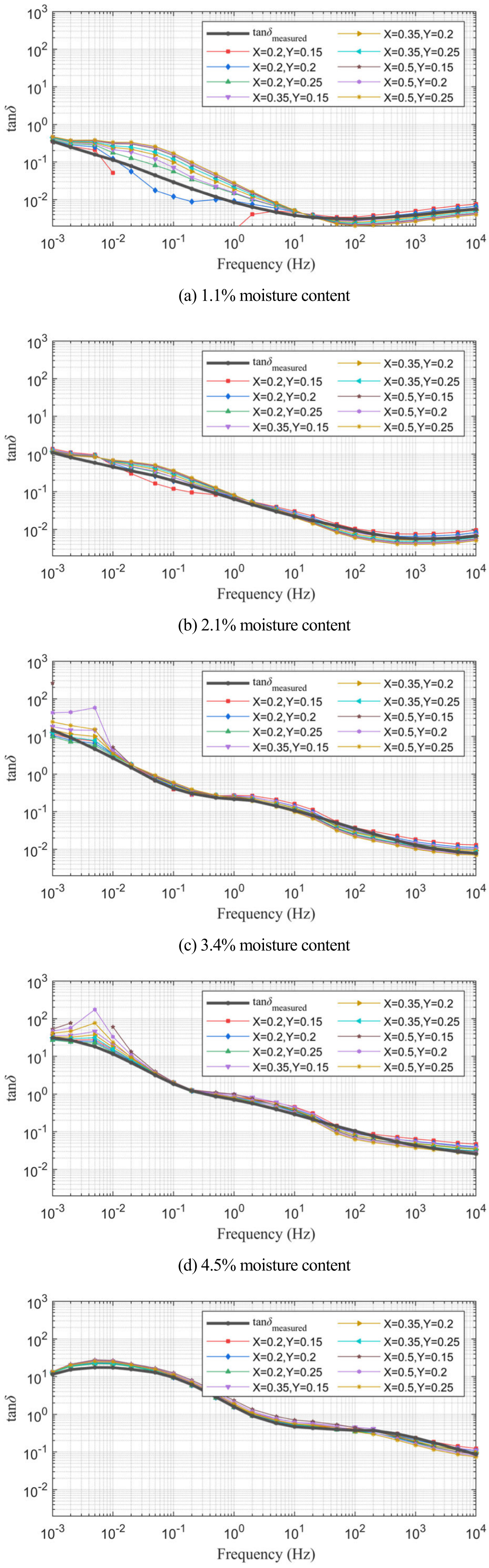
B. ANALYSIS OF MOISTURE ASSESSMENT RESULTS

As shown in Fig. 18, when the moisture content is 1.1%, at 10^{-3}-10^{-2}Hz and around 10 Hz, the tanδ of oil-immersed paper's calculated frequency spectroscopy using different X and Y is rather close to the measured tanδ. According to the moisture criterion in Fig. 13, the moisture assessment result is 1.1% at these frequencies regardless of the X and Y used. On the contrary, the moisture assessment result could be 2.1% at 0.1Hz when $X = 0.5$, $Y = 0.25$.

Under other moisture conditions, for the tanδ curves of oil-immersed paper's calculated frequency spectroscopy using different X and Y with moisture content of 1.1%, 2.1%, 3.4% and 4.5%, there are some frequencies at which tanδ is not influenced by X and Y and is close to the measured value. These frequencies are the "characteristic frequencies" in the moisture assessment.

The "characteristic frequency" is the frequency at which oil-immersed paper's tanδ is equal to that of the mineral oil in the oil-paper insulation. At these frequencies, the tanδ of oil, oil-immersed paper and oil-paper insulation are the same. The proof goes as follows.

As $\tan\delta_{paper} = \tan\delta_{oil}$, define $\varepsilon^*_{paper} = m - jn$, $\varepsilon^*_{oil} = C(m - jn)$ $(m, n > 0, 0 < C < 1)$. According to (1), ε^*_{whole} can be



(a) 1.1% moisture content

(b) 2.1% moisture content

(c) 3.4% moisture content

(d) 4.5% moisture content

(e) 5.5% moisture content

FIGURE 18. **$\tan\delta$ of calculated frequency spectroscopy of oil-immersed paper using different X and Y under different moisture conditions.**

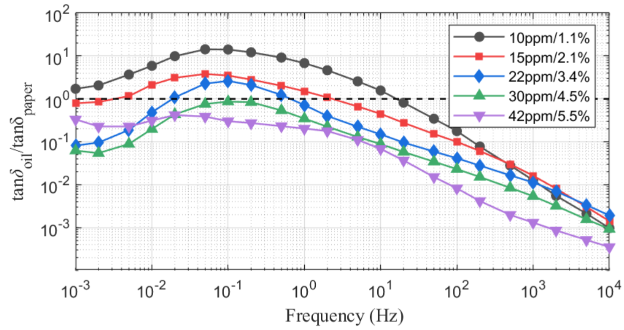


FIGURE 19. **Ratio of $\tan\delta$ of mineral oil to that of oil-immersed paper in oil-paper insulation.**

TABLE 3. **Characteristic frequencies with different moisture contents.**

Moisture content (%)	1.1	2.1	3.4	4.5	5.5
Characteristic frequency I	1mHz	5mHz	0.02Hz	0.2Hz	/
$\chi(f)$	0.34	0.63	0.51	0.63	/
Characteristic frequency II	20Hz	2Hz	0.5Hz	/	/
$\chi(f)$	0.79	0.65	0.42	/	/

written as follows:

$$\begin{aligned}\varepsilon^*_{\text{whole}} &= \frac{1-Y}{\frac{1-X}{C(m-jn)} + \frac{X}{m-jn}} + Y(m-jn) \\ &= (\frac{1-Y}{(1-X)/C+X} + Y)(m-jn) \end{aligned} \tag{26}$$

Therefore, when $\tan\delta_{\text{oil}} = \tan\delta_{\text{paper}}$, $\tan\delta_{\text{paper}}$ and $\tan\delta_{\text{whole}}$ are always the same and not influenced by X and Y. The ratio of the $\tan\delta$ of mineral oil to that of oil-immersed paper is shown in Fig. 19. The characteristic frequencies are the frequencies at which the ratio is near 1. The characteristic frequencies with different moisture contents are shown in Table 3. There are two characteristic frequencies of each $\tan\delta$ curve under the low moisture condition. With the increase of the moisture content, the characteristic frequencies approach 0.1Hz gradually. When the moisture content of paper is 5.5%, $\tan\delta_{\text{oil}}/\tan\delta_{\text{paper}} < 1$ at all frequencies, which indicates that there is no characteristic frequency within [10^{-3}, 10^4] Hz.

According to (25), χ is defined as the slope of the $\tan\delta$ curves of oil-immersed paper to the moisture content, which indicates the sensitiveness of the assessed moisture to the calculated $\tan\delta$. The bigger χ is, the less sensitivity of the assessed moisture to the error of $\tan\delta$. The χ of the characteristic frequencies for each moisture content is also shown in Table 3. Therefore, as there are two characteristic frequencies when the moisture content is less than 4.5%, the better characteristic frequency can be chosen.

TABLE 4. Moisture assessment result with different moisture conditions.

Moisture content (%)	1.1	2.1	3.4	4.5	5.5
Assessing frequency	20Hz	2Hz	0.02Hz	0.2Hz	500Hz
$\tan\delta$	0.0038	0.054	1.69	1.26	0.246
Assessed moisture (%)	1.14	2.2	3.48	4.52	5.46
$\Delta_{moisture}$ (%)	3.6	4.7	2.4	0.4	-0.7

When the moisture content is 5.5%, there is no characteristic frequency within $[10^{-3}, 10^4]$ Hz. But the best accessing frequency can still be chosen based on χ. As seen in Fig. 20, the maximum of χ is 0.877 when the frequency is 500Hz, which is the assessing frequency.

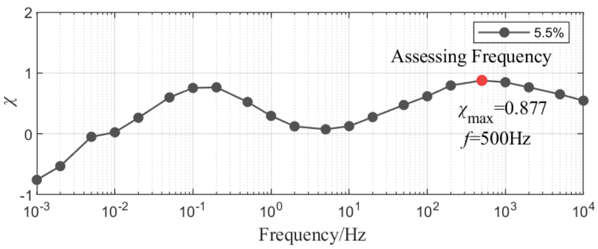


FIGURE 20. Relationship between χ and frequency with 5.5% mositure content of oil-immersed paper.

Therefore, for the measured frequency spectroscopy of the oil-paper insulation in Fig. 7, assuming the structural parameters are unknown, the frequency for the assessment of moisture content and the assessed moisture content are shown in Table 4. The relative error of the assessed moisture compared with the actual value is defined as:

$$\Delta_{\text{moisture}} = \frac{m_{\text{ass}} - m_{\text{act}}}{m_{\text{act}}} \times 100\% \tag{27}$$

where:

m_{ass} = assessed moisture content

m_{act} = actual moisture content

As seen in the table, the relative error of assessed moisture content is rather small. It is concluded that without the structural parameters of the oil-paper insulation, the moisture assessment based on the dynamic characteristic frequency is effective.

VI. CONCLUSION

This paper proposed a moisture assessment method for oil-immersed paper based on the dynamic characteristic frequency to evaluate the moisture content with the unknown structure of the transformer. The moisture criterion of oil-immersed paper at different frequencies was discussed, and the influence of the structural parameters on oil-immersed paper's calculated frequency spectroscopy was analysed. The moisture content of oil-immersed paper was assessed according to the frequency spectroscopy of the oil-paper insulation without the structural parameters. The main conclusions are as follows:

1) With the known insulation structural parameters X and Y, oil-immersed paper's frequency spectroscopy can be calculated from the oil-paper insulation with minor deviation compared with measured frequency spectroscopy.

2) Under most moisture and frequency conditions, oil-immersed paper's moisture content can be assessed by $\tan\delta$ at any frequency. The effectiveness of the moisture criterion, indicating the sensitivity of assessed moisture content to the error of $\tan\delta$, changes at different frequencies with different moisture contents.

3) With the unknown structure of the transformer, the influence of the structural parameters used in the calculation on the $\tan\delta$ of oil-immersed paper differs. There are some frequencies at which $\tan\delta$ is not influenced by structural parameters and is close to the measured value, which are regarded as "characteristic frequency."

4) Based on the characteristic frequency, oil-immersed paper's moisture content can be assessed according to the frequency spectroscopy of the oil-paper insulation without its structural parameters. The assessing frequency changes under different moisture conditions, and the error of the assessed moisture content is less than 0.1%.

REFERENCES

[1] G. Xia and G. Wu, "Study on the impact of initial moisture contents on ageing characteristics of transformer oil-paper insulation," in *Proc. IEEE Int. Conf. High Voltage Eng. Appl. (ICHVE)*, Chengdu, China, Sep. 2016, pp. 1–4.

[2] L. Yang, T. Zou, B. Deng, H. Zhang, Y. Mo, and P. Peng, "Assessment of oil-paper insulation aging using frequency domain spectroscopy and moisture equilibrium curves," *IEEE Access*, vol. 7, pp. 45670–45678, 2019.

[3] S.-Q. Wang, G.-J. Zhang, J.-L. Wei, S.-S. Yang, M. Dong, and X.-B. Huang, "Investigation on dielectric response characteristics of thermally aged insulating pressboard in vacuum and oil-impregnated ambient," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 17, no. 6, pp. 1853–1862, Dec. 2010.

[4] M. A. Ansari, D. Martin, and T. K. Saha, "Advanced online moisture measurements in transformer insulation using optical sensors," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 27, no. 6, pp. 1803–1810, Dec. 2020.

[5] A. K. Pradhan and S. Tenbohlen, "Estimation of moisture content in oil-impregnated pressboard through analyzing dielectric response current under switching impulse," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 28, no. 3, pp. 938–945, Jun. 2021.

[6] J. Gao, L. Yang, Y. Wang, C. Qi, J. Hao, and J. Liu, "Quantitative evaluation of ageing condition of oil-paper insulation using frequency domain characteristic extracted from modified cole-cole model," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 5, pp. 2694–2702, Oct. 2015.

[7] R. Liao, J. Liu, L. Yang, K. Wang, J. Hao, Z. Ma, J. Gao, and Y. Lv, "Quantitative analysis of insulation condition of oil-paper insulation based on frequency domain spectroscopy," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 1, pp. 322–334, Feb. 2015.

[8] G. Xia and G. Wu, "Study on the aging characteristics of transformer oil-paper insulation based on improved time domain dielectric spectroscopy," in *Proc. IEEE Electr. Insul. Conf. (EIC)*, Baltimore, MD, USA, Jun. 2017, pp. 112–115.

[9] T. K. Saha and Z. T. Yao, "Experience with return voltage measurements for assessing insulation conditions in service-aged transformers," *IEEE Trans. Power Del.*, vol. 18, no. 1, pp. 128–135, Jan. 2003.

[10] D. Giselbrecht and T. Leibfried, "Modelling of oil-paper insulation layers in the frequency domain with cole-cole-functions," in *Proc. IEEE Int. Symp. Electr. Insul.*, Toronto, ON, Canada, Jul. 2007, pp. 59–62.

[11] M. Koch, M. Krueger, and S. Tenbohlen, "On-site methods for reliable moisture determination in power transformers," in *Proc. IEEE Trans. Distrib. Conf. Expo.*, New Orleans, LA, USA, Apr. 2010, pp. 1–6.

[12] J. Gao, L. Yang, Y. Wang, X. Liu, Y. Lv, and H. Zheng, "Condition diagnosis of transformer oil-paper insulation using dielectric response fingerprint characteristics," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 2, pp. 1207–1218, Apr. 2016.

[13] S. M. Gubanski *et al.*, "Dielectric response diagnoses for transformer windings," CIGRÉ Tech. Brochure 414-WG D1.01 (TF 14), Tech. Rep., 2010.

[14] M. Koch and M. Kruger, "A fast and reliable dielectric diagnostic method to determine moisture in power transformers," in *Proc. Int. Conf. Condition Monitor. Diagnosis*, 2008, pp. 467–470.

[15] H. Wen, Z. Ma, Y. Wang, X. Zhao, R. Liao, and J. Hao, "Experimental investigation and XY model simulation on the frequency domain spectroscopy characteristics of transformer oil-paper insulation," *High Voltage Eng.*, vol. 38, no. 8, pp. 1956–1964, 2014.

[16] J. Cheng, D. Robalino, P. Werelius, and M. Ohlen, "Improvements of the transformer insulation XY model including effect of contamination," in *Proc. IEEE Int. Symp. Electr. Insul.*, San Juan, PR, USA, Jun. 2012, pp. 169–174.

[17] U. Gafvert, "Influence of geometric structure and material properties on dielectric frequency response of composite oil cellulose insulation," in *Proc. Int. Symp. Electr. Insulating Mater. (ISEIM)*, Kitakyushu, Japan, 2005, pp. 73–76.

[18] X. Fan, J. Liu, B. Lai, Y. Zhang, and C. Zhang, "FDS measurement-based moisture estimation model for transformer oil-paper insulation including the aging effect," *IEEE Trans. Instrum. Meas.*, vol. 70, pp. 1–10, 2021.

[19] J. Liu, X. Fan, C. Zhang, C. S. Lai, Y. Zhang, H. Zheng, L. L. Lai, and E. Zhang, "Moisture diagnosis of transformer oil-immersed insulation with intelligent technique and frequency-domain spectroscopy," *IEEE Trans. Ind. Informat.*, vol. 17, no. 7, pp. 4624–4634, Jul. 2021.

[20] V. Vasovic, J. Lukic, D. Mihajlovic, B. Pejovic, Z. Radakovic, U. Radoman, and A. Orlovic, "Aging of transformer insulation—Experimental transformers and laboratory models with different moisture contents: Part I—DP and furans aging profiles," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 26, no. 6, pp. 1840–1846, Dec. 2019.

[21] C. Ekanayake, S. M. Gubanski, A. Graczkowski, and K. Walczak, "Frequency response of oil impregnated pressboard and paper samples for estimating moisture in transformer insulation," *IEEE Trans. Power Del.*, vol. 21, no. 3, pp. 1309–1317, Jul. 2006.

[22] J. Gao, "Study on aging and moisture condition assessment of transformer main insulation base on dielectric fingerprint characteristic identification," Ph.D. dissertation, College Electr. Eng., Chongqing Univ., Chongqing, China, 2017.

[23] H. Wang, J. Yin, L. Cheng, R. Liao, and L. Yang, "A non-destructive testing method for moisture content of oil-paper insulation based on terahertz dielectric response," in *Proc. IEEE Conf. Electr. Insul. Dielectr. Phenomena (CEIDP)*, Richland, WA, USA, Oct. 2019, pp. 741–744.

[24] G. Li, J. Hao, S. Li, R. Liao, X. Zhao, and L. Yang, "AC breakdown and frequency dielectric response characteristics of the mixed oil-paper insulation with different moisture content," in *Proc. 1st Int. Conf. Electr. Mater. Power Equip. (ICEMPE)*, Xi'an, China, May 2017, pp. 478–481.

[25] J. Liu, T. Sun, X. Fan, Y. Zhang, and B. Lai, "A modified simulation model for predicting the FDS of transformer oil-paper insulation under nonuniform aging," *IEEE Trans. Instrum. Meas.*, vol. 70, pp. 1–9, 2021.

[26] Y. Liu, D. Ming, and R. Ming, "Comparison and research of XY model and finite element model in the simulation of frequency domain spectroscopy of oil-paper insulation," *High Voltage Eng.*, vol. 40, no. 11, pp. 3483–3490, 2014.

[27] J. Blennow, C. Ekanayake, K. Walczak, B. Garcia, and S. M. Gubanski, "Field experiences with measurements of dielectric response in frequency domain for power transformer diagnostics," *IEEE Trans. Power Del.*, vol. 21, no. 2, pp. 681–688, Apr. 2006.

[28] M. Dong, M. Ren, F. Wen, C. Zhang, J. Liu, C. Sumereder, and M. Muhr, "Explanation and analysis of oil-paper insulation based on frequency-domain dielectric spectroscopy," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 5, pp. 2684–2693, Oct. 2015.

[29] S. Bhumiwat, S. Lowe, P. Nething, J. Perera, P. Wickramasuriya, and P. Kuansatit, "Performance of oil and paper in transformers based on IEC 61620 and dielectric response techniques," *IEEE Elect. Insul. Mag.*, vol. 26, no. 3, pp. 16–23, May 2010.

[30] *Insulating Liquids—Oil-Impregnated Paper and Pressboard—Determination of Water by Automatic Coulometric Karl Fischer Titration*, Standard IEC 60814, 1997.

QINGCHUAN XU was born in Zhejiang, China, in 1995. He received the master's degree in electrical engineering from the Huazhong University of Science and Technology, in 2019. His major research interests include dielectric response of the oil-paper insulation systems and insulation diagnostic of the transformer.

SHENGKANG WANG was born in Hubei, China, in 1998. He received the bachelor's degree in electrical engineering from the Huazhong University of Science and Technology, in 2020. His major research interests include dielectric response of the oil-paper insulation systems and insulation diagnostic of the transformer.

FUCHANG LIN (Senior Member, IEEE) was born in Zhejiang, in 1969. He received the Ph.D. degree in electrical and electronic engineering from the Huazhong University of Science and Technology (HUST), in 1996. He is currently a Professor at the School of Electrical and Electronic Engineering, HUST. His main research interests include pulsed power technology and high-voltage engineering.

HUA LI (Senior Member, IEEE) was born in Wuhan, China, in 1979. She received the B.Eng. and Ph.D. degrees from the Huazhong University of Science and Technology, Wuhan, China, in 2004 and 2007, respectively. She is currently a Professor at the State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical and Electronic Engineering, Huazhong University of Science and Technology.