Investigating a New Approach for Moisture Assessment of Transformer Insulation System

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\section*{ABSTRACT}
With the wide application of vegetable insulating oil in power transformers, it is essential to investigate the influence of moisture on the frequency domain dielectric spectrum (FDS) analysis in order to propose an accurate moisture assessment method for vegetable oil-paper insulation system. In this regard, various vegetable oil-paper samples are prepared in a laboratory environment. FDS curves for all samples are obtained at different moisture contents and operating temperatures. A new method to estimate the moisture content in insulation paper is proposed based on the low-frequency characteristic quantity. Also, the effect of operating temperature and water migration between the oil and paper insulation on the FDS analysis is investigated. Based on this analysis, a compensation factor is introduced to eliminate the influence of temperature on paper moisture assessment. Furthermore, an improved normalization method for the temperature effect on the FDS of vegetable oil-paper insulation with different moisture contents is proposed. The proposed moisture assessment and temperature normalization methods are validated thorough their application on an operating power transformer.

\section*{INDEX TERMS}
Vegetable oil-paper insulation, frequency domain dielectric spectrum, moisture assessment, temperature normalization.

\section*{I. INTRODUCTION}
Moisture is the main factor affecting the insulation dielectric strength of oil-immersed power transformers [1]. At present, moisture equilibrium curves are used to assess the moisture content within the insulating paper [2], [3]. However, this method is temperature dependent and is not very accurate. At the same time, vegetable insulation oil has been gradually utilized in power transformers because of its high flammability point, easy decomposition and good hygroscopicity [4]. As moisture assessment method for conventional mineral oil is not suitable for vegetable oil, developing a new reliable moisture assessment method for vegetable oil is necessary.

Recently, frequency dielectric spectrum (FDS) has widely used to diagnose water content in paper-oil insulation system [5]–[7]. The accuracy of this method depends on the operating temperature which may cause errors in the FDS test results [8], [9]. Results presented in [10] reveal that the transformer operating temperature affects the insulation dielectric loss curve of water content and a method to eliminate the influence of temperature is proposed. However, this method is effective for mineral insulating oil only. The principle of frequency-temperature translation is proposed to eliminate the influence of temperature on FDS and the transformer water content is evaluated using normalized curves in [11]. However, these curves are not very accurate due to the continuous migration of water between paper and oil [12], which also affects the activation energy of the solid insulation [13]. In [14], a frequency-temperature normalization curve for mineral oil under different moisture contents is proposed, but the effect of water migration between solid and liquid insulation is not taken into account in the process of normalization, which affects the results of this method.

From the above discussion, the main contribution of this paper can be summarized as below:
proposing a moisture assessment method, which can eliminate the influence of temperature on the obtained results.
proposing a new normalization method for FDS curves for vegetable oil-paper insulation system.

II. PREPARATION OF OIL-PAPER INSULATION SAMPLES
The proposed methods are examined on samples of vegetable oil and insulating Kraft paper, the insulating Kraft paper used in the experiment had a diameter of 130 mm and a thickness of 5 mm. Each insulation system consists of five sheets of insulation papers and vegetable insulating oil samples. Before the experiment, all new oil and paper samples are dried at 90°C for 48 hours to control the initial moisture content of oil is between 100-120mg/kg and that of insulating paper is about 0.1%. The initial moisture content of samples is detected by HKF700 moisture measuring instrument, and the operating steps are carried out according to the standard IEC 60814.

After the drying process, the insulating paper sample is immersed in the oil for 48 hours at 30°C. The vegetable oil-paper moisture measurement is then carried out as below.

Firstly, the paper sheet is weighted to determine its initial weight $m_0$. Secondly, the weight $m_1$ of the impregnated insulation paper with moisture content $w$ is calculated using (1).

$$w = \frac{m_1 - m_0}{m_0} \times 100\%$$ (1)

Thirdly, the paper sample is then placed on an open glass dish to moist it naturally and its weight is measured every 5 minutes until the weight of the paper reaches $m_1$. Finally, when the moisture content of the insulating paper calculated using (1) reaches 0.2%, 1.4%, 2.5% and 3.4%, the insulating paper and oil are put into three-electrode device to emulate the power transformer insulation system as shown in Fig. 11 in the Appendix.

The FDS of the oil-paper samples is then tested at different operating temperatures. FDS tests at 30°C, 50°C, 70°C and 90°C are carried out and the FDS curves of the investigated samples at various time intervals (0, 2, 4 and 6 days at different temperatures) during steady and transient states are obtained. During the test, samples should be placed in the thermostat until the end of the experiment.

When an AC voltage $U^*(\omega)$ is applied to the oil-paper sample, interfacial polarization and steering polarization occur within the insulation system, and a current $I^*(\omega)$ will flow in the system:

$$I^*(\omega) = j\omega C^*(\omega)U^*(\omega) = (j\omega C(\omega) + G(\omega))U^*(\omega)$$ (2)

where $C^*(\omega)$ is the complex capacitor of the oil-paper insulation, $C'(\omega) = C_0\varepsilon'$, $C''(\omega) = \omega C_0\varepsilon''$, and thus (2) can be simplified to:

$$I^*(\omega) = j\omega C_0(\varepsilon'(\omega) - j\varepsilon''(\omega))U^*(\omega)$$

$$= j\omega C_0\varepsilon' U^*(\omega)$$ (3)

FDS analyzer is used to detect the current flowing through the oil-paper insulation system, and the dielectric response of the oil-paper insulation can be analyzed using (3).

Dielectric response analyzer IDAX300 of frequency range $10^{-4}$-$10^3$Hz as shown in Fig. 1 is used for FDS measurements.

III. RESULTS AND ANALYSIS
A. EFFECT OF MOISTURE ON FDS
The permittivity ($\lg\varepsilon'$) curves for the vegetable oil-paper samples of different moisture contents at 30°C are shown in Fig. 2. To facilitate better understanding for these curves, a logarithmic scale in the scale $-4$ to $3$, representing a test frequency band $10^{-4}$ to $10^3$Hz is utilized for the $x$-axis.

It can be seen from Fig. 2 that the real and imaginary parts of the insulation permittivity ($\lg\varepsilon'$-$\lg\varepsilon''$) curves increase with the increase of water content in the oil-paper sample within the frequency range of $10^{-4}$-$1$Hz. This is attributed to the fact that moisture increase results in an increase in the polarization performance of the oil-paper insulation system. With the decrease of the test frequency, the rapid polarization process of water can be established completely, so the permittivity of the insulation system in the low frequency band increases with the increase of water content. The more water content, the rapidly increase in the dielectric constant. Owing to the relatively high frequency, polarization process of the oil-paper insulation system cannot be developed in the frequency range 1 to $10^3$Hz and the $\lg\varepsilon'$ curve doesn’t exhibit obvious change within this range.

It is to be noted that moisture not only affects the polarization loss of the oil-paper insulation system, but also increases its conductivity. The conductivity loss is dominant for the oil-paper insulation system in the low frequency range, so the $\lg\varepsilon''$ curve increases with the increase of water content. However, in the high frequency range, the insulation system polarization process cannot be developed and there is only instantaneous polarization loss.

In conclusion, the effect of moisture on the frequency domain spectrum of vegetable oil-paper insulation system can be obviously seen in the change of $\lg\varepsilon'$ within the frequency range $10^{-4}$-$1$Hz. In this range, the moisture content accelerates the rate of change of $\lg\varepsilon'$ with a peak value at $10^{-4}$Hz.
Under the action of an applied electric field, the dielectric response of the insulation system can be described using the Debye dielectric mathematical model as below:

\[
\varepsilon' = \varepsilon_{\infty} + \frac{\varepsilon_s - \varepsilon_{\infty}}{1 + \omega^2 \tau^2}
\]

(4)

\[
\varepsilon'' = \frac{j \omega \tau \cdot (\varepsilon_s - \varepsilon_{\infty})}{1 + \omega^2 \tau^2}
\]

(5)

where \( \tau \) represents the relaxation time during dielectric polarization and its value varies according to several external factors. The \( \varepsilon_{\infty} \) and \( \varepsilon_s \) are the optical frequency dielectric constant and the static dielectric constant, respectively, their values depend on the insulation system properties.

Using the Debye dielectric model to derive the real part of the dielectric constant, the following formula can be obtained:

\[
L_f = \left| \frac{d \varepsilon'}{df} \right| = \frac{8\pi^2 \tau^2 f \cdot (\varepsilon_s - \varepsilon_{\infty})}{(1 + 16\pi^2 \tau^2 f^2)^2}
\]

(6)

The \( L_f \) is the rate of change of the dielectric constant curve at all frequency points.

It can be seen from (6) that there is an obvious mathematical correlation between \( L_f \) and the dielectric parameters \( \tau, \varepsilon_{\infty}, \varepsilon_s \) along with the electric field frequency \( f \). Under the action of external electric field, the polarization process takes place in the dielectric. Different dielectric materials exhibit different polarization time \( \tau \) and dielectric constants \( \varepsilon_{\infty}, \varepsilon_s \). At the same time, when the frequency of the external electric field changes, the moving speed of the internal polar molecules in the insulation material changes. Hence, the polarization time \( \tau \) and \( L_f \) will change accordingly.

When the oil-paper insulation is misted, the molecules polarization process of the insulation material is accelerated. The dielectric constant curves of the oil paper insulation also increases in the frequency range \( 10^{-4}-1 \) Hz with a maximum value at \( 10^{-4} \) Hz.

According to (6), the moisture causes the relaxation time \( \tau \) of the oil-paper to decrease and hence changing the \( L_f \) value. The \( L_f \) value at \( 10^{-4} \) is mainly affected by the relaxation time. This shows that the change rate of the dielectric constant of the oil-paper insulation at \( 10^{-4} \) can be used as a characteristic quantity to describe the degree of moisture absorption of the oil-paper insulation system.

To express this process mathematically, let \( L \) be the rate change of \( \text{lg} \varepsilon' \) of the insulation system at \( 10^{-4} \) Hz, then \( L \) can be expressed as:

\[
L = \left| \frac{d (\text{lg} \varepsilon')}{d (\text{lg} f)} \right|_{f=10^{-4}}
\]

(7)

Polynomial fitting of \( \text{lg} \varepsilon' - \text{lg} f \) curves at different moisture contents (w%) is carried out and the fitting results are used into (7) to calculate the correlation coefficient \( R^2 \) and \( L \) at \( 10^{-4} \) Hz. Results are shown in Table 1 in which \( x \) represents \( \text{lg} \varepsilon' \), and \( y \) represents \( \text{lg} f \).

As can be seen from Table 1, the more water contents in the insulation paper, the greater the value of \( L \). Since water is polar molecule, its addition increases \( \varepsilon' \) and hence \( L \). Fitting \( L \) with the moisture content \( w \) of insulation paper, the following exponential correlation is obtained:

\[
L = 0.5106 \cdot \exp(0.2917w)
\]

(8)

The above equation can be used to assess the moisture content within the vegetable oil-paper insulation system.

### TABLE 1. Correlation coefficient and \( L \) of real part curves of permittivity with different moisture contents.

| w% | Fitting Polynomial | \( R^2 \) | \( L \) |
|----|--------------------|----------|------|
| 0.2 | \( y = 0.44 \times 10^3 x^5 - 0.23 \times 10^3 x^4 - 0.01 x^3 + 0.07 x^2 - 0.11 x - 0.55 \) | 0.9998 | 0.54 |
| 1.4 | \( y = -0.26 \times 10^3 x^5 - 0.26 \times 10^3 x^4 - 0.36 \times 10^2 x^2 + 0.09 x^2 - 0.17 x + 1.096 \) | 0.9938 | 0.77 |
| 2.5 | \( y = -0.12 \times 10^3 x^5 - 0.47 \times 10^3 x^4 + 0.012 x^3 + 0.12 x^2 - 0.36 x + 1.188 \) | 0.9938 | 1.06 |
| 3.4 | \( y = 0.18 \times 10^3 x^5 - 0.5 \times 10^3 x^4 + 0.03 x^3 + 0.14 x^2 - 0.59 x + 1.325 \) | 0.9985 | 1.38 |

**FIGURE 2.** Frequency domain dielectric spectrum of oil-paper with different moisture contents at constant temperature (30\(^{\circ}\)C). (a) Real part of permittivity. (b) Imaginary part of permittivity.
Fig. 3 reveals that frequency domain spectrum of vegetable oil-paper moves toward the high frequency band as the temperature rises. This is attributed to the relaxation time $\tau$ which is correlated to the test temperature $T$ by [15]:

$$\tau(T) = \tau_0 \exp \frac{\Delta E}{kT}$$  \hspace{1cm} (9)

where $\tau_0$ is the relaxation time constant, $\Delta E$ is the dielectric activation energy and $k$ is the Boltzmann constant.

Equation (9) implies that as the temperature rises, the relaxation insulation polarization time decreases while the polarization velocity accelerates which leads to polarity enhancement of the oil-paper insulation system. At the same time, the imaginary part of the dielectric constant also increases in the low frequency band with the temperature increase because of the relaxation polarization and conductance losses.

Similar to the above case study, polynomial fitting is conducted for the $\lg \varepsilon'$-$\lg f$ curves at different temperatures and the value of $L$ at $10^{-4}$ Hz is calculated using (7). Results of the fitting process are shown in Table 2 in which $x$ represents $\lg \varepsilon'$ and $y$ represents $\lg f$.

It can be observed from Table 2 that as the temperature increases, both $\lg \varepsilon'$ and $L$ increase.

Additionally, the $\lg \varepsilon'$-$\lg f$ curves of the insulating paper immersed in insulating oil with 2.5% moisture content in the paper for 0 days, 2 days, 4 days and 6 days at 90°C are analyzed to investigate the water migration between paper and oil over a period of time. The values of $L$ that change with the immersing time are shown in Fig. 4 and Table 3.

It can be seen from Fig. 4 and Table 3 that the $\lg \varepsilon'$-$\lg f$ curves decrease in the low frequency band with the increase of the soaking time of the oil-paper at 90°C. According to the moisture equilibrium curves of oil-paper insulation [12], as transformer operating temperature increases, water in the paper migrates to oil. Because of the good hygroscopicity of the vegetable oil, the moisture in the paper decreases rapidly, which reduces the polarization of the oil-paper interface and

\begin{table}[H]
\centering
\caption{Correlation coefficient and $L$ of real part curves of permittivity with different temperatures.}
\begin{tabular}{|c|c|c|}
\hline
$T$/$^\circ$C & Fitting Polynomial & $R^2$ & $L$ \\
\hline
30 & $y=0.44 \times 10^{5}e^{-0.23 \times 10^{5}x-0.01x^{2}+3.6\times 10^{4}x^{2}}+0.7e^{2}-0.11x-0.55$ & 0.9987 & 0.53 \\
50 & $y=0.26 \times 10^{5}e^{-0.22 \times 10^{5}x-0.011x^{2}+0.98e^{2}-0.21x+1.055}$ & 0.9984 & 0.62 \\
70 & $y=0.48 \times 10^{5}e^{-0.37 \times 10^{5}x+0.16 \times 10^{5}x^{2}+0.11x^{2}-0.25x+1.113}$ & 0.9989 & 0.72 \\
90 & $y=0.72 \times 10^{5}e^{-0.36 \times 10^{5}x+0.89 \times 10^{5}x^{2}+0.38 \times 10^{5}x^{2}+1.214}$ & 0.9987 & 0.95 \\
\hline
\end{tabular}
\end{table}

\begin{table}[H]
\centering
\caption{Correlation coefficient and $L$ of real part curves of permittivity with different soaking time.}
\begin{tabular}{|c|c|c|}
\hline
Days & Fitting Polynomial & $R^2$ & $L$ \\
\hline
0 & $y=-1.32 \times 10^{5}x^{2}-0.51x+10^{5}x^{2}+0.73 \times 10^{5}x^{2}+0.11x^{2}-0.23x+1.325$ & 0.9988 & 1.68 \\
2 & $y=-1.21 \times 10^{5}x^{2}-0.65x+10^{5}x^{2}+0.68x+10^{5}x^{2}+0.31x+1.311$ & 0.9984 & 1.51 \\
4 & $y=-1.07 \times 10^{5}x^{2}-0.75x+10^{5}x^{2}+0.38x+10^{5}x^{2}+0.21x+1.183$ & 0.9971 & 1.26 \\
6 & $y=-0.83 \times 10^{5}x^{2}-0.95x+10^{5}x^{2}+0.28x+10^{5}x^{2}+0.51x+1.052$ & 0.9977 & 1.05 \\
\hline
\end{tabular}
\end{table}
resulting in a decline of the FDS curve in the low frequency band.

In conclusion, the influence of temperature on the characteristic factor \( L \) is composed of two parts:
- when the temperature of the oil-paper system rises to \( T \), the \( \lg e' - \lg f' \) curves are affected and \( L \) increases to \( L_T \).
- with the increase of the immersion time, the moisture in the paper begins to migrate to the oil at a particular temperature \( T \), resulting in the decrease of \( \lg e' - \lg f' \) curve at low frequency band and \( L \) decreases to \( L_w \).

Therefore, the mathematical effect of the temperature on \( L \) can be expressed as:

\[
\Delta L = LT - Lw
\]  

(10)

In (10), \( L_T \) represents the increase of \( L \) due to temperature change and \( L_w \) represents the decrease in \( L \) due to moisture migration.

C. ELIMINATING THE EFFECT OF TEMPERATURE ON \( L \)
The above results show that the operating temperature affects \( L \), which in turn affects the accuracy of the moisture assessment in vegetable oil-paper insulation system. In order to improve the accuracy of moisture assessment, this section proposes a compensation factor \( \gamma \) as in (11) to eliminate the effect of temperature on \( L \).

\[
\gamma = \frac{LT}{L'} = \frac{L - L'}{L'}
\]  

(11)

where \( L \) is the measured value when the temperature just rises to \( T \). \( L' \) represents the characteristic factor after eliminating the influence of \( L_T \). In this study, the characteristic factor \( L \) at 30\(^\circ\)C is assumed to be \( L' \).

The \( \lg e' - \lg f' \) curves of the oil-paper with different moisture contents at different temperatures are measured and the compensation factor \( \gamma \) is calculated according to (11) as shown in Table 4. It can be seen that the compensation factor \( \gamma \) increases rapidly with the increase of the moisture content and operating temperature. It indicates that the operating temperature has a great influence on the characteristic factor \( L \). The higher the temperature, the more inaccurate the moisture assesses. When the temperature rises to 90\(^\circ\)C, the effect of temperature on \( L \) is obvious. So, it is impossible to accurately estimate the moisture content of vegetable oil-paper using \( L \) only.

MATLAB interpolation function is used to fit the moisture compensation factor \( \gamma \), the temperature \( T \) and the moisture content \( w \). The fitting results are shown in Fig. 5.

As can be seen from Fig. 5, the influence of moisture and temperature on \( L \) is not simply superimposed but interacts with each other. The temperature at different moisture contents has different effects on the characteristic factor, and as the moisture increases, the effect of temperature becomes more prominent. It can be also observed that the moisture compensation factor is unique at particular temperature and moisture values.

### Table 4. Proposed compensation factor.

| \( T \)\(^\circ\)C | \( w=0.2\% \) | \( w=1.4\% \) | \( w=2.5\% \) | \( w=3.4\% \) |
|---|---|---|---|---|
| 30 | 0 | 0 | 0 | 0 |
| 50 | 0.09 | 0.14 | 0.28 | 0.41 |
| 70 | 0.20 | 0.35 | 0.48 | 0.58 |
| 90 | 0.42 | 0.49 | 0.58 | 0.69 |

A method based on the compensation factor is proposed to accurately assess the moisture within the vegetable oil-paper insulation system at different temperatures. The specific steps are as follows:

1) Measure the \( \lg e' - \lg f' \) curve of the insulation sample to find the low-frequency characteristic factor \( L \), and calculate the initial moisture content \( w \) according to (7), and then record the test temperature \( T \).

2) Use \( w \) and \( T \) in the surface of the compensation factor (Fig. 5), to obtain the moisture compensation factor \( \gamma \). Use \( \gamma \) to modify the characteristic factor \( L \) to obtain \( L' \), and use \( L' \) to calculate the moisture content \( w' \).

3) Repeat the above two steps until \( \frac{(w' - w)\times 100}{w} < 1\% \), then \( w' \) is taken as an accurate moisture content of the insulating paper.

It is to be noted that the proposed compensation factor only eliminates the influence of temperature (\( L_T \)) on \( L \) but does not eliminate the reduced \( L_w \) part due to water migration between paper and oil. The flow chart of this method is shown in Fig 6.

D. ELIMINATING THE EFFECT OF TEMPERATURE ON FDS
In order to obtain more accurate information about the oil-paper insulation, it is necessary to eliminate the influence of temperature on the frequency spectrum. Therefore, a method to normalize the FDS curves at a pre-set reference temperature (30\(^\circ\)C) is proposed below.
-First, the relationship between the relaxation time $\tau$ and frequency is [14]:

$$f(T_1) \times \tau(T_1) = f(T_2) \times \tau(T_2) = \text{CONST} \quad (12)$$

-Second, the dielectric activation energy $\Delta E$ is obtained using (9) and (12) as below (derivation is given in the Appendix):

$$\Delta E = \frac{k}{(T_1 - T_2)} \left( \ln f(T_2) - \ln f(T_1) \right) \quad (13)$$

In (12) and (13), $f(T_1)$ and $f(T_2)$ represent the frequency at the inflection temperature points of the curve; $T_1$ and $T_2$, respectively while $\tau(T_1)$ and $\tau(T_2)$ represent the relaxation time at $T_1$ and $T_2$.

Using (13), the average activation energy of the vegetable oil-paper sample comprising 0.2% moisture content is 22 eV.

-Third, the normalization function of the frequency domain spectrum is obtained from:

$$f(T) = f_0 \exp \left( \frac{\Delta E}{k} \left( \frac{1}{T} - \frac{1}{T_0} \right) \right) \quad (14)$$

where $f(T)$ represents the frequency corresponding to a preset main temperature $T$. $f_0$ is the frequency before normalization. $T_0$ is the temperature of the curve to be normalized to a temperature $T$.

The above process is used to normalize the frequency domain spectrum at 50°C, 70°C and 90°C to 30°C curve as shown in Fig. 7 which reveals perfect matching of all curves regardless the operating temperature.

Each curve in Fig. 7 is fitted, and $L$ of the normalized curve is calculated as shown in Table 5. It can be seen from the table that the equations and $L$ value for all curves are comparable. Also it can be seen that, the values of $L$ after normalization are significantly reduced compared with the case before normalization (Table 2), which indicates a reduced influence of the temperature on the low frequency curves of the oil-paper FDS.

### TABLE 5. Correlation coefficient and $L$ of curves after normalization to 30°C.

| $T^\circ C$ | Fitting Polynomial | $R^2$ | $L$ |
|------------|--------------------|-------|-----|
| 50→30      | $y =-0.26 \times 10^{-3} e^{5.0.17}+10-2e^{4.0.04}+0.014 e^{3}$ +0.07 e^{2} -0.08 e +1.022 | 0.9988 | 0.54 |
| 70→30      | $y =-0.48 \times 10^{-3} e^{5.0.53}+10-2e^{4.0.011}+0.09 e^{2} -0.08 e +1.013$ +0.09 e^{2} -0.07 e +1.028 | 0.9981 | 0.59 |
| 90→30      | $y =-0.85 \times 10^{-3} e^{5.0.79}+10-2e^{4.0.015}+0.09 e^{2} -0.07 e +1.028$ +0.09 e^{2} -0.07 e +1.028 | 0.9976 | 0.58 |

E. NORMALIZATION METHOD FOR VEGETABLE OIL-PAPER INSULATION

As mentioned above, when the operating temperature of the oil-paper insulation system increases for a period of time, the
moisture in paper migrates to the oil [12]. Furthermore, as the water comprises strong polar molecules, breakage of the cellulose chain within the paper is accelerated and changes the polarity of the oil-paper system, which in turn affects the polarization process of the paper. Moreover, moisture will affect the activation energy of the insulating paper [13]. Therefore, an improved method for normalizing the frequency domain spectrum of vegetable oil-paper with another compensation factor is proposed. In the proposed compensation technique, the average activation energy of the vegetable oil-paper with moisture contents of 1.3%, 2.5% and 3.4% is calculated first as shown in Table 6. The moisture content and activation energy in the table are then fitted as shown in Fig. 8.

From (8) and (9), the frequency domain spectral normalization equation at different water contents and temperatures can be obtained as below.

\[
f(T) = f_0 \exp\left(\frac{0.6653 \exp(w/\text{1.006}) + 20.8}{k} \left(\frac{1}{T} - \frac{1}{T_0}\right)\right) \quad (15)
\]

According to the temperature normalization equation and moisture assessment method proposed in this paper, the influence of temperature on the frequency domain spectrum of the vegetable oil-paper with different moisture contents can be eliminated.

The overall normalization method can be summarized as follows:

1) Test FDS curves of the vegetable oil-paper insulation system at \( T \) temperature, and perform polynomial fitting on each curve to calculate \( L \).
2) Calculate the compensation factor of \( L \) at \( T \) temperature to eliminate the influence of temperature on \( L \).
3) Find the frequency point \( f_T \) at which the minimum dielectric constant is located based on the frequency domain spectrum, and calculate the average activation energy \( \Delta E \) according to (14).

The flow chart of this normalization method is shown in Fig 9.

### IV. FEASIBILITY OF THE PROPOSED COMPENSATION METHODS

To validate the feasibility of the proposed moisture assessment and temperature normalization methods, the FDS data of a 10kV vegetable oil immersed transformer are used. The transformer was put into operation in the year 2018 and its insulation overall condition was good during the testing period. During the testing time, moisture content in oil was only 25.9mg/kg, which has less influence on the FDS.

IDAX300 is used to measure the FDS curve of the transformer insulation oil-paper sample at 37°C from which initial characteristic factor \( L \) is calculated as \( L = 0.98 \). Based on the proposed compensation factor method, \( L \) is modified to \( L' = 0.91 \). The moisture content of the extracted vegetable oil sample is calculated using the above proposed moisture assessment method and is found to be \( w = 1.98\% \). Finally, the normalized FDS curve is obtained by introducing \( w \) into the proposed normalization equation as shown in Fig. 10.

The measured and the normalized curves in Fig. 10 are fitted and the corresponding values of \( L \) are calculated as shown in Table 7 in which \( x \) represents \( \log \varepsilon' \), and \( y \) represents \( \log f \).

Results show that \( L \) of the normalized curve is close to the measured curve and the influence of temperature on the measured curve has been significantly reduced and thus \( L \) can be used to assess the solid insulation moisture content. When \( L \) is substituted into (2), the moisture content in the insulating paper is calculated and is found to be 2\%, which is 0.08\% different from 2.06\% detected by the compensation.
V. CONCLUSION

In this paper, a method for accurate moisture content assessment of vegetable oil-paper insulation is proposed. This method is aimed at eliminating the influence of temperature on the assessment of moisture content in the solid insulation. The proposed method also improves the normalization of the frequency domain spectrum of the transformer insulating vegetable oil. The main conclusions of the obtained results can be drawn as below:

- Moisture accelerates the change rate of the permittivity of the vegetable oil-paper insulation system within the frequency range $10^{-4}$-1Hz. Moisture content is strongly correlated to the characteristic factor $L$ which can be used for moisture assessment.
- Operating temperature influences the characteristic factor at low frequency range. Thus, the overall influence can be divided into two parts: temperature effect that increases $L$ and moisture migration effect that decreases $L$.
- Moisture and temperature affect the activation energy of the oil-impregnated paper, and there is an exponential correlation between the moisture content and activation energy.
- According to the principle of frequency-temperature superposition and the influence of moisture, a method for normalizing the FDS curves of insulating oil-paper with different moisture contents at a pre-set temperature is proposed and validated through practical case study.

APPENDIX

See Fig. 11.

Derivation of Eq. (13):
Substituting Eq. (3) into Eq. (7):

$$f(T_1) \times \tau_0 \exp \left(\frac{\Delta E}{kT_1}\right) = f(T_2) \times \tau_0 \exp \left(\frac{\Delta E}{kT_2}\right) \quad (A1)$$

$$f(T_1) \times \exp \left(\frac{\Delta E}{kT_1}\right) = f(T_2) \times \exp \left(\frac{\Delta E}{kT_2}\right) \quad (A2)$$

Taking the Logarithm for both sides of A2

$$\ln f(T_1) + \frac{\Delta E}{kT_1} = \ln f(T_2) + \frac{\Delta E}{kT_2} \quad (A3)$$

$$\frac{\Delta E}{k} \left(\frac{1}{T_1} - \frac{1}{T_2}\right) = \ln f(T_2) - \ln f(T_1) \quad (A4)$$

$$\Delta E = k \left(\frac{1}{T_1} - \frac{1}{T_2}\right) \ln \left(\frac{f(T_2)}{f(T_1)}\right) \quad (A5)$$

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LINDUO LI, photograph and biography not available at the time of publication.

JIANGWEI HAN, photograph and biography not available at the time of publication.

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