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Dielectric Spectroscopy Techniques as Quality Control Tool: A Feasibility Study

Key Words: Oil-Impregnated Paper (OIP) condenser bushings, dielectric spectroscopy, time domain, frequency domain.

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In this article, the feasibility of using time and frequency domain dielectric spectroscopy techniques to monitor the condition of oil-impregnated paper (OIP) condenser bushings is discussed.

Introduction

Bushings are essential elements of many power equipments, including circuit breakers, capacitors, reactors, etc. Both high- and low-voltage windings are insulated from the core and from each other, and leads are brought out through insulating bushings. The two basic bushing designs are non-graded and capacitance-graded. The former is the simplest and the oldest. Capacitance graded bushings are available in four technologies: Resin Bounded paper (RB), Oil-Impregnated Paper (OIP), Resin Impregnated Paper (RIP) and Epoxy Resin Impregnated Paper (ERIP). OIP bushing, developed in the 1920s, is one of the most common types [1]. About 80% of all bushings in use today are of the OIP type.

Explosive failure often follows bushing deterioration/degradation, frequently resulting in catastrophic and expensive failure of a transformer and heavy damage to adjacent equipment. Accurate monitoring of the condition of bushings in service is therefore of vital importance.

At present, routine maintenance tests most often used for checking the condition of bushings involve visual inspection and power factor/capacitance tests at line frequency [2]. The need to test power system insulation non-destructively and reliably in the field has driven the development of diagnostic tools based on changes in the dielectric properties of the insulation [3]–[14].

In this article, the feasibility of using time- and frequency-domain dielectric spectroscopy measurements to monitor the fabrication of OIP condenser bushings is discussed. Such measurements have been made on a laboratory OIP bushing model. The manufacturing process consisted of three stages, namely fabrication, drying and impregnation. Short-circuit between some of the condenser layers has also been simulated.

Dielectric Spectroscopy Techniques

The fundamental theories behind dielectric measurements are well known [6], [11], [13]. Dielectric phenomena are discussed in Jonscher's publications [5]. However, to facilitate interpretation of the measurements presented in this paper, a short review

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of the theory behind time and frequency domain measurement techniques follows.

A. Time Domain Spectroscopy

The measurement of polarization and depolarization currents (PDC) following application of a dc voltage step is one way to investigate slow polarization processes in the time domain [5], [7]–[14]. A dc charging voltage U(t) with the following characteristics is applied to the initially relaxed insulation system:

$$U(t) = \begin{cases} 0 & t \leq 0 \\ U_C & 0 \leq t \leq t_C \\ 0 & t \geq t_C \end{cases}$$

A long charging time is required (e.g., 10,000 s) in order to assess interfacial polarization and sample condition. During charging, the polarization (or absorption) current $I_{pol}(t)$ through the test object is measured. $I_{pol}(t)$ can be expressed as [4]–[12]:

$$I_{\text{pol}}(t) = C_0 U_c \left[\frac{\sigma_o}{\varepsilon_o} + \varepsilon_\infty \delta(t) + f(t) \right] \tag{1}$$

where C_0 is the geometrical capacitance of the bushing = 29.4 pF, U_c is the step voltage (charging voltage), σ_o is the dc conductivity of the dielectric material, $\varepsilon_0 = 8.852 \times 10^{-12}$ F/m is the vacuum permittivity, ε_∞ is the high frequency component of the permittivity, δ(t) is the delta function arising from the applied step voltage at t = 0, and f(t) is the response function of the dielectric material.

Following the polarization period, the test sample is short-circuited by removing the applied voltage at $t = t_C$, enabling the measurement of the depolarization (or resorption) current $I_{depol}(t)$ in the opposite direction. $I_{depol}(t)$ has zero dc conductivity component [13].

According to the superposition principle, the sudden reduction of the voltage U_c to zero may be regarded as application of a negative voltage step at time $t = t_c$. Neglecting the delta function in (1) we get, for $t > t_C$ [4]–[11]:

$$I_{\text{depol}}(t) = -C_o U_c \left[f(t - t_C) - f(t) \right] \tag{2}$$

Figure 1 shows the PDC measuring circuits while Figure 2 shows typical variation of I_{pol} and I_{depol} following application and removal of the step charging voltage U_C [6], [13]. From the PDC measurement currents, the dc conductivity σ_0, can be estimated. If the test object is charged for a sufficiently long time, then $f(t_C) \cong 0$, and the dielectric response function f(t) will be proportional to the depolarization current. Rewriting (1) as

$$f(t_1) = \frac{I_{\text{pol}}(t_1)}{C_0 U_C} - \frac{\sigma_0}{\varepsilon_0} \tag{3}$$

and (2) as

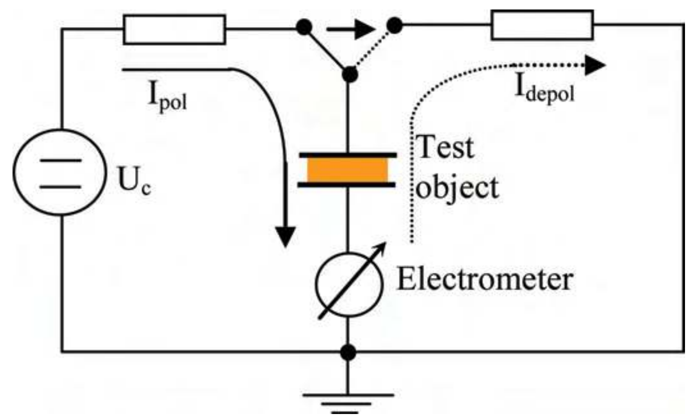

Figure 1. PDC measuring circuitry.

$$f(t - t_C) \approx \frac{-I_{\text{depol}}(t - t_C)}{C_0 U_C} \tag{4}$$

we obtain

$$\sigma_o \approx \frac{\varepsilon_0}{C_0 U_C} \left(I_{\text{pol}}(t_1) + I_{\text{depol}}(t - t_C) \right) \tag{5}$$

for any t and t_1 such that t_1 (during charging) = $t - t_C$ (during discharging) [13], [14].

Even without performing direct conductivity measurements on an oil sample, the oil conductivity can be obtained using (5). In the same way, the conductivity of the paper can be estimated from the long term values of the polarization and depolarization currents.

B. Frequency Domain Spectroscopy

Instead of studying the polarization in the time domain we can study the dielectric response in the frequency domain when an

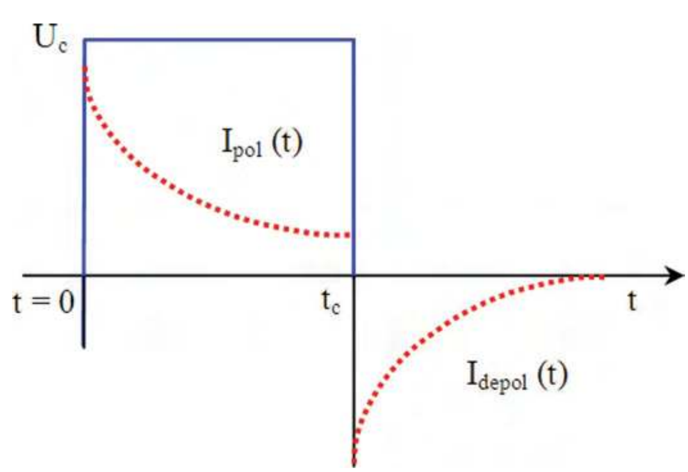

Figure 2. Typical polarization and depolarization currents [6], [13].

AC sinusoidal voltage U(ω) is applied. Fourier transforming the polarization current yields [6], [13]:

$$\hat{I}(\omega) = j\omega C_o \left[\underbrace{\varepsilon_\infty + \chi'(\omega)}_{\varepsilon'(\omega)} - j \underbrace{\left(\frac{\sigma_o}{\varepsilon_o \omega} + \chi''(\omega) \right)}_{\varepsilon''(\omega)} \right] \hat{U}(\omega) \quad (6)$$

where $\chi(\omega) = \chi'(\omega) - j\chi''(\omega)$ is the Fourier transform of the dielectric response function f(t), defined as the complex dielectric susceptibility. Given that $\varepsilon(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega)$, the loss factor tan δ can be defined as [6]:

$$\tan\delta(\omega) = \frac{\varepsilon''(\omega)}{\varepsilon'(\omega)} = \frac{\frac{\sigma_o}{\varepsilon_o \omega} + \chi''(\omega)}{\varepsilon_\infty + \chi'(\omega)} \quad (7)$$

Frequency domain spectroscopy (FDS) has been implemented in the Insulation Diagnostic Analyzer IDA 200 [15]. This instrument allows frequency scanning of the capacitance, power factor, dielectric constant and dielectric loss from 0.1 mHz to 1 kHz.

OIP bushing design

A laboratory OIP condenser bushing model has been designed to evaluate the feasibility of using FDS to monitor the fabrication processes (Figure 3). This condenser bushing is essentially a series of concentric capacitors between the center conductor and the ground sleeve or mounting flange. The design offers a capacitively graded, oil impregnated paper condenser bushing. The condenser consists of an electrical grade paper wound over a central conductor. The condenser is fabricated by inserting aluminum foil layers at predetermined locations in order to smooth the field distribution in the bushing. The condenser core is placed inside an insulating envelope of Plexiglas, then heated, vacuum dried, and impregnated with an electrical grade mineral oil.

Cellulose paper used in the OIP laboratory bushing model is a Diamond Pattern Paper (DPP), manufactured by Weidmann [16] with a thickness of 0.125 mm and a dielectric breakdown voltage of 8.5 kV (measured according to ASTM D-202, Section 143).

Design equations used to manufacture the bushing models can be found in the literature [17], [18]. An overview of the OIP condenser bushing construction is provided in Figure 4.

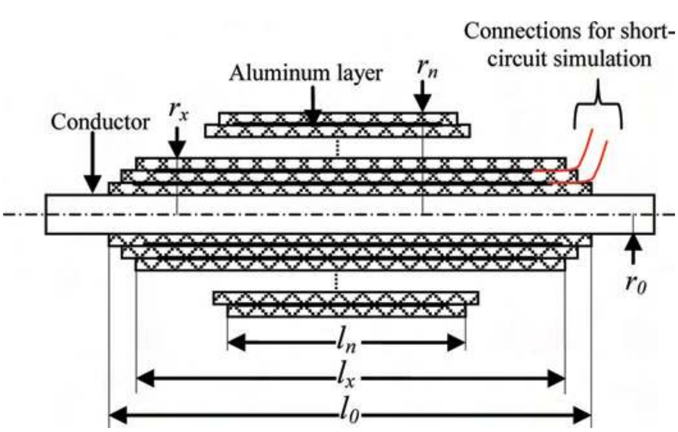

Figure 3. Construction details of a typical condenser bushing rated up to 69 kV.

Experimental Investigations

In these investigations, polarization and depolarization current (PDC) measurements using a stabilized DC power source up to 2500 V were analyzed to obtain the dielectric response in the time domain. Analysis in the frequency domain was performed using the IDA 200. Such data are known to be influenced by insulation aging, geometry, moisture content, and operating temperature [6], [7], [10], [13], [19]–[22]. As insulation aging is not part of these investigations, and measurements were made close to room temperature, the most important factors influencing the present data would be voids, moisture, and grading capacitance coupling (short-circuit).

In the present study, the dielectric response was used to investigate the change in the OIP bushing insulation after three steps, namely

1. Immediately after fabrication (machining) of the bushing,
2. after vacuum drying
3. after oil impregnation.

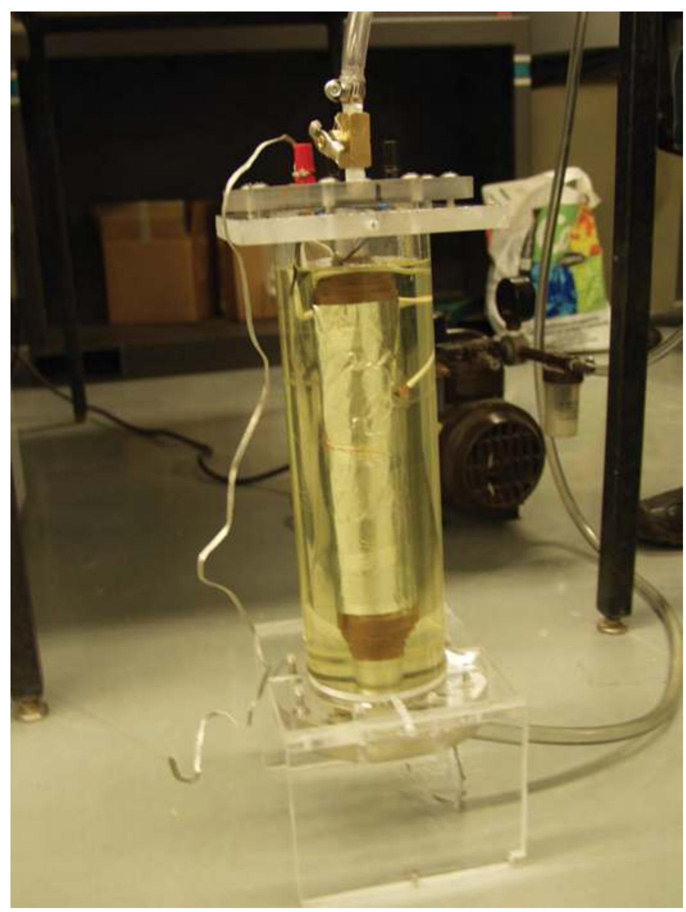

Figure 4. Overview of the OIP condenser bushing.

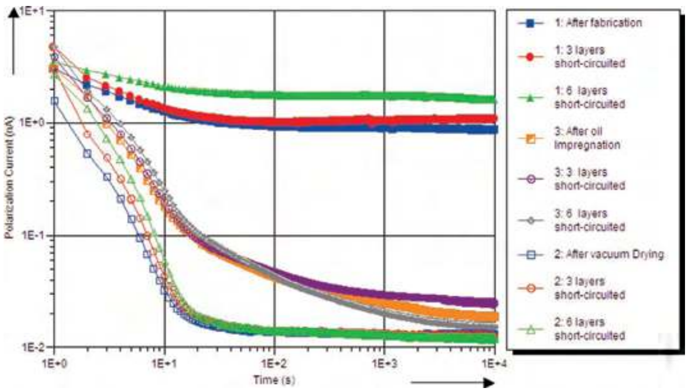

Figure 5. Measured polarization currents for normal and short-circuited bushing layers following the three processing steps.

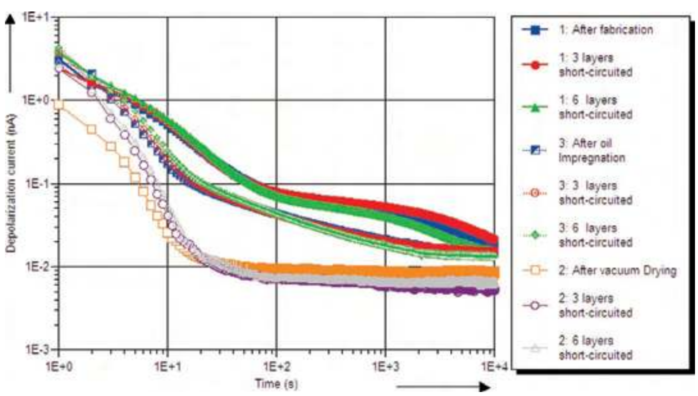

Figure 6. Measured depolarization currents for normal and short-circuited bushing layers following the three processing steps.

The effect of short-circuiting introduced between some of the grading capacitance layers following each step was also investigated. Thus "1:3 layers short-circuited" means that measurements were performed immediately after step 1, with 3 grading capacitance layers short-circuited.

The moisture content of the cellulose paper, as delivered, was measured as 6% (= the weight of the moisture divided by the weight of the dry, oil-free paper) using a Karl Fisher coulometer. Pumping and heating (<1 mbar, 105 °C for 48 hr) reduced the water content of the samples to 0.1%. Oil impregnation was then carried out using commercial grade mineral oil which had been purified and vacuum degassed in a two-stage drying unit [23] in order to ensure very low gas (less than 0.5 %) and water (< 5 ppm) content.

Table I. **Oil and paper conductivity for three different conditions.**

	σ_{oil} (pS/m)	σ_{paper} (pS/m)
1. After fabrication	—	1.02
2. After vacuum drying	—	0.0052
3. After impregnation	0.0942	0.005

Results and Discussion

A. PDC

PDC measurements can provide reliable information about the condition of oil-paper insulation. In this section, the feasibility of using such measurements to monitor the bushing fabrication process is investigated. The user-friendly Labview interface enables the operator to choose the voltage and time for charging and discharging. Polarization and depolarization currents are stored for analysis.

PDC measured at the end of each of the three processing steps are plotted in Figures 5 and 6. It can be seen that the PDC currents measured after drying and impregnation are lower than those measured just after machining.

During the first 20 s of measurement the PDC currents increase with the number of short-circuited layers. This phenomenon is obviously related to the bushing capacitance. It is clear that further research is needed to understand the specific influence of short-circuited layers on the PDC.

Conductivity values for oil and paper, calculated from the measured PDC using (5), are presented in Table I. The conductivity of paper decreases after the vacuum drying, indicating the removal of moisture from the insulation.

B. Frequency Domain Spectroscopy

The complex permittivity can be used to characterize the insulation. It is a dimensionless quantity consisting of a real part ε' representing the energy stored in the electric field within the sample, and an imaginary part ε'' representing the energy losses. The frequency scans of ε'' (Figure 7) demonstrate the possibility of separating the three fabrication steps.

Vacuum drying clearly affects ε''. Following oil impregnation, ε'' increases, but remains below the values immediately after fabrication. This increase could be due to increased losses at low frequency.

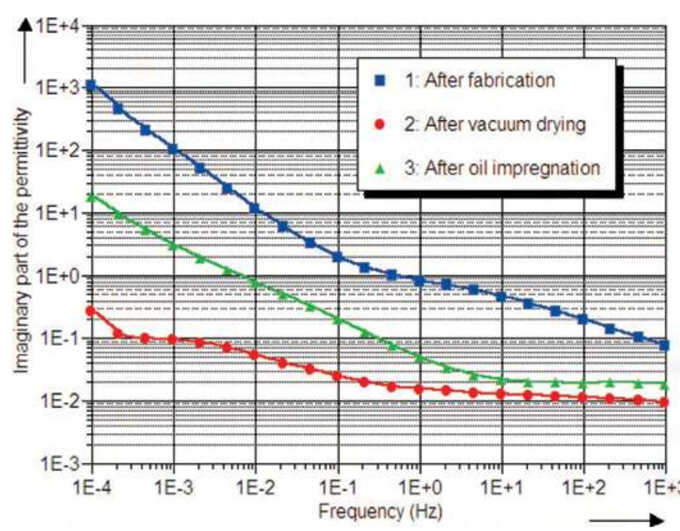

Figure 7. Frequency scan of the imaginary part of the permittivity following the three processing steps.

Figure 8 shows that short-circuit condition may be detected using ε´ measurements in the frequency range below 1 mHz. The ac conductivity of the bushings, shown in Figure 9, is remarkably reduced when moisture is removed from the insulating paper.

The dielectric dissipation factor (DDF), also known as the loss factor (tan δ), is defined in (7). The power factor (PF), defined as sin δ, is particularly useful in monitoring the bushing condition [1], [2]. Figure 10 shows the results of PF measurements performed after each of the manufacturing steps. The behavior is similar to that of ε´´ (Figure 7). After drying and impregnation, the PF drops to values (at power frequency) lower than those obtained just after machining. After impregnation, the PF at higher frequencies is almost the same as after drying, but at lower frequencies it is larger.

The DDF and capacitance (C) values are shown in Figures 11 and 12 respectively. They increase with increasing moisture content, particularly at very low frequencies. This is in agreement with the work of Supatra [12].

The existence of short-circuited sections in the bushing causes an increase in capacitance. To evaluate the feasibility of detecting a short-circuit in the bushing taps, two conditions, namely with and without short-circuiting of some of the layers of two accessible parts of the foils, are considered. The results presented in Figure 12 show that capacitance measurements on bushing taps can be used to detect short-circuit in the layered capacitance. They also highlight the possibility of using FDS techniques to monitor in-service bushings.

The Capacitance Ratio (CR), which is important for machine insulation diagnosis [12], is the ratio between C at 0.1 mHz and C at 60 Hz. Lower ratios indicate better insulation quality [12]. Figure 13 shows CR computed from the values of Figure 12. It can be seen that when the moisture content is greater (just after fabrication), the CR is higher. It decreases after the vacuum drying process and increases slightly after impregnation.

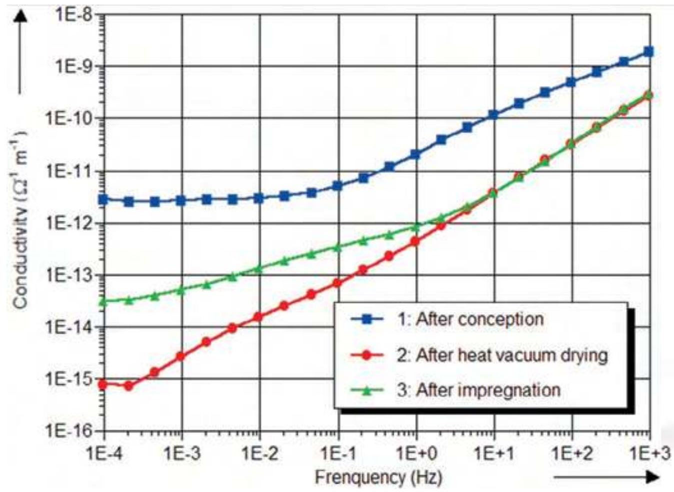

Figure 9. Frequency scan of the conductivity following the three processing steps.

CR seems to be effective in detecting short-circuit just after fabrication. However, after the subsequent steps it is less sensitive to short-circuit. The capacitance itself (Figure 12) is more sensitive.

By measuring the impedance of the bushing model over a wide range of frequencies, the frequency response of the system can be plotted. Figure 14 and 15 show respectively the argument and absolute value of the impedance, Z, of the bushing layers following each processing step. The insulation condition significantly influences both these quantities at frequencies below 0.1 Hz.

Conclusions

In this article we have described the possible use of dielectric spectroscopy to monitor three steps in the OIP condenser

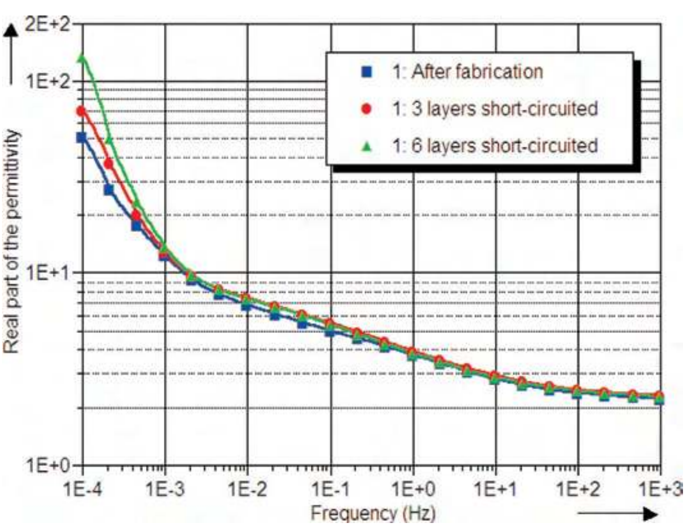

Figure 8. Frequency scan of the real part of the permittivity for normal and short-circuited bushing layers.

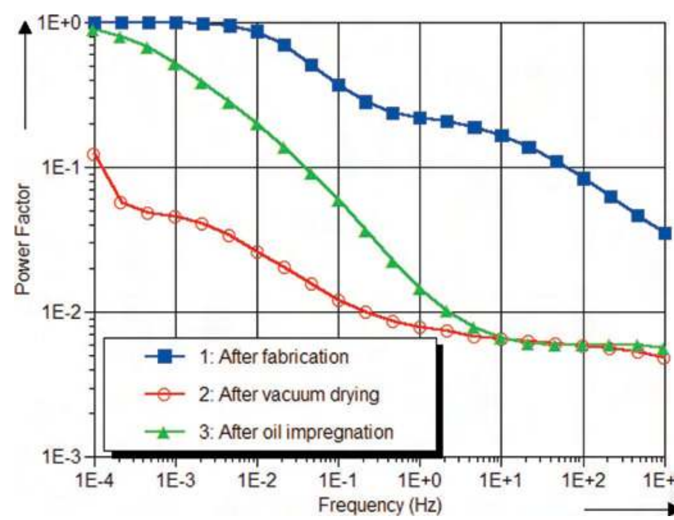

Figure 10. Frequency scan of the power factor following the three processing steps. The moisture content of the oil used for impregnation was 15 ppm.

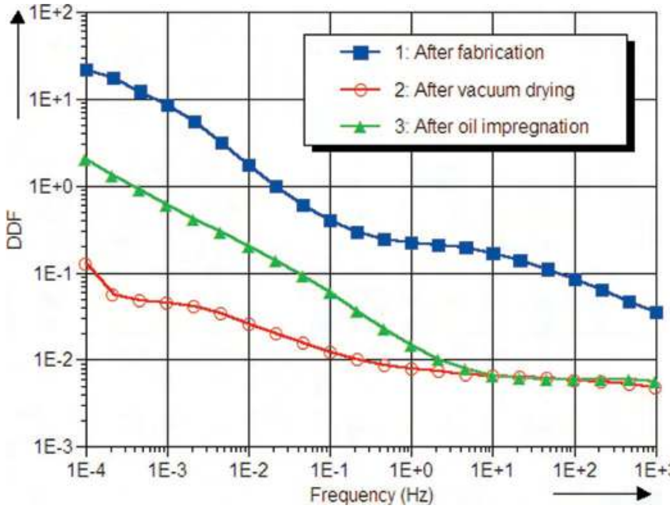

Figure 11. Measured dielectric dissipation factor (DDF) as a function of frequency following the three processing steps.

bushing manufacturing process. These measurements provide a more comprehensive evaluation of the insulation condition than measurements performed only at power frequency.

We have shown that DDF, C, and permittivity measurements on bushing taps at low frequency will detect short-circuiting, as will PDC measurements within 20 s of application or removal of the poling voltage.

FDS and PDC measurements give a good indication of the insulation condition. These methods are sensitive to moisture content, voids, and short-circuit. The effects of moisture content and short-circuit can also be separated.

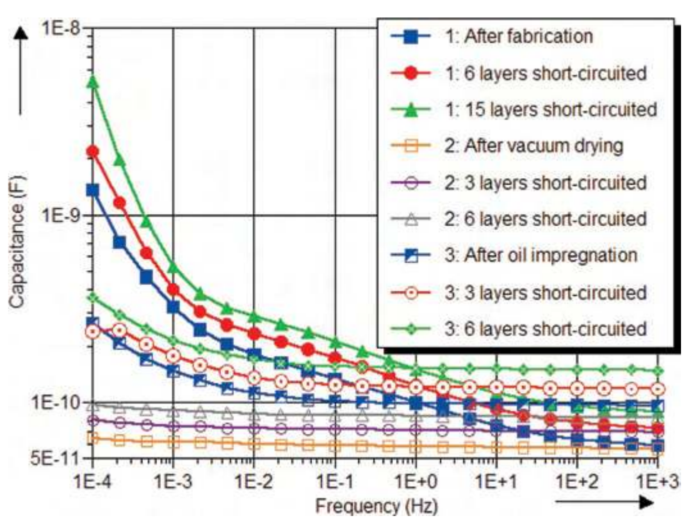

Figure 12. Frequency scans of the capacitance for normal and short-circuited bushing layers following the three processing steps.

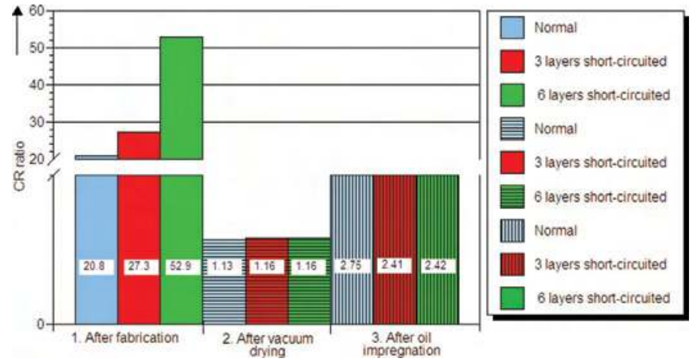

Figure 13. CR computed from values given in Figure 10.

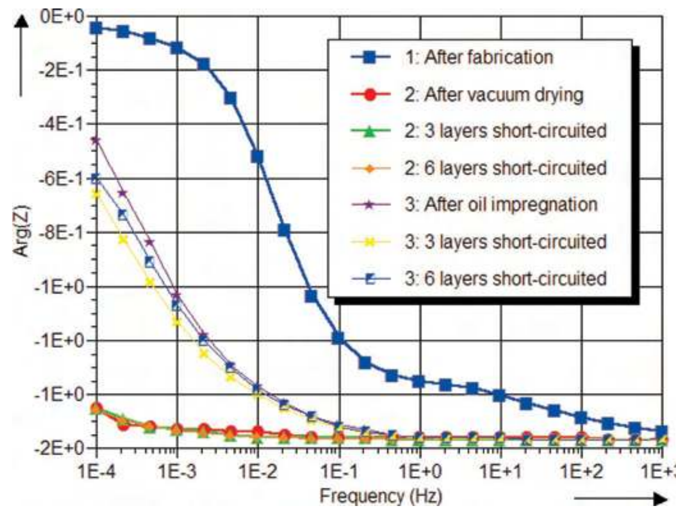

Figure 14. Frequency scans of the argument of the impedance, Z, for normal and short-circuited bushing layers following the three processing steps.

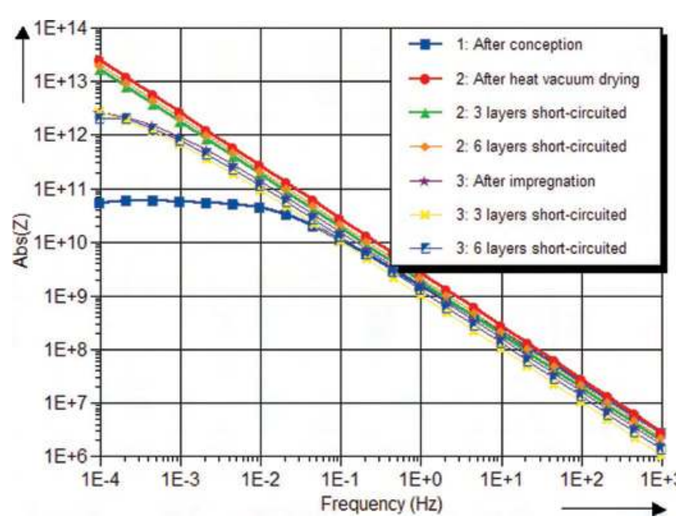

Figure 15. Frequency scan of the absolute value of the impedance, Z, for normal and short-circuited bushing layers following the three processing steps

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