Time Optimization of Dielectric Response Measurements

A.A. Shayegani, H. Borsi, E. Gockenbach
Division of High Voltage Engineering, Schering-Institut
University of Hannover

H. Mohseni
High Voltage Laboratory
University of Tehran

Abstract

Determination of moisture in paper and pressboard of HV apparatus insulation is a feature of dielectric response method. Dielectric spectroscopy in frequency (FDS) and in time (PDC and RVM) domain are forms of dielectric response measurements. However one disadvantage of this method is the time consuming procedure. It takes several hours and shorter procedures give information only with lower accuracy. In this paper is shown that the transformation of data from time domain gives frequency domain data with sufficient accuracy in the low frequency range. Hamon has shown that with the data of polarization current at a time \( t \) the dielectric loss at a frequency \( f = 0.1 \text{Hz} \) can be calculated. This means data of 1000s represent data of 0.1mHz. The proposed measurements of dielectric response are performed from 1kHz to 10mHz with FDS method and from 1s to 1000s with PDC method. This saves time of dielectric measurements and gives reliable data for the determination of the moisture content of solid insulation too.

1. Introduction

Nowadays measurement of dielectric response becomes a powerful diagnostic tool for high voltage apparatus [1,2,3]. Frequency Domain Spectroscopy (FDS), Polarization and Depolarization Current (PDC) measurement and Recovery Voltage Measurement (RVM) are different approaches for measurement of dielectric response function. FDS gives information of dielectric response from 1kHz to 0.1 mHz in form of resonance. PDC is most used for a time range from 1s to more than 10000s. RVM gives several recovery voltages of specimen, each obtained after a sequence of charging and discharging time.

Based on dielectric theory, it is not essential to use the sine wave excitation of the frequency domain measurements. A non-periodic excitation can be used in time domain measurements where the resulting current is measured as a function of time to obtain frequency domain data. This experimental simplicity is offset by the computational difficulty of driving the \( \epsilon'(\omega) \) and \( \epsilon''(\omega) \) curves from \( f(t) \) [5].

It is especially common to transform PDC data to frequency domain since it is in many cases easier to measure and more accepted to interpret data in frequency domain than in time domain [6]. Calculation of frequency domain data from recovery voltage data is difficult due to the re-polarization that occurs in a measurement [6].

2. Dielectric Response Function

The electrical polarization \( P(t) \) in a dielectric material can be divided into two parts, one part representing “rapid” polarization and one part representing “slow” polarization processes [3,6].

\[
P(t) = \varepsilon_0 (\varepsilon_r - 1) E(t) + \Delta P(t) = \varepsilon_0 (\varepsilon_r - 1) E(t) + \varepsilon_0 \int_0^t f(\tau) E(t - \tau) d\tau \]  

(1)

The “rapid” part follows the applied electric field whereas “slow” part is built up from a convolution integral between the applied electric field and a function called the dielectric response function \( f(t) \). With assumption of a step voltage excitation at time \( t=0 \) and for \( \tau>0 \), Eq. 2 describes the polarization current:

\[
\begin{align*}
\dot{i}_{\text{pol}}(t) &= C_0 U_c \left( \frac{\sigma_0}{\varepsilon_0} + f(t) \right) \\
&= -C_0 U_c \left( \frac{\sigma_0}{\varepsilon_0} + f(t) \right)
\end{align*}
\]  

(2)

\( C_0 \) is the geometric or vacuum capacitance of the test object and \( U_c \) the charging voltage. For the depolarization current an application of \(-U_c\) step voltage after charging time \( T_c \) can be assumed. Eq. 3 shows the relation between \( f(t) \) and the depolarization current:

\[
\begin{align*}
i_{\text{dpol}}(t) &= -C_0 U_c \left( f(t) - f(t+T_c) \right) \\
&= -i_{\text{pol}}(t) - C_0 U_c \int_0^t f(t) e^{-\omega t} dt
\end{align*}
\]  

(3)

As \( f(t) \) is a monotonically decaying function, the second term in (3) can be neglected for large values of \( T_c \) and the depolarization current becomes proportional to the dielectric response function for \( t<T_c \).

\[
f(t) \approx - \frac{i_{\text{dpol}}(t)}{C_0 U_c} \]  

(4)

If the DC conductivity part of the polarization current is very small, Eq. (2) can be written similar to (4). The complex dielectric susceptibility \( \chi'(\omega) \) is related to \( f(t) \) by the Fourier transform shown in Eqn. (5) [7].

\[
\chi'(\omega) - j\chi''(\omega) = \frac{1}{\pi} \int_0^\infty f(t) e^{-\omega t} dt
\]  

(5)

If \( f(t) \) is an analytic function, which has a Fourier transform, the transform can then analytically be calculated [6]. However a numerical integration can perform the transformation [8,9] too.
ε′(ω) and ε″(ω), real and imaginary part of the complex relative permittivity are measurable values and related to the dielectric response function according Eqn. (6).

\[
\varepsilon'(\omega) = \varepsilon_0 + \chi'(\omega)
\]

\[
\varepsilon''(\omega) = \sigma_0 \omega \varepsilon_0 + \chi''(\omega)
\]  

(6)

Both function χ′(ω) and χ″(ω) can thus be derived from the same function f(t) and, therefore, are not independent. Eqn. (7) shows the relation between χ′(ω) and χ″(ω) [10,11].

\[
\chi'(\omega) = \frac{\mu}{\mu^2 - \omega^2} \int_0^\infty \exp(i \mu \tau) \frac{1}{\tau} \chi''(\omega) \, d\omega
\]

(7)

\[
\chi''(\omega) = \frac{\omega}{\omega^2 - \mu^2} \int_0^\infty \exp(i \mu \tau) \mu \chi'(\omega) \, d\omega
\]

The polarization current is equal to the depolarization current plus conduction current. The Fourier transform of a step function is imaginary with a magnitude of 1/ω. Therefore instead of the depolarization current, the polarization current can be used for the transformation of time domain data into frequency domain data. This case the measurement of the conductivity is not necessary and the imaginary part of Fourier transform gives ε″(ω) directly.

In [12,13] the polarization current has been used to obtain frequency domain data. This polarization current may be disturbed with noise of power supply especially in very low current values. Battery source for charging voltage can be used to noise reduction of polarization current measurement. Thus for calculation of transformation, depolarization current (polarization current), charging voltage and capacitance (permittivity) at the upper limit of the transformation frequency is needed. The geometric capacitance is needed for the calculation of the permittivity and the transformation can be calculated without it.

3. Hamon Approximation

An alternative for fast calculation of the frequency domain data from the time domain is the Hamon approximation if the dielectric response of insulation can be approximated with Airf function (a line in log-log scale “Curie – von Schweidler”) [14]. The analytic transform of the function is equal to Eqn. (8) or (9).

\[
\chi''(\omega) = \frac{A}{\omega^{1-n}} \Gamma(1-n) \cos\left(\frac{n \pi}{2}\right)
\]

(8)

or

\[
\chi''(\omega) = \frac{A}{\omega} \left(\frac{0.1}{f}\right)^n \left[0.2 \pi \Gamma(1-n) \cos\left(\frac{n \pi}{2}\right)\right]
\]

(9)

Figure 1 shows the value of the expression in brackets. Hamon approximated the expression with 1 in the range 0.3<n<1.2. From Figure 1 is clear that n can varies from 0 to 1.2. According to the Hamon approximation only the imaginary part of the complex susceptibility (χ″) will be considered and it can be written as:

\[
\chi''(\omega) \approx \frac{-i \sigma_0}{2 \pi f C_0 U_c} \left(0.1 / f\right)
\]

(10)

Hamon has proved, that this approximation can be used for the dielectric function with two slopes (Universal function) too. Eqn. (11) shows the universal function whose frequency domain response can be calculated analytically.

\[
f(t) = A \left[ e^{-t/\tau} \left(\frac{t}{\tau}\right)^{m} + \left(1 - e^{-t/\tau} \right) \left(\frac{t}{\tau}\right)^{-n} \right]
\]

(11)

The frequency response of (11) is (12).

\[
\chi'(\omega) = \frac{A}{\omega} \left(\frac{0.1}{f}\right)^n \left[0.2 \pi \Gamma(1-n) \cos\left(\frac{n \pi}{2}\right)\right]
\]

(12)

Therefore the result of Hamon approximation and analytical calculated result can be compared. The relative error of approximation is defined as mean of relative errors by Eqn. (13).

\[
E = \frac{1}{n} \sum_{n} \left| \frac{\chi''(\text{Analytic})}{\chi''(\text{Hamon})} - 1 \right|
\]

(13)

Figure 2 shows the error as function of n and m. The time is considered from 1s to 10000s with steps of 1s which is equal to 0.1 Hz to 0.01mHz. The time constant of the universal dielectric function (τ) was assumed 100s.

To obtain the maximum deviation of the Hamon approximation from the analytic solution, Figure 3 shows the maximum relative error. If n and m are close together, the dielectric function is close to “Curie – von Schweidler” model, the error of Hamon approximation is small. The maximum error occurs at frequency that corresponds to the time constant of universal dielectric function (τ).
The Hamon approximation is important for two reasons. It makes a relation between dielectric response in time domain at $t$ and $f=0.1/t$ in frequency domain. Another advantage of the method is the calculation of $\varepsilon''(\omega)$ by polarization current according Equ. (14).

$$\varepsilon''(\omega) \approx \frac{i_{pol}(0.1/f)}{2\pi C_0 U_c}$$

But Hamon approximation is only applicable for the imaginary part of susceptibility or permittivity. The real part of susceptibility or permittivity must be calculated from Equ. (7) or other methods. It is furthermore necessary to calculate the geometry capacitance ($C_0$) of the insulation system to obtain the permittivity.

If polarization current gives small value for $\varepsilon''(\omega)$, it indicates dry and health condition for insulation and it saves time of diagnosis. Measurement of polarization currents in order of pA may be disturbed by the power supply. In this case a battery power supply may be helpful for a noise free measurement of $i_{pol}$.

4. Experiment and Results

Figure 4 shows PDC of a 200 kVA 10kV distribution transformer, measured at 200V. In a linear dielectric system the polarization current is equal with the depolarization current plus conduction current. Therefore the polarization current can be used instead of depolarization current for the transformation from time domain into frequency domain and reduces the test time. The calculated depolarization current is shown in Figure 4. It shows that the error of approximation is small especially for times where the polarization current has not reached the time independent conduction current.

Using the polarization current has the advantage that the monitoring and diagnosis of power apparatus with the dielectric response method is shorter in time. Figure 5 shows the transformation results with Hamon approximation using the polarization current and depolarization current. A good accuracy of transformation is observed in this case. The error of calculated capacitance at low frequency in case of calculated depolarization current may be due to error of the calculated current at long time. If the frequency domain spectroscopy from 10 mHz to 1kHz is used (almost 15 minutes), and lower frequency range (from 100mHz to 0.1mHz) is calculated from PDC (almost 20 min, only polarization current), it can save measurement time up to 10h.

The approximated dielectric spectroscopy can be useful as monitoring tool for asset manager to obtain information as short as possible in order to rank e.g. the power transformers. The approximation constraint ($n<1.2$) can be checked to estimate the error.
5. Conclusion

Transformation of dielectric time domain measurement to frequency domain is possible with good accuracy, however the accuracy is limited by the different behaviors in conduction and polarization at DC and AC electric field as a result of the non-linearity of dielectric medium, which is negligible in low electric field. Results of Hamon approximation show the ability of this method for transformation of PDC data of impregnated pressboard to frequency domain, although the depolarization current of impregnated pressboard has more than 1 slope in the log-log diagram. If the slope of curve is not within the limitation of approximation, the accuracy of transformation will be reduced.

Dielectric spectroscopy can be done in the time domain in a shorter time than frequency spectroscopy. The results are similar and the error in low electric field is small. Frequency spectroscopy for very low frequency (below than 0.1 mHz) is not practically, however time domain spectroscopy can be used successfully in this time range. Frequency or time limits for an effective diagnosis with dielectric spectroscopy are not yet clear defined.

FDS instruments, which allow low frequency measurements with PDC method and the transformation of data, or PDC instruments, which contain high frequency measuring range, can reduce the measuring time duration, give enough information about insulation system and are highly desirable.

6. Acknowledgment

We wish to thank Deutsche Forschungsgemeinschaft for their support and GE Energy Management Services GmbH and Programma Electronic AB for letting us to use the IDA 200 Insulation Diagnostic System for the frequency domain measurements.

7. References