Calculation and Measurement of Dielectric Response Function in Insulation Systems of High Voltage Rotating Machines

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Abstract: In this work the possibility of the dielectric response measurement for the evaluation of the actual status of insulation system of high voltage rotating machines are investigated. As test object, model stator bars were used, which are close to real stator bars of high voltage rotating machines. An accelerated ageing procedure was applied to the model bars and the dielectric response was measured in time domain. The dielectric response function was calculated from depolarization current measuring results and the change of this function was evaluated.

INTRODUCTION

The insulation system of high voltage rotating machine is subjected to combined thermal, mechanical, electrical and environmental stresses during the operation which may alter the dielectric properties. The condition of the electrical insulation systems of high voltage equipment will strongly influence the economical and technical lifetime as well as the quality of the generated or distributed electrical power.

The dielectric response analysis method, which is based on wide range measurements in time and frequency domains, is a useful tool to evaluate the condition of the electrical insulation systems. The used methods of quantifying the dielectric response in time domain are polarization-depolarization current and recovery voltage measurement and in frequency domain the loss factor $\tan \delta$ and the complex capacitance measurement.

DIELECTRIC RESPONSE IN TIME DOMAIN

Assuming a linear, homogenous and isotropic material. The material will than follow Ampere’s law [1]:

$$\nabla \times B = \sigma_0 E + \varepsilon_0 \frac{\partial D}{\partial t}$$

(1)

In vacuum the displacement $D(t)$ is proportional to the applied electric field $E(t)$. In presence of an isotropic dielectric material, the displacement $D(t)$ is increased by the polarization $P(t)$ of material to[2]:

$$D(t) = \varepsilon_0 E(t) + P(t)$$

(2)

If a given electric field $E(t)$ is applied over a dielectric material both the “free” and “bond” charges will lead to sources inside the material in form of charge and current densities which will then lead to a magnetic field $B$ according to Maxwell’s equations. The current density in the dielectric material will be given by Ampere’s Law as:

$$\nabla \times H = \sigma_0 E + \varepsilon_0 \frac{\partial E}{\partial t} + \frac{\partial P}{\partial t}$$

(3)

The first part, the induced current, is the contribution from the materials volume conductivity $\sigma_0$, the second part is the vacuum displacement current and the third part is the polarization current.

The electrical polarization $P$ can be divided into two parts, one part representing “rapid” polarization and one part representing “slow” polarization processes.

$$P(t) = \varepsilon_0 \chi E(t) + \Delta P(t)$$

$$= \varepsilon_0 \chi E(t) + \varepsilon_0 \int_0^t f(\tau)E(t-\tau)d\tau$$

(4)

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 $f(t)$. The dielectric response function represents the “memory” effect in a dielectric material [3] and has following characteristics:

$$f(t) \equiv 0 \quad \forall t > 0, \quad \lim_{t \to +\infty} f(t) = 0$$

The total current density $J(t)$ through a dielectric material in an electric field $E(t)$ can then be expressed as:

$$J(t) = \sigma_0 E(t) + \varepsilon_0 \frac{\partial}{\partial t} \left\{ \varepsilon_0 E(t) + \int_0^t f(\tau)E(t-\tau)d\tau \right\}$$

(5)

Equ. (5) shows that DC conductivity $\sigma_0$, the high frequency component of relative permittivity $\varepsilon$ and the dielectric response function $f(t)$ will characterize the behaviour of the dielectric material. This gives in the time domain the possibility to apply an electric field, measure the current density and then try to estimate parameters that characterize the material in terms of dielectric response behaviour as function of the change within the insulating material of the high voltage equipment [4].
CALCULATION OF DIELECTRIC RESPONSE FUNCTION

The slow polarization processes in materials cannot be measured directly, but measurements of polarization and depolarization current in time domain allow the investigation of the slow polarization processes in a dielectric material. Assuming a homogeneous material the field strength $E(t)$ can be considered as generated by an external voltage $u(t)$. Then, the current $i(t)$ can be rewritten from equ. (5) as:

$$i(t) = C_0 \left[ \frac{\sigma_0}{\varepsilon_0} u(t) - \varepsilon \frac{du(t)}{dt} + \frac{d}{dt} \int_0^t f(t-\tau)u(\tau)d\tau \right]$$

(6)

with $C_0$ as the geometric or vacuum capacitance of test object investigated.

Assuming that the test object is totally discharged and that a step-voltage $U_c$ is applied at a time $t=0$ (Fig. 1), the polarization current $i_{pol}(t)$ can be expressed by the following equation:

$$i_{pol}(t) = U_c C_0 \left[ \frac{\sigma_0}{\varepsilon_0} + f(t) \right]$$

(7)

Figure 1: Principle of polarization and depolarization current measurement

The polarization current due to the step-voltage $U_c$ is built up by two parts. One part is related to the conductivity of the test object and one part is related to the activation of the different polarization processes within the test object. When the step-voltage $U_c$ is removed after $T_c$ and test object is grounded immediately, the depolarization current flows. This current represent the relaxation of polarization processes. According to superposition principle, the depolarization current $i_{depol}(t)$ after the short-circuit is then given by:

$$i_{depol}(t) = -U_c C_0 \left[ f(t) - f(t + T_c) \right]$$

(8)

As $f(t)$ is a monotonically decaying function, the second term in equ. (8) can be neglected for large values of $T_c$ and the depolarization current becomes proportional to the dielectric response function [6]:

$$f(t) \approx \frac{i_{depol}}{C_0 U_0}$$

(9)

It is also possible from equ. (7) and (8) to estimate the DC conductivity $\sigma_0$:

$$\sigma_0 \approx \frac{\varepsilon_0}{C_0 U_0} \left[ i_{pol}(t) + i_{depol}(t) \right]$$

(10)

Each dielectric material has its own and unique dielectric response function [5]. Typical response functions representing slow polarization processes found in electrical insulation materials are shown in Fig. 2.

Figure 2: Different type of dielectric response functions $f(t)$ in time domain.

For polar liquids response functions like the “Debye” function are commonly found and described with the following equation:

$$f(t) = \frac{\Delta \varepsilon}{\tau_D} e^{-t/\tau_D}$$

(11)

The dielectric response function of many solid material follow over wide range of times the so called “Curie-von Schweidler” model.

$$f(t) = At^{-n}$$

(12)

Another often seen behavior called “General response”, represents a transition at $t=\tau$ between different processes in a dielectric material [4].

$$f(t) = \frac{A}{(t/\tau)^m + (t/\tau)^n} \quad m > 1 > n > 0$$

(13)

EXPERIMENTAL DETAILS

Test Object

The model stator bars used for this investigation belong to an insulation system with a rated voltage of 13.8 kV. The bar insulation is based on the epoxy VPI technology, according to manufacturer’s standard. The bars are finished with 900 mm length semi conducting anti-corona varnish and 70 mm stress-grading tape to prevent unwanted discharges at these points. The thermal class of insulation is F (155°C). A stator slot model was designed to simulate the actual stator slot with cooling ducts. The model bar is fixed during the ageing and measurement procedures in the slot model which simulates also the mechanical forces.
**Ageing Procedure**

The accelerated cycling thermo-mechanical ageing procedure includes numerous current heating and active cooling cycles. During each aging cycle the test object is heated by a current of 1500A in 30 minutes from ambient temperature to 150 °C and cooled down afterwards by fan in 30 minutes to ambient temperature. This ageing procedure represents processes during the machine life due to on-off-operations or load changes. With these load changes the insulation is thermomechanically stressed and ages because of the different thermal expansion coefficients of the materials involved and due to local and temporal gradients.

**Measurement Set-up**

An automated experimental set-up was developed and implemented to measure continuously the polarization and depolarization current as shown in Fig. 3. A DC-source was used for charging the test object and a developed Pico-Amperemeter was used to measure polarization and depolarization current. The whole measurement set-up was controlled automatically by a personal computer.

![Image](image.png)

**Figure 3:** Polarization and depolarization current measurement system

For low current measurements with high accuracy a guard ring is necessary and therefore a guard ring was established at both ends of the measuring electrode (semi conducting tape). Due to the rectangular geometry of the model stator bar, the preparation of a high quality guard ring with good electrical contact was difficult. The model stator bar was then put inside a grounded metal box to reduce the influence from external noise.

**Test Results**

In Fig. 4 the polarization and depolarization currents of a new stator bar measured at $U_c=2kV$ are plotted in a log-log scale. The sign of the depolarization current values have been changed so that both polarization and depolarization current values are positive. The stator bar has a geometric capacitance $C_0=420$ pF and a total capacitance $C = 1.46$ nF. The measurement of the currents was started with a certain time delay after the step voltage application or after the short circuit. In most measurements the delay time was chosen to $1$ s.

![Image](image.png)

**Figure 4:** Polarization and depolarization current in new stator bar

The estimated dielectric response function $f(t)$ from equ. (9) are plotted in Fig. 5.

![Image](image.png)

**Figure 5:** Dielectric response function of a new stator bar

To compare the result with other insulation system of different geometry and charging voltage this dielectric response function is very useful. Fig. 5 shows that the dielectric response function of the insulation system of high voltage rotating machines follows the “Curie- von Schweidler” model with the following parameters of equ. (12):

$$f(t) = 0.0198 t^{-0.80}$$

Fig. 6 shows the dielectric response function $f(t)$ of the same stator bar after 5000 cycle (5000 hours) thermo-mechanical ageing. The dielectric response function $f(t)$ changed in the constant and the time exponent according to equ. (15):

$$f(t) = 0.0126 t^{-0.88}$$

The slope of the function and the absolute values has changed and this information can be used for the evaluation of the material behaviour as consequence of the ageing or the relevant service stress, but it seems to be necessary to have some reference measurements. The results in Fig. 4 to Fig. 6 are measurements on only one new and aged stator bar. Further measurements will confirm the validity of the approximation of equ. 14 and 15, concerning the uncertainty and the statistical spread.
To compare the dielectric response measurements with measurements of other methods, the change of the dielectric loss factor $\tan \delta$ due to the ageing is shown in Fig. 7 at different test voltage levels.

The change in the $\tan \delta$ values indicates also clearly the ageing of the material, but it is also necessary to take into account the influence of the humidity which may be reduced by the number of thermal aging cycles. Therefore the change of the $\tan \delta$ and the tendency of the change can be used as a sensitive parameter for the evaluation of the ageing of the insulation system. Furthermore the change in the loss factor as function of the applied test voltage gives some important information. In Fig. 8 the incremental change of the $\tan \delta$ at different voltages related to the $\tan \delta$ at 0.2 $U_N$ is shown. The incremental change already starts to change after some ageing cycles and both differences are similar in their sensitivity. Again should be mentioned, that humidity plays an important role and should be taken into account in the interpretation of the results.

CONCLUSION

The measurements confirm the sensitivity of the dielectric response on the changes in the insulation system of high voltage rotating machines. The dielectric response function seems to be a good tool for the evaluation of the actual status of the insulation system of high voltage rotating machines. The dielectric response function can be described by some simple equations based on the polarization processes in the insulating material. However there a number of parameters which influences the dielectric behaviour of the insulating material and which can not be separately evaluated. Therefore the measurements of the dielectric response and the loss factor $\tan \delta$ give an information concerning the change in the material. With reference measurements of new and aged material and for typical design of high voltage machine insulation it will be possible in future to evaluate the actual status of the high voltage insulation by measurements of the dielectric response function.

REFERENCES


