# DIELECTRIC SPECTROSCOPY FOR HIGH VOLTAGE MACHINES

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**ABSTRACT**

About 35%-40% of failures of high-voltage rotating machines occur in the stator insulation. Stator insulation is a critical part of the high-voltage rotating machines that are used as generators to produce practically all electrical power, and as large motors to consume some of this power in driving industrial processes. The high capital-costs of high-voltage machines themselves, and the exorbitant costs arising from a machine's forced outage,makes it indispensable to use best available 'diagnostic' measurements. Diagnostic measurements are a useful way to predict and avoid failure for those types that occur over timescales long enough for warning to be given.

Many types of diagnostic measurement are in widespread use on stator insulation, yet the complexity of the insulation and of the aging and failure processes make each method just a further indication of insulation condition. So to have good prediction of how long the insulation will tolerate given stresses without failure, proper diagnostic methods must be used to have a better insight into the healthiness of the stator's insulation.

It is common industrial practice to use electrical measurement like tan-delta, polarization index and some form of current-voltage measurement as part of the condition assessment of stator insulation at maintenance times. Extension of these methods by dielectric spectroscopy(DS) can prove instrumental in determining the condition of the stator's insulation more accurately and correctly pin point the reason of its deterioration if any.

Dielectric Spectroscopy (DS) is a name of a group of methods for measuring time or frequency dependent properties of the polarization of charges in materials. These properties are the material's Dielectric Response (DR). DS considers offline electrical measurements on the main insulation of stator windings. Constant voltage with variable frequency is applied between the winding and the stator-core. The varied frequency, down to the millihertz range, provides additional information about the insulation which remains obscure in tan delta or other conventional diagnostic methods normally practiced. Also, DS requires less power from the test voltage than with conventional power-frequency measurements.

## MECHANISMS AND DESCRIPTIONS OF DIELECTRIC RESPONSE

Measurements of dielectric response usually consider just a narrow band of the whole range of times or frequencies over which polarization mechanisms operate. The mechanisms with significant dynamics in this band are the interesting dielectric response, and other mechanisms are treated as instantaneous if much faster or as nonexistent if much slower. If the frequency of the applied electric field is varied, a frequency-dependent response can be observed in the measured permittivity values. This characteristic response (or dielectric relaxation) is known as the beta dispersion, and occurs mainly between 1 milliHz and 1000Hz for high voltage stator winding insulation. Beta dispersions may consist of a single relaxation or a sum of multiple relaxation

Electric displacement D occurs in response to an electric field E, related by the free-space permittivity $\varepsilon 0$ as $D = \varepsilon 0E$. The significance of D to measurements is its relation to charge-density $\rho = \nabla .D$; its surface integral determines the charge on an electrode whose potential is held constant by an external circuit, and the time rate of change in this charge is the measured current in the circuit. Polarization in a material increases *D* by the total volume-density of dipole moment $\boldsymbol{P}_t$ so that $\boldsymbol{D} = \boldsymbol{\varepsilon}_0\boldsymbol{E} + \boldsymbol{P}_t$.

In practical insulation materials exposed to service-levels of electric field the steady-state polarization is close to proportional to the electric field, and therefore gives the same effect as an increased ε0. The total electric displacement can then be treated as a part due to free-space and a part due to all polarization, or as a single effective permittivity ε with no explicit polarization term. An intermediate form is relevant to cases where some polarization takes long enough that it is not instantaneous compared to the changes in electric field applied and therefore cannot be included in a constant ε.The free-space permittivity together with the components of the polarization that are practically instantaneous are the prompt response, treated as a single value of high-frequency permittivity ε∞, and the remaining, slower polarization P is kept separate. These three ways of distributing the polarization between an explicit and implicit part are

$$D = \varepsilon 0E + Pt$$

$$= \varepsilon E$$

$$= \varepsilon\infty\, E + P \quad \text{........(1)}$$

The fastest polarization mechanisms are the electronic or atomic, displacements between electrons and nuclei or between ions in a lattice, happening in times short enough to correspond to optical or infra-red frequencies, and without strong temperature-dependence. Slower mechanisms that give dynamic dielectric response at the frequencies met in electric circuits are dipolar, carrier- dominated and interfacial polarizations. Interfacial polarization is a consequence of in homogeneity rather than a microscopic feature of a simple material, with charge conduction through the volume being blocked at barriers and building up to the equilibrium where its electrostatic field prevents further movement

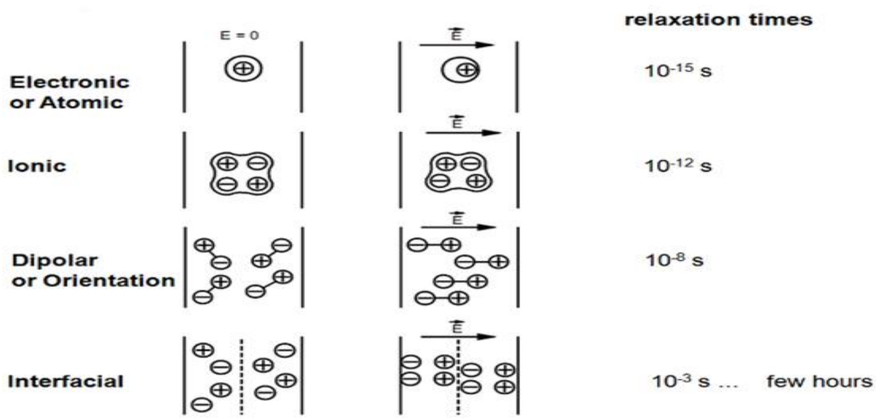
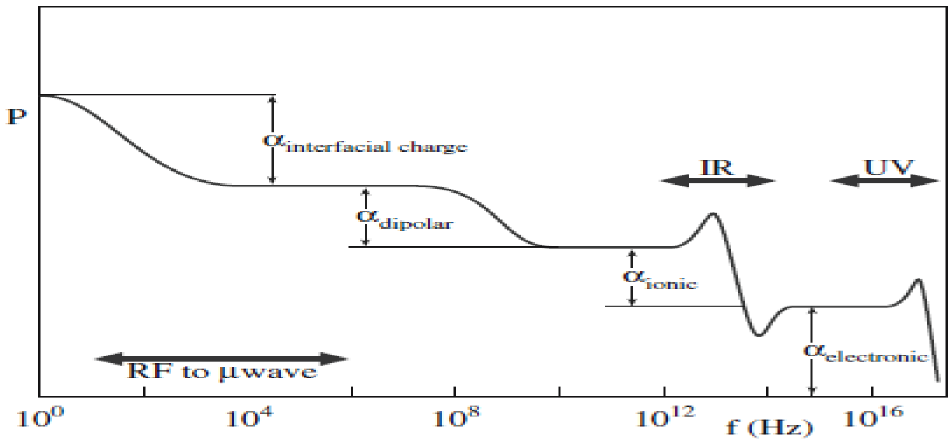



Fig-1




This study is quite relevant to the composite material of stator insulation used in high machines

Fig-2

which generally a combination of epoxy resin, mica, glass tapes and varnishes.
For all uses of the concept of permittivity, such as the high-frequency value or the complex frequency-dependent value , a relative permittivity $\varepsilon r = \varepsilon/\varepsilon 0$ is often preferred to the absolute permittivity $\varepsilon$, as it results in numbers close to unity.

This study concentrates on two methods of dielectric spectroscopy time domain DS (TD-DS) frequency domain DS(FD-DS)

**TIME DOMAIN DIELECTRIC SPECTROSCOPY (TD-DS)**

The dynamic polarization mechanisms measured as dielectric response are described by the dielectric response function f(t). f(t) can be obtained by plotting a graph between displacement current and time This relates a dielectric's polarization P at time t to the applied electric field E. One of the methods of measuring dielectric response in time domain technique is measuring polarization depolarization current (PDC).

**Principle of PDC**

- A voltage step is applied for some time in the winding and then it is shorted
- Charging and decaying current at times t1, t2, t3……is measured
- Tan(δ) at the corresponding frequencies f1 = 1/t1, f2 = 1/t2 using convolution theorem and Fourier transformation is calculated.

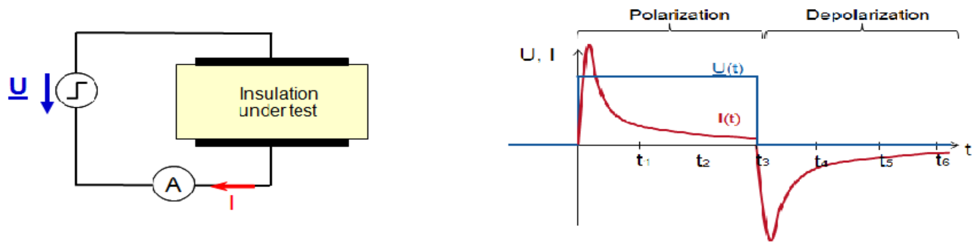



Fig-3

f(t) is calculated from the graph obtained above I(t) obtained by the application of voltage.

$$P(t) = \varepsilon_0 \int f(\tau)E(t-\tau)\,d\tau. \text{ (convolution)}$$

Convolution in the time-domain is multiplication in the frequency domain", and *vice versa* may be transformed to

$$P(\omega) = \varepsilon_0 \chi(\omega) E(\omega)$$

where the frequency-dependent 'susceptibility' $\chi(\omega)$ is the Fourier Transform of the dielectric response in time domain.

$$\chi(\omega) = \chi'(\omega) - i\chi''(\omega) = \mathscr{F}\{f(t)\} = \int_0^\infty f(t)e^{-i\omega t}dt$$

from which the total displacement due to this dynamic polarisation and the

prompt response is as follows after putting the values in equation(1).

$$D(\omega) = E(\omega)\left[\varepsilon_\infty + \varepsilon_0\chi'(\omega) - \mathrm{i}\varepsilon_0\chi''(\omega)\right] \quad \text{……….(2)}$$

Several common notations for splitting up the total $\varepsilon(\omega)$ are

$$\begin{aligned}\varepsilon(\omega) &= \varepsilon_\infty + \varepsilon_0\chi'(\omega) - \mathrm{i}\varepsilon_0\chi''(\omega) \\ &= \varepsilon_\infty + \Delta\varepsilon'(\omega) - \mathrm{i}\varepsilon''(\omega) \\ &= \varepsilon'(\omega) - \mathrm{i}\varepsilon''(\omega) \\ &= \varepsilon_0\left[\varepsilon'_\mathrm{r}(\omega) - \mathrm{i}\varepsilon''_\mathrm{r}(\omega)\right],\end{aligned} \quad \text{………(3)}$$

where $\Delta\varepsilon'(\omega)$ denotes just the dynamic component of the real permittivity, and the components of relative permittivity are the dielectric constant $\varepsilon'_r$ and the loss-index $\varepsilon''_r$. The imaginary part of $\chi(\omega)$makes it possible to describe a delayed response the delay implies some dissipation of energy, a dielectric loss due to polarization mechanisms that take a significant time on the scale of the frequency being studied. In fact, a change of $\chi'(\omega)$ with  is always accompanied by a nonzero value of $\chi''(\omega)$.

For high-voltage apparatus, convenient concept is the geometric capacitance $C_0$, sometimes known as the vacuum capacitance. This is the capacitance that a pair of electrodes would have in free space: if they are instead surrounded by a homogeneous dielectric of permittivity $\varepsilon(\omega)$, the complex capacitance $C(\omega)$ is

$$\mathbf{C(\omega) = C'(\omega) - iC''(\omega) = C_0\varepsilon(\omega)}$$

In this thesis the real, non-lossy component $C'(\omega)$ is referred to as capacitance and the imaginary component $C''(\omega)$ as loss. Similarly to $\varepsilon(\omega)$ in (5.6), $C(\omega)$ can be split into prompt and polarization parts, $C_\infty$ and $\Delta C'(\omega)$.

A common description of the loss is the *loss tangent*

$$\tan\delta = \varepsilon''/\varepsilon' = C''/C',$$

In this $\delta$ is the dielectric loss angle. This quantity has the endearing feature of dividing out geometric terms and distinctions of absolute or relative permittivity; at least for an homogeneous material, $\tan\delta$ is a material property even when based only on measurements of current and voltage.

## USEFUL RELATIONS BETWEEN FREQUENCY-DOMAIN VALUES

The frequency dependent susceptibility has both its components calculated as the real and imaginary parts of a complex number that comes from the Fourier transform of the time-domain response function *f* (*t*). As long as *f* (*t*) is linear, time- invariant, causal, finite and has a finite integral from 0 to $\infty$ there is a necessary  relation between these two parts, such that either can be calculated from the other. The relations in both directions between these parts of the frequency-dependent susceptibility (or indeed any Fourier transforms of a function fulfilling the above criteria) are called the Kramers-Kronig relations

$$\begin{aligned}\chi'(\omega) &= \frac{2}{\pi}\int_0^\infty \frac{x\chi''(x)}{x^2-\omega^2}\mathrm{d}x \\ \chi''(\omega) &= -\frac{2\omega}{\pi}\int_0^\infty \frac{\chi'(x)}{x^2-\omega^2}\mathrm{d}x\end{aligned}$$

from which, for the static ($\omega$ = 0) polarisability gives

$$\chi'(0) = \frac{2}{\pi}\int_{-\infty}^{\infty} \chi''(x)\mathrm{d}(\ln x)$$

The following are some of the consequences of the Kramers-Kronig relations :-

From equation (3), any polarization mechanism is associated with a loss in some frequency range; more specifically, moving down from the very high frequencies where insignificant polarization and loss exist for a particular mechanism, the polarization at frequency $\omega$ is the integral of loss with respect to the logarithm of frequency from the high frequency down to $\omega$. Hence, there is association of the sharpest increases of polarization with the peaks in loss, is fundamental characteristic of polarization mechanisms .No dispersion-free material exists, since any material has some polarizability. At practical frequencies even for microwave work, some mechanisms are so fast that they can be treated as dispersion free..

If a measurement on a linear dielectric system gives results that are not Kramers-Kronig compatible, $\chi'$ and $\chi''$ are not properly measured or cal- culated: perhaps some conduction current has affected $\chi''$ or a bad value for $C_0$ has affected $\chi'$.

If one has a good measurement of $\chi'$, from a good knowledge of the geometry of the tested material, but has the a problem of unknown conductivity causing a current that affects $\chi''$, $\chi''$ may instead be calculated from $\chi'$ and the conduction current found as the difference of the measured and the Kramers- Kronig calculated values of $\chi''$.

Additive quantities such as conductivity are lost in the transformation: the removal of unknown conductance from the loss and prompt capacitance from the capacitance by transformation both ways from $\chi'$ to $\chi''$ is a way to remove these *if* the actual polarization response really did fulfill the requirements for the Kramers-Kronig relation.

**FREQUENCY-DOMAIN DS (FD-DS)**

FD-DS methods generally apply a single sinusoidal electric field and have the ad- vantage that the detected current can be very finely filtered to remove noise, since only a particular frequency, or small range of harmonic frequencies if some current harmonics must be measured on account of suspected non-linearity, is expected at each measurement point.

**PRINCIPLE OF FDS**

Constant Sinusoidal voltage of different frequencies (f1, f2, ...) is applied

Tan(δ) at different frequencies is measured and Tan(δ) at the frequencies (f1, f2, ...) is determined.

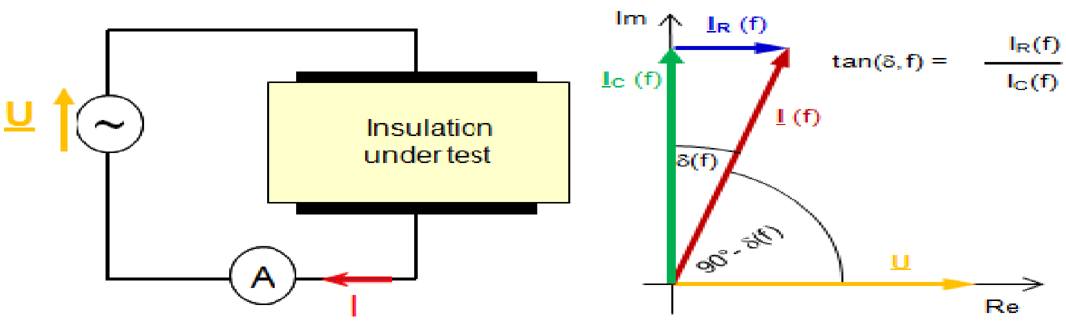



Fig-4

| Frequency | Duration of 1 sine wave |
|---|---|
| 5000 Hz | 0.2 ms |
| 1000 Hz | 1 ms |
| 50 Hz | 20 ms |
| 1 Hz | 1 s |
| 0.1 Hz | 10 s |
| 10 mHz | 100 s |
| 1 mHz | 16.7 min |
| 0.1 mHz | 2.7 h |
| 10 μHz | 27 h |

| PDC | FDS |
|---|---|
| **Advantage** | |
| Fast and accurate at low frequencies | Fast and accurate at high frequencies |
| **Disadvantage** | |
| Inaccurate at high frequencies | Very slow at low frequencies |

Table-1

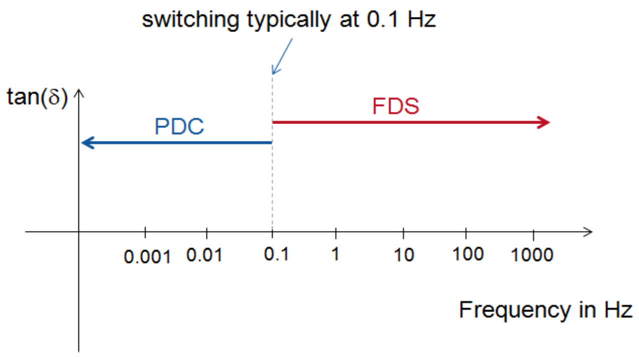



Fig-5

It can be seen from table-1 testing time increases drastically. The advantages and disadvantages of DS-TD and DS-FD is give alongside table-1. By combining both methods the advantages can be used and the disadvantages are avoided:

Measurements can be made from high frequencies like 1 kHz downwards in FDS mode, delivering fast and accurate results. At 0.1 Hz the mode can be switched from FDS towards PDC, decreasing drastically the measurement time giving advantages of both DS-TD and DS-FD giving better diagnostic results

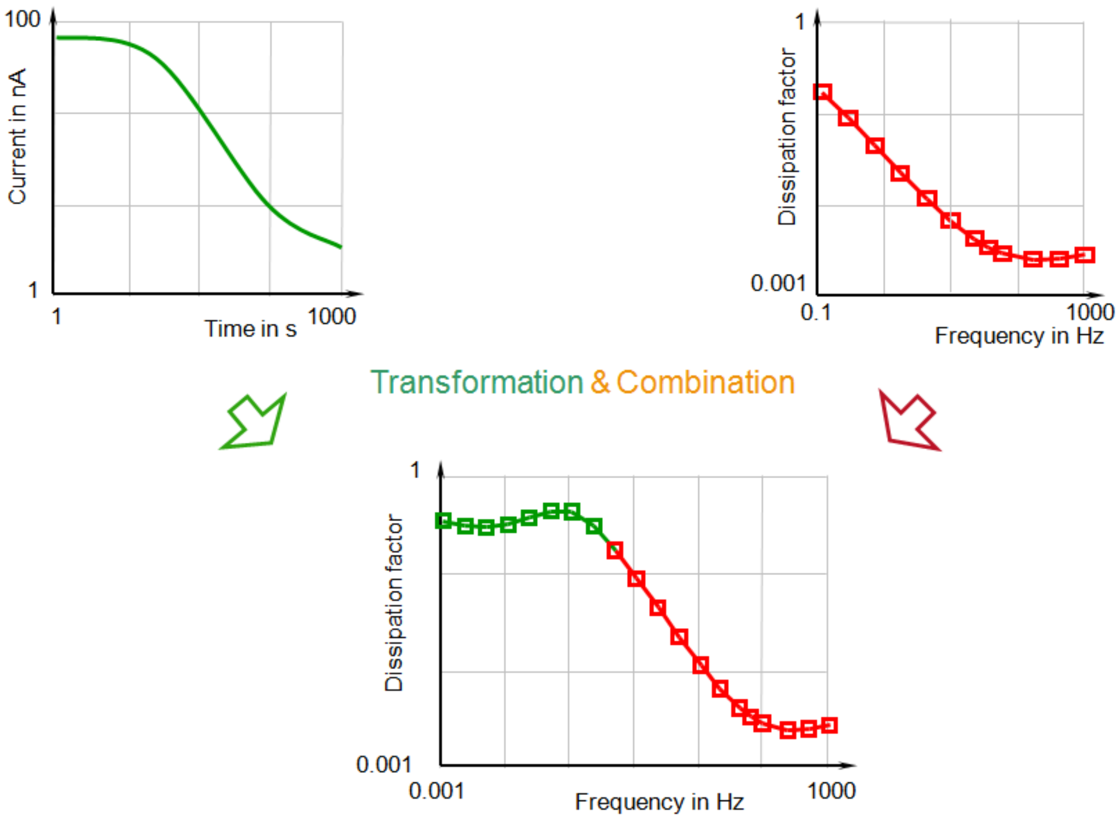



Fig-6

**RECOMMENDATIONS**

From the study in the above paper can be deduced that polarization in a insulation is function of the frequency and this typical property can be very well harnessed to know the healthiness of our high voltage machines. Moreover standard test in the measurement of the dissipation (or power) factor at mains frequency is insensitive to moisture below 2% and is strongly dependent on oil conductivity and temperature. Up to 2% moisture content in the winding tan delta increases marginal. Only for values higher than 2%, the increase is stronger, making a differentiation possible. This happens because exactly around the mains frequency is the minimum of the tan delta occurs. Only a higher moisture content of above 2% tan delta significantly increases. But by applying variable frequency we can easily detect even minimum content of moisture in the winding.DS also identifies the kind of problem the insulation has whether it due to voids or water etc.

In a era where zero forced outage is expected DS can be instrumental in achieving this target. It is recommended to carry this test on all HV equipment in capital overhauling to have holistic knowledge of the condition of our stator winding so as to have full preparedness to take corrective course of action and thus saving forced outages and plenty of revenue loss.