Partial discharge measurement at varied low frequency, and some results from thermally aged stator insulation

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Abstract

Measurement of partial discharge (PD) at varied low frequency has the potential for greater information about an insulation system than is obtained with single-frequency measurements, and the advantage of low current-requirements of the driving source. With frequency becoming another controlled variable, there is a heightened need to consider how to present the data. From the desire to compare and interpret results of measurements at different frequencies there arises the need for appreciation of the effect of recent excitations on the result of a PD measurement. Results of low-frequency PD measurements on three stator coils are presented here: a comparison of two shows strong variation in frequency dependence, and measurements on the other show the variation of a PD measurement due to varied recent history of excitation of the test-object. Some indices for comparison of data at different frequencies and amplitudes are considered.

1. Introduction

PD measurement is often used as part of condition assessment of high-voltage insulation. Two commonly used methods are measurement of the apparent increase in capacitance and dielectric-loss due to PD (C and $\tan\delta$ measurements), and measurement of individual PD pulses, usually resolved in amplitude and by the phase of the applied voltage at which they occurred.

These measurements are made at or near the power-system frequency, 50 or 60 Hz, at which the insulation system normally operates. For simple apparatus in which the voltage distribution in the high-voltage conductors is similar during the measurement to during operation, the measured PD activity will be quite similar to the PD activity during operation as long as the dielectrics are not in a different state, e.g. of temperature. More complex equipment such as a rotating machine's stator insulation has very different conditions between off-line and on-line measurements: the off-line case applies a single-phase supply to set an entire winding or group of windings to a uniform potential, and the thermal conditions are generally very different. There is then not so strong an advantage in keeping other factors similar for the sake of measuring the PD activity of normal operation.

The purpose of each one of a repertoire of diagnostic measurement methods is to provide extra hints about the physical state of the insulation system and thereby of its likelihood of needing imminent attention to prevent failure. To this end there is no overpowering need for diagnostic measurements to reflect the normal operating conditions, yet there is reason to deviate from these conditions if one can thereby acquire some extra information that can be interpreted to enhance significantly the knowledge of insulation condition. We consider the use of varied low-frequency of the applied voltage to fit this description.

2. Varied, low frequency

Our group is interested in the use of varied low-frequency excitation of insulation systems for diagnostic measurements by high-voltage frequency-domain dielectric spectroscopy (DS) and by partial discharge measurement. Since both of these types of measurement can use the same excitation, their simultaneous use offers a saving in time and equipment, and even the possibility of direct comparison of the results, for example relating PD charge measurements with the current measured by DS.

The "low-frequency" range used for laboratory work with PD is from 100 Hz down to 1 mHz, and for field-measurements the test-object's capacitance and the available time typically move each boundary in by at least an order of magnitude, i.e. a few hertz down to tens of millihertz. Over this range there are observable changes in various descriptions of the measured PD, depending on the nature of the PD source. There is ongoing work on applying these methods to stator insulation together with DS methods, modelling cavity PD at varied frequency, and investigating the aging of insulation materials.

In order for good use to be made of results from PD measurements at variable frequency, the method of presentation is important, in order to show trends in frequency and indeed even in the traditional controlled variable of voltage amplitude. The way in which the measurements are performed is also important, since PD behaviour is dependent on the recent history of excitation. These two matters are dwelt on in the following sections, before the presentation of example PD measurements at varied frequency on stator insulation.

3. Sources of frequency-dependence

For much of the later discussion, some basic concepts of PD frequency-dependence are used. Significant parameters of a cavity PD object are shown in figure 1.

The bulk dielectric's properties, permittivity $\varepsilon_{\mathrm{bulk}}(\omega)$ and conductivity σ_{bulk}, affect together the time taken for a

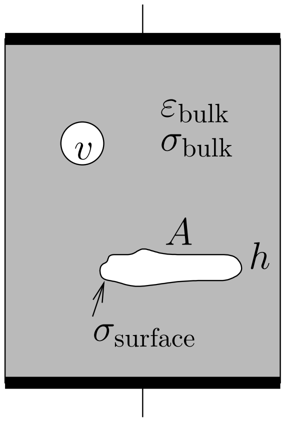

Fig. 1: Origins of frequency-dependence of cavity PD

redistribution (relaxation) of space-charge to a new equilibrium when the applied voltage or the charge across a cavity is changed. $\varepsilon_{\rm bulk}$ affects the distribution of applied voltage, over the cavities and the solid insulation. $\sigma_{\rm bulk}$ affects whether PD activity can continue at low frequencies due to significant conduction current in the solid insulation, or whether the amount of charge per cycle is limited by a well-insulating dielectric.

The surface conductivity $\sigma_{\rm surface}$ of a cavity determines the rate of movement of charges between the faces of the cavity; if this is high then at low frequencies the surface charges may shield the cavity from the applied voltage so much that no PD occurs. The shape of the cavity or delamination (a wide, shallow cavity), A and h, is important in a similar way to $\sigma_{\rm surface}$ in that it affects how rapidly the polarisation of surface charges across the cavity can occur, in the absence of PD.

The volume v has an effect on how likely an ionisation due to background radiation is within the cavity within a given period; such an ionisation can be needed to start a discharge, so as frequencies become high or cavities small, the time-delay between attainment of sufficient theoretical breakdown voltage in the cavity and the occurence of a PD can become large and varied, often leading to larger PDs.

[1] gives a more detailed description of frequency-dependence, including consideration of the discharge itself.

4. Presentation of data

The conventional PD measurements at power frequency give typically the changes in C and $\tan\delta$ from smooth-current, e.g. bridge, measurement, or the phase-resolved PD pattern (PR-PDP) from PD pulse measurement, for several voltage amplitudes, e.g. 0.4, 0.6, 0.8, 1.0 and 1.2 of the nominal line-voltage, applied between phase and earth. This small number of measurement points makes it quite reasonable to see the values in a list and to compare the PR-PDPs by flicking between them.

When measuring at several voltage amplitudes but also at many points over several decades of frequency, the use of indices — single values describing some aspect of the measured PR-PDP — is desirable, to allow plotting of trends. Direct viewing of PR-PDPs is of course possible too, as a complement: some marked changes in pattern, with possible physical significance, may be very little shown in certain indices, while on the other hand some trends in indices may be difficult for the eye to unravel from a set of PR-PDPs. Some statistical distribution-based indices (e.g. moments: variance, skew, kurtosis) have been popular in PD literature, but more physically based ones are considered here. Particularly the final two are not current practice for diagnostics.

4.1. Maximum, total and mean PD charge

The maximum PD charge is often shown along with PD patterns. It has some importance in its representation of a single large PD source with probable high wear to the surrounding insulation. The “largest repeatedly occurring”[2] value may be used to prevent bias due to exceptionally high PD in a single cycle.

The total measured PD charge per cycle is a measure of the degree of cavity polarisation that was not acheived by conduction. This would, for example, reduce with reduced frequency if there is significant conduction around a cavity PD source but not in the bulk insulation.

The number of measured PDs per cycle is sometimes seen to have a strong trend with frequency; it is often interpreted together with total charge per cycle. The mean PD charge is a derived index from total charge and number of PDs.

Separate treatment of the positive and negative charges may be helpful for the above indices, for distinguishing asymmetrical PD sources.

4.2. Complex capacitance

This is a convenient measure when interested in the effect of PD charges on measured currents from DS or simple C and $\tan\delta$ measurements. It also has some virtue in its own right, since normalisation by voltage amplitude makes the extent of non-linearity clearer.

By summing the total charge per phase channel of a PR-PDP, and calculating the resulting average current for the corresponding period of time, a discrete current waveform is formed from a PR-PDP. To calculate the effect that polarisation due to the PD would have on measurement of capacitance C and loss $\tan\delta$ (usually used in the context of a linear system), an FFT can be used to obtain just the fundamental frequency component of the current. The usual expression for complex capacitance, $C' - \mathrm{i}C'' = I(\omega)/(\mathrm{i}\omega V(\omega))$, in which I and V are complex current and applied voltage for the test-object, ω is the angular frequency and i is the imaginary unit, can then be used to obtain what is effectively a current normalised by the amplitude and frequency of the applied voltage. The same basic failings as for total PD charge apply, in that much charge may be missed due the system limitations, and the amount missed may vary with frequency.

If the supply voltage is sinusoidal, only the components of current of the same frequency (fundamental) and with an in-phase (loss, C'') component can dissipate power;

the value for C'' therefore describes all the energy consumption due to PD with sinusoidal excitation.
The ratio $\tan\delta = C''/C'$ describes the deviation of the peak of the fundamental current from the zero of the applied voltage. This is typically quite small for cavity PD but large for external PD (corona).

4.3. Harmonics

Having established a smoothed PD current, as for the calculation of the complex capacitance from the fundamental-frequency component of this current, the (higher) harmonics that are expected in so non-linear a system may also been displayed and analysed.
The harmonics describe some general features of the PD pattern, in a few scalar values [3]. For example, the presence of even-order harmonics implies a difference between the positive and negative sets of charges, and the ratios of harmonic orders, e.g. 3rd to 1st, indicates the sharpness of the distribution of PD charges.

5. Variation of results

For simple diagnostic measurements, differences between measurement occasions have to be considerable in order to cause worry. For use of varied low-frequency methods, and particularly when in the laboratory or trying to model the PD sources, more attention will be given to the physical interpretation of differences between between occasions and between different V-f (voltage amplitude and frequency) points, making use of indices such as mean charge, maximum charge, total charge, number of discharges and change in complex capacitance due to the PD's polarisation. The sequence of V-f points used is likely to vary depending on time-constraints and the range of these variables of interest in a particular case. The short-term effects of excitation upon following measurements are therefore important for us to consider.
Earlier measurements on thermally aged stator coils, comparing results from sequential and randomised V-f points, have suggested a strong effect of the foregoing measurement, with HV LF (high V, low f) ones apparently having the largest effect on the next; this led to the idea of trapped charge or polarisation in the material due to previous excitation as being of importance.
The ideal result of a PD measurement the result that one would have obtained if the physical system had been in equlibrium for the applied V-f point throughout the measurement. The physical equilibrium of alternating excitation implies that there should be no cycle-to-cycle trend; this might for example be acheived by starting a measurement only after many cycles of the same excitation. The typical situation of moving between different V-f points with only a short pause will not provide such an equilibrium.
As the start of an investigation of the factors influencing PD measurement, PD measurements at varied frequency were made on a single 7.2 kV epoxy-mica stator coil whose PD sources have been produced by accelerated thermal aging at 160°C for 4 weeks. The measurement system is described in [4]; its main components are

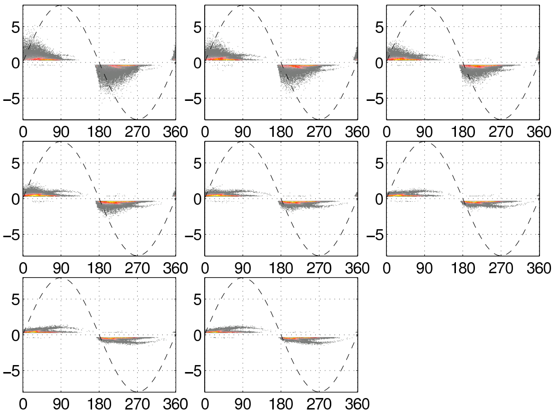

Fig. 2: PD patterns, to same scale, for eight decreasing lengths of time between last excitation and measurement point. y-axis labels show PD apparent charge in nC, x-axis labels show phase in degrees. All measurements are 9 kV, 10 Hz, 200 s. The chronological order of the plots is left to right, top to bottom, and the corresponding dead-times prior to measurement are 10000, 3600, 1800, 900, 300, 180, 60, 30 seconds.

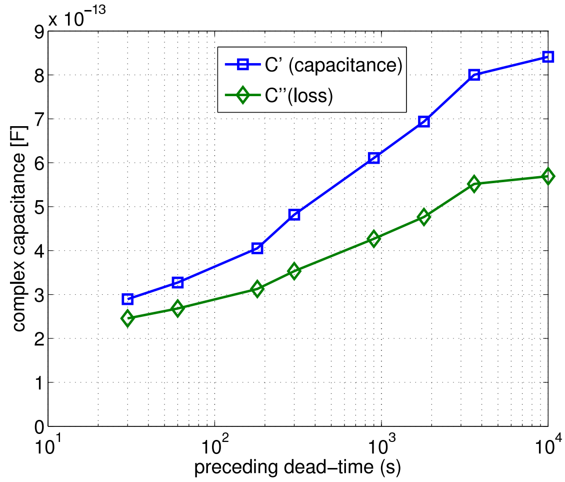

Fig. 3: PD charges of the patterns shown in fiure 2, seen as C' and C'' as described in section 4.2.. The x-labels refer to the length of the dead-time since the previous measurement: all measurements are at 9 kV, 10 Hz, 200 s. The order of measurement was with longest dead-time first.

a Power Diagnostix Systems Gmbh phase-resolved detection system, a computer-controlled high-voltage amplifier, a low-pass filter in the supply, and a parallel pair of 100 pF coupling capacitors. The PD detection was done in the earth connection of the test-object. Calibration was performed at 500 pC, at which apparent charge level there was seen to be much PD activity.
Figures 2 and 3 show the results, as PR-PDP and as complex capacitance, for the same 9 kV, 10 Hz, 200 s PD measurement performed at different intervals from the preceding such measurement. This series has been repeated with similar results on the same test-object. It is notable that the high-charge PDs in the pattern increase greatly when the test-object has not had excitation for a long time, and that the extra capacitance value due to PD more than doubles between 30 s and 3600 s. Increases of

some tens of percent have been seen when the previous excitation has been low frequency (1 mHz) rather than high frequency (20 Hz). A sequence that increases amplitude and decreases frequency would seem the best for reducing these effects, and starting measurement some cycles after the start of excitation is desirable.

6. An example, on stator insulation

Three form-wound stator coils have been used as test-objects for the initial work with using LF PD measurements. The coils were obtained newly cured, and two similar coils, 'A1' and 'A2', have been thermally aged in air in an oven, with accelerated aging at 180°C for 1 week.

Results of PD measurements are shown as complex capacitance in figures 4 and 5, against frequency, for several voltage amplitudes. The measurement system is as described in the previous section. Only 5 cycles per measurement were used, so statistical effects can make the curves 'noisy' when the activity is low. The measurements were made in amplitude up, frequency down, sequence, with 2 cycles of excitation at any V-f point being run before measurement. Due to the equipment, there is a pause of some 10 s between this pre-excitation and measurement. The broad behaviour of increasing or decreasing complex capacitance with decreased frequency was observed regardless of measurement sequence, but the curves were less distinct with, e.g. random sequence.

It is clear that the frequency dependence of an PD index of two similar coils, aged at similar temperatures, differs strongly. This may be a consequence of slightly different contruction in spite of the same production process, or of 'A1' having had less effective mechanical support during the aging. Examples of possible differences in the PD sources responsible the difference are greater surface conductivity of cavities in 'A2', or smaller or flatter cavities or greater bulk insulation conductivity in 'A1'.

Continuation should be with measurements at various stages of aging, on groups of several objects in order to see the effects of random variation; the need to borrow remote oven facilities has so far prevented detailed study of the effect of aging. Dissection of aged insulation to test ideas of the significance of PD results should be tried, but this is probably more suitable for smaller laboratory insulation test-objects where the PD sources can more easily be located.

7. Conclusions

Low varied frequency PD measurement can make distinctions that are not clear at power frequency. Recent excitation can have a very large effect on PD measements, even after many cycles of measurement. A 'complex capacitance' index of PD current is a useful index for comparing many PD measurements, particularly when comparing results with those from DS. Further investigation of recent excitation and of variations in frequency dependence of PD during the aging process will be made.

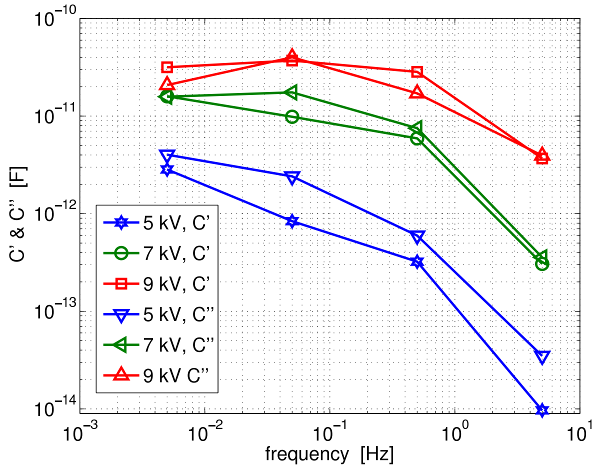

Fig. 4: Complex capacitance representation of PD current for the stator coil 'A1'.

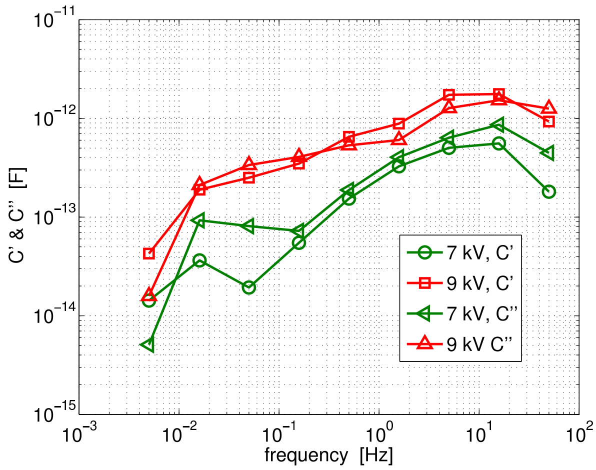

Fig. 5: Complex capacitance representation of PD current for the stator coil 'A2'.

8. References

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