Partial Discharge Activity in Rotating Machine Type II Insulation Systems as a Function of Temperature and AC Supply Frequency

Torstein Grav Aakre, Emre Kantar, and Espen Eberg

***Abstract*—The main purpose of this study was to investigate if the application of very low frequencies for PD measurements in type II generator bar insulation is relevant when compared to applying power line frequency at different test temperatures. Laboratory experiments were performed on two stator bar types rated 6.4 kV and 7.4 kV, labeled as Group A and Group B. The stator bars were taken from service and spare part storage (pristine). The samples were preconditioned at the maximum test voltage of 1.5 U_0 before sweeping the AC high voltage supply from 0.1 Hz and 50 Hz. The test temperature was varied between 20 °C and 155 °C. Investigation of cross sections of the generator bars was done to qualitatively describe the voids. The main results showed that the partial discharge inception voltage (PDIV) for Group A was temperature independent at 50 Hz and decreased by 40 % at 0.1 Hz with increased temperatures, whereas the PDIV for Group B was frequency independent and increased by 70 % with temperature. Similarly, the PD magnitude and total apparent charge decreased by 90 % for Group B with increased temperature, whereas it more than doubled for Group A with temperature. The tested bars from Group A showed significantly larger voids, located close to the copper conductors, compared to Group B, where voids were mainly located within the mainwall insulation. Results indicated that tests performed at 0.1 Hz cannot directly represent results obtained at 50 Hz. Using a wide range of frequencies and test temperatures broadens the understanding of the behavior of the voids inside the mainwall insulation.**

***Index Terms*— Hydropower generator bar insulation, electrification, VLF, partial discharges, internal discharge.**

I. Introduction

OFF-LINE condition assessment of high-voltage equipment with a large capacitance, for example, generators and cables, is advantageous to perform at very low frequency (VLF), typically at 0.1 Hz, due to the small capacitive charging current compared to the power line frequency (PLF) sources that require considerably higher output current to be operated. Relevant IEC and IEEE standards for condition assessment of hydropower stator insulation [1], [2] have been developed for power frequency testing but can also be used for VLF and 400 Hz. The VLF is referred to as a possible condition assessment method in [3], but with the caution that VLF might produce different results than power line frequency. The electric field distribution along the end corona protection (ECP) on generator stator bars is, for example, frequency-dependent [4]. This extends the region with high voltage potential throughout the ECP section with 0.1 Hz compared to 50/60 Hz, which the ECP is designed for. Additionally, condition assessment is performed on hot or cold generators, depending on the waiting time between turning off the generator and when the measurements start, causing further complications if the test conditions vary.

Type II generator bar insulation has resistance to partial discharge (PD), typically due to mica filler. It has two main production processes [5]: In the resin-rich (RR) process, insulation tapes prewetted with resin are wrapped around the conductor bundle and then heated and cured under press, whereas in the vacuum pressure impregnation (VPI) process, dry tapes are wrapped around the conductor bundle, and the whole assembly is put under vacuum before impregnated with epoxy liquid to remove voids. Experience has shown that VPI insulation can be in good condition after more than 50 years of service [6]–[8]. The main defects inside the mainwall insulation are voids or delaminations depending on the success of the taping technique, curing, and deterioration during service [9]; for example, the tolerance of the taping of RR is more critical than for VPI insulation.

There exist just a few papers dealing with testing PD in voids at different voltage frequencies and test temperatures. Model studies of defined, single voids in pure polymer materials are therefore included to show expected trends and possible mechanisms. In [10], Miller and Black found that for epoxy-bonded mica insulation, Partial Discharge Inception Voltage (PDIV) was 7-10 % higher at 0.1 Hz compared to PLF, but for increased voltages, the measurements conducted at 0.1 Hz were representative of PD at PLF. For samples with increased conductivity on the void surface, the voltage frequency had to be raised to 1 Hz for PD measurements to be representative of PD at PLF. Nair et al. [11] studied slot discharges between 0.1 Hz and

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50 Hz between 20 °C and 60 °C, that is, 'voids' between the mainwall insulation and stator core. They observed that the total apparent charge per period (discharge current) and maximum apparent charge strongly increased with temperature and became frequency dependent as the temperature raised, with the highest values at 50 Hz. Further, in [12], the opposite was seen, as the total apparent charge from internal delamination discharges was about 50 % higher at 0.1 Hz than at 50 Hz. The maximum apparent charge was, however, only 60 – 70% at 0.1 Hz of what was measured at 50 Hz. A large cylindrical void in RR mainwall insulation was used as a model in [13] to mimic delaminations. It was found that the PD inception voltage was frequency independent below 90 °C. Above that, the PDIV at 0.1 Hz decreased, and at 50 Hz remained unchanged. Similarly, in a polycarbonate sample [14], the measured number of PDs per cycle was frequency independent at PDIV, whereas increasing with frequency at higher voltages. Conversely, the average PD magnitude was frequency dependent at PDIV (increasing with frequency) but frequency independent at higher voltages. They explained the frequency dependence by a statistical time lag and the charge transport in the cavity surface at different applied frequencies [15]. Differences were seen for spherical voids in epoxy, as the maximum apparent charge was either decreasing with frequency in a 1 mm void in [16] or frequency independent in a 1.5 mm void in [17]. A possible mechanism was concluded to be a surface charge decay that might significantly influence PD behavior. The presented model studies show variations in PD behavior that need to be investigated for real stator bars.

The main purpose of this work is to compare partial discharges obtained at VLF (0.1 Hz) to those obtained at PLF (50 Hz) to evaluate if VLF is feasible for the condition assessment of type II machine insulation. The testing temperature is also introduced as a variable because off-line assessment often is performed at lower temperatures than the operating temperature of the machine. The work is conducted for two groups of type II insulation systems.

II. Theoretical Background

Comparing results from unknown voids to simplified models is often useful, as this can provide insight into involved parameters and important trends. The theoretical background is therefore based on the very simplified case of a cylindrical void with a homogeneous gap giving rise to the abc-model. The void is in the theoretical treatment assumed to completely discharge in each discharge.

It is reasonable to assume Laplacian conditions before the first PD occurs; thus, the generalized abc-model can be assumed valid. The inception voltage U_s in homogeneous void gaps with void gap distance d_c is described experimentally by the Paschen curve [18]:

$$U_\mathrm{s} = 6.72\sqrt{pd_\mathrm{c}} + 24.36(pd_\mathrm{c}) + \frac{0.00411}{\sqrt{pd_\mathrm{c}}}\,[\mathrm{kV}]. \qquad (1)$$

The expression is valid for pressure multiplied by distance, pd_c, values in the range of 10^{-3} to 10^{2} (bar·cm). An idealized void can be modeled as a capacitance and resistance in series with an insulation capacitance C, resistance R, and generic complex impedance $Z(\omega)$ measured by the dielectric response, as illustrated in Fig. 1. This is an expansion of the capacitive abc-model [13].

Using this model, the initiation voltage U_i applied to the complete system to get PD inception U_s is

$$U_\mathrm{i} = \left(1 + \frac{d_\mathrm{b}}{d_\mathrm{c}} \frac{\sigma_\mathrm{c} + j\omega\varepsilon_0\varepsilon_\mathrm{r,c}}{\sigma_\mathrm{b} - \omega\mathrm{Im}\{\varepsilon_\mathrm{b}^*\} + j\omega\mathrm{Re}\{\varepsilon_\mathrm{b}^*\}}\right) \cdot U_\mathrm{s}, \qquad (2)$$

where d_b is the insulation system thickness, d_c the void gap distance, σ_c and σ_b the conductivity of the void and insulation, respectively, ε_b^* the complex permittivity in the insulation, $\varepsilon_\mathrm{r,c}$ the relative permittivity of air, and ω the angular frequency. The conductivity is, in general, increasing with temperature according to the Arrhenius law:

$$\sigma(T) = \sigma_0 \cdot e^{-\frac{E_\mathrm{a}}{k_\mathrm{B}T}}, \qquad (3)$$

where k_B is Boltzmann's constant, σ_0 is a constant, and E_a is the activation energy, and T is the temperature in Kelvin.

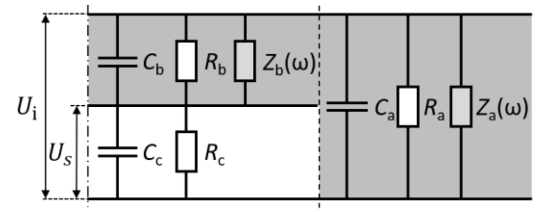


Fig. 1: Equivalent circuit of an insulation system with a void. The insulation is shaded grey, whereas the void is white.

The measured apparent charge within the simplified scheme can be approximated to

$$q_\mathrm{a} \approx C_\mathrm{b} \cdot (U_\mathrm{s} - U_\mathrm{r}), \qquad (4)$$

where C_b is the capacitance in series with the void, U_s is the ignition voltage in the void and U_r is the remanent voltage. Similarly, the theoretical PD repetition rate per period is [15]

$$n = 4 \cdot \frac{U_0 - U_\mathrm{r}}{U_\mathrm{s} - U_\mathrm{r}}, \qquad (5)$$

where U_0 is the maximum applied voltage across the void during a voltage cycle assuming no PDs and no remanent charges. The total apparent charge per period can be written as the product of repetition rate and apparent charge:

$$q_\mathrm{a}^\mathrm{T} = \sum q_\mathrm{a} = n_0 \cdot q_\mathrm{a} = 4 \cdot C_\mathrm{b} \cdot (U_0 - U_\mathrm{r}). \qquad (6)$$

If then, assuming that many voids coexist within the same insulation system with approximately the same voltage, it is possible to sum all PDs in all voids by the superposition principle:

$$Q_\mathrm{a}^\mathrm{T} = \sum\nolimits_\mathrm{voids} q_\mathrm{a}^\mathrm{T} = 4 \cdot C_\mathrm{b}^\mathrm{TOT} \cdot (U_0 - U_\mathrm{r}). \qquad (7)$$

where $C_\mathrm{b}^\mathrm{TOT}$ now represents the total series capacitance of all the voids.

Another approach to describe the PDs is to consider the available energy, $\mathcal{E}$, inside the void that can give rise to PDs is stored in the electric field by

$$\mathcal{E} = \frac{1}{2}\int \varepsilon_0\varepsilon_r\,|E|^2\,dV. \qquad (8)$$

where V is the volume of the void. The energy is expressed as

$\mathcal{E} = \frac{1}{2}U_0^2 C_c = \frac{1}{2}QU_0$ when the capacitance can be defined. Thus, the smaller the volume or electric field, the smaller the available energy, which implies that the available energy for PDs is reduced.

III. Materials and Methodology

A. Test Objects

Generator bars with two different type II insulation systems were tested, i.e., Group A and Group B, with characteristic properties given in Table 1. The Group A bars were cut to 50 cm in length to reduce the capacitance. Later, the Group B bars were tested with improved equipment enabling a longer sample of about 2 m. All test objects (samples) had the end windings removed, and a new ECP was applied according to the manufacturer's instructions. The bars were clamped between aluminum bars to ensure a defined ground potential and simulate a real stator slot.

TABLE 1
Important Specifications of the Test Objects.

	Group A	Group B
Total sample length (m)	0.5	2
Active length (m)	0.2	1.4
Strands (#)	18 parallel	64 Roebel
Cross section (mm x mm)	20x56	22x70
Insulation thickness (mm)	3	3.7
Rated voltage (U_0 kV$_{rms}$)	6.4	7.4
Installation year	1976	1965
Years in service	35	52
Insulation method	Resin rich	VPI
Insulation type	MicaMat [19]	Micadur [20]

The bars were divided into two groups, as shown in Table 2. The Group B spare bars were still spare for a generator in service, and testing could not be destructive or degrade the bars by any chance. Hence, the maximum testing voltage and temperature were lower in these specific bars. An earlier published work for the screening of the Group B bars has shown no correlation between location and PD level [21]. The same was also observed for the Group A bars, and the locations in the stator were not investigated.

TABLE 2
The Different Test Groups

Service aged state	Group A	Group B
Spare bar (# samples)	3	2
HV terminal (# samples)	3	5
N terminal (# samples)	3	1

B. Material characteristics

A selected population of bars was characterized by dielectric spectroscopy at both a broad frequency and temperature range. The test objects were guarded mechanically with a 2-mm wide removal of the semiconducting paint to remove the effect of the ECP. The voltage frequency range was between 10^{-4} Hz to 10^3 Hz, the applied voltage was 200 V, and the temperature was in the range of 20 °C to 155 °C.

Similarly, a polarization- and depolarization test was performed on a selected population of the bars to find the DC conductivity, using a high-resolution setup for the Group A bars [22] and a Megger MIT 252 for the Group B bars, which provide accurate results for type II insulation systems.

A selection of Group A and B bars were cut into 1.5 cm thick sections after completing the electrical tests. The sections were polished and investigated for voids and delaminations in an optical microscope.

C. PD Test Setup

A sketch of the experimental test circuit for PD detection is shown in Fig. 2. The test object (stator bar) is situated in a heating cabinet. The measurement circuit is in compliance with IEC 60034-27 and calibrated according to IEC 60270 (Integration frequencies: 250 kHz ± 150 kHz). The measurement impedance is commercially available from Omicron, CPL 542, and is connected to the data processing unit MPD 600. The high-voltage signal is set by a DAQ or function generator and amplified by a TREK high-voltage amplifier in series with an RC low-pass filter, with a cut-off frequency of 1.5 kHz. Values for the involved capacitances and power sources are shown in Table 3.

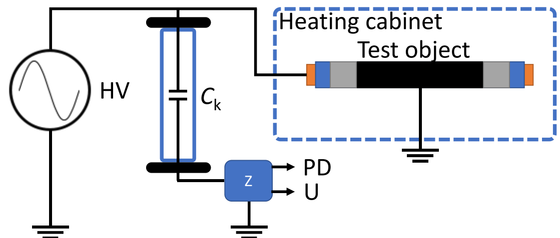


Fig. 2: Schematic of the PD test setup. It is based on a direct measurement where the PD signal is measured across an impedance Z in series with the measure capacitance C_k.

TABLE 3
Test Circuit Elements.

Test parameter	Group A	Group B
Test object capacitance	400 pF	2.7 nF
Coupling capacitor	3.4 nF	2 nF
Power source	TREK 20/20B	TREK 30/30C

D. PD test procedure

The PD test procedure is given in the list below with details in Table 4:

1. Obtain a stable temperature in the bar.
2. Precondition the bar at 50 Hz at maximum test voltage. The test time was reduced to the second frequency to ensure stable 50-Hz conditions throughout the sweep at different temperatures.
3. Increase the voltage stepwise from zero until the maximum voltage is reached.
4. Reduce the voltage stepwise until zero voltage.
5. Repeat step 2 to 4 at lower frequencies.

Table 4
Test Parameters for the PD Testing

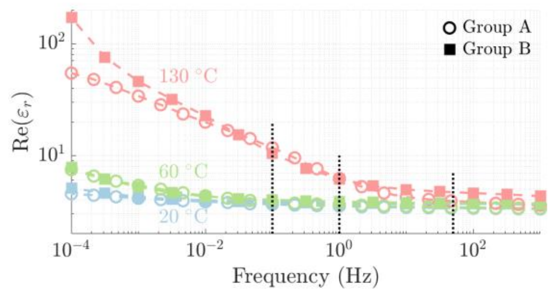
Test parameter	Group A	Group B	Group B spare
Frequency range	0.1 Hz, 1 Hz and 50 Hz		
Maximum voltage	1.5U_0	1.6U_0	1.2U_0
Number of voltage steps	10	10	3*
Preconditioning, 1st time	5 min	5 min	5 min
Preconditioning, 2nd+ time	10 s	10 s	5 min
Step length	10 s or 10 T	30 s or 30 T	9000 T
Temperature	20°C to 155°C	20°C to 130°C	30°, 70°, and 130°C
Time between temperatures	2 h	1 d	1 d

*{PDIV+0.1U_0, U_0, 1.2 U_0}

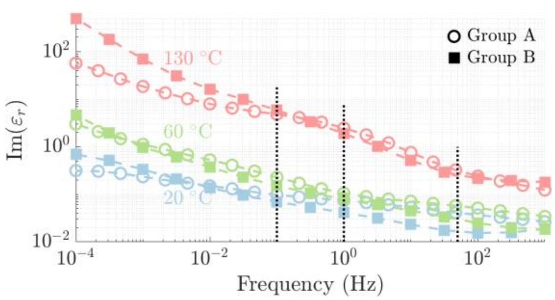
IV. Results

A. Dielectric properties

The complex permittivity as a function of frequency at three different temperatures for service-aged bars for both Group A and B bars is presented in Fig. 3. Vertical lines indicate 0.1 Hz, 1 Hz, and 50 Hz. The shown permittivities are representative of all Group A and B bars, respectively. The general trend in Fig. 3 is that the complex permittivity decreases with frequency and increases with temperature. The complex permittivity is similar for Group A and B above 0.1 Hz.



a) Real part of complex permittivity



b) Imaginary part of complex permittivity

Fig. 3: Measured complex permittivity of Group A and B bars at indicated temperatures as a function of frequency at 200 V. Vertical lines indicate 0.1 Hz, 1 Hz, and 50 Hz.

The DC conductivity of the Group A and B bars were measured at room temperature to be 10^{-16} S/m and 10^{-14} S/m, respectively. The variation between the different samples was insignificant. Such low DC conductivities do not influence the extended abc-model in (2); it thus can be considered purely capacitive at low temperatures when the dielectric loss is low.

B. Phase-resolved PD Patterns

Typical phase-resolved PD (PRPD) patterns for Group A and B are shown in Fig. 4 at 0.1 Hz and 50 Hz and 20 °C and 130 °C. The patterns clearly indicate that we are investigating void and delamination discharges. The overall trends demonstrate that the PD activity increases with temperature for Group A and decreases for Group B. The shapes of the PD patterns do not change with temperature; thus, there are mainly voids and delaminations present.

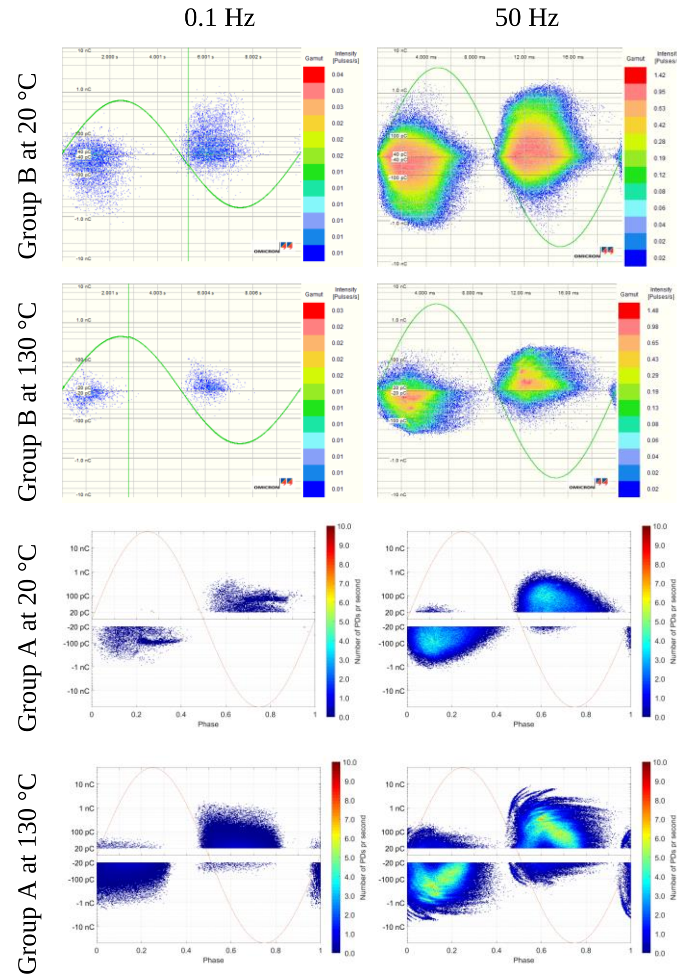


Fig. 4: Typical PRPD patterns (log-y) at 0.1 Hz and 50 Hz for Group A and B at 20 °C and 130 °C. The applied voltage is such that the average electric field is equal at 4.5 kV/mm for both groups.

C. Partial Discharge Inception Voltage - PDIV

PDIV was defined as the first voltage at which a sustained PD activity of a minimum of 100 pC occurred. This is a basic parameter defining if there are PDs or not in the system. The first PD inception is related to the weakest defects in the insulation system. The average measured PDIV for Group A and B are shown in Fig. 5. For the Group A bars, the PDIV at 50 Hz is almost temperature independent, whereas the PDIV at 0.1 Hz and 1 Hz decreases with temperature. The trend for the Group B bars is the

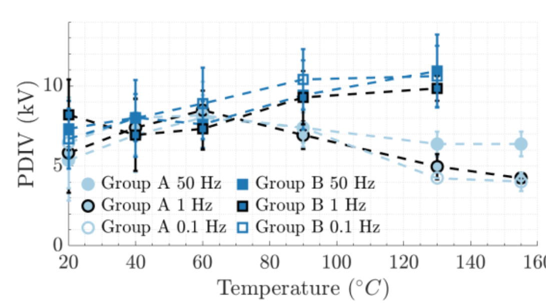


Fig. 5: Average PDIV as a function of temperature at 50 Hz for Group A and B.

opposite; the PDIV increases with temperature at 0.1 Hz, 1 Hz, and 50 Hz. Only three temperatures were tested for the Group B spare bars, and they align well with the other Group B bars presented in Fig. 5.

D. The apparent charge

The apparent charge is a calibrated measure of the PD magnitude. A generator bar may contain many unknown and undefined defects, which produce PDs with a variety of magnitudes and intensities. A typical graph for PD repetition rate per period as a function of indicated voltages is given in Fig. 6 at PLF. It is seen that there is a large spread in the magnitudes, with a few large and many small PDs. The amplitude in the distribution seems to increase with the same proportionality factor as a function of applied voltage. The shapes of the curves in the presented figure were qualitatively similar for all tested bars at all frequencies and temperatures. The distributions in Fig. 6 are challenging to compare directly between different temperatures, frequencies, etc. Therefore, derived quantities, like the maximum and total apparent charge, related to available energy in the voids, can be used.

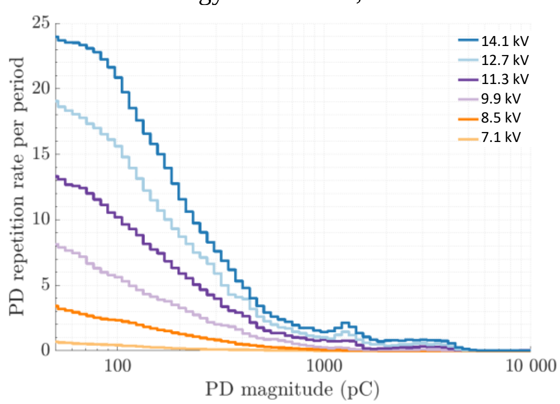


Fig. 6: A typical graph for PD repetition rate per period as a function of PD magnitude at PLF at indicated voltages. This is a representative figure for all tested samples, exemplified by a Group A bar close to the HV terminal at 90 °C.

E. The maximum apparent charge

The measured maximum apparent charges are shown in Fig. 7 as a function of temperature at 0.1 Hz, 1 Hz, and 50 Hz. The applied voltage is such that the average electric field in the insulation in the two bar types is 4.5 kV/mm. For the Group A samples, the maximum apparent charge increases from 1 nC at 20 °C to 5.5 nC at 130 °C at 50 Hz, while there is no significant increase at 0.1 Hz. For Group B bars, the trend is the opposite, with the maximum apparent charge decreasing with temperature. There is no significant difference at different temperatures, neither at 0.1 Hz nor at 50 Hz for the Group B bars.

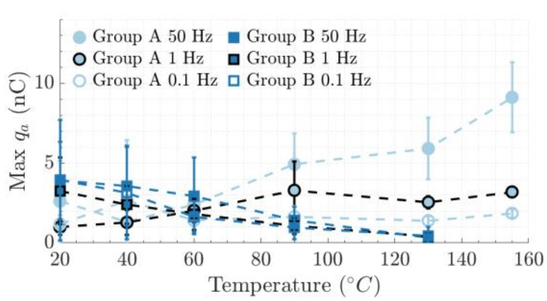


Fig. 7: Measured maximum apparent charge vs temperature at E = 4.5 kV/mm (13.6 kV_{pk} and 16.7 kV_{pk}) for Group A and B. measured at 0.1 Hz and 50 Hz.

F. The total apparent charge per period

The measured total apparent charge per period can be treated as a measure of the available energy in the discharged voids in the bars. The average total apparent charge per period-volume as a function of temperature at indicated frequencies for the Group A and B bars are given in Fig. 8. The total apparent charge per period was normalized to per volume to easier compare the PD activity between the samples of different size (insulation volume). The total apparent charge per period for Group B decreases with temperature as does the maximum apparent charge for all frequencies. Conversely, for Group A, the total apparent charge per period increases with temperature, as for the maximum apparent charge. There are some differences related to the applied frequency. The highest increase with temperature for the maximum apparent charge was at 50 Hz; particularly, a significant increase at 130 °C at 1 Hz in the total apparent charge per period was observed.

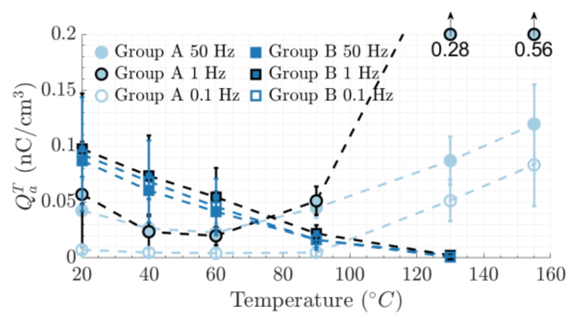
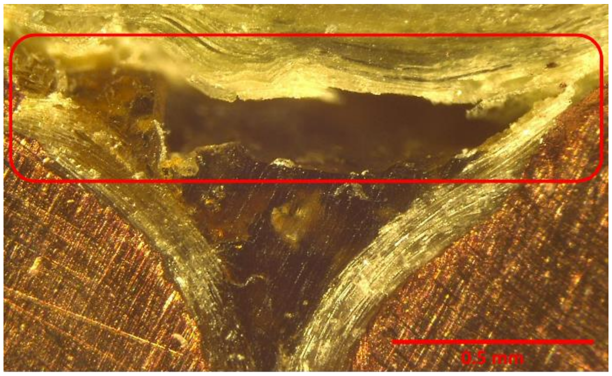


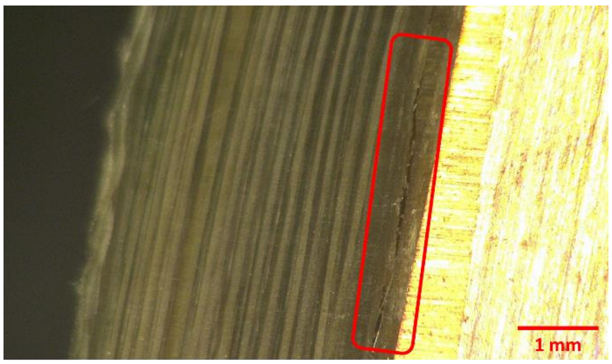
Fig. 8: General trend of the measured total apparent charge per volume insulation as a function of temperature at indicated frequency at E = 4.5 kV/mm (13.6 kV_{pk} and 16.7 kV_{pk}) for Group A and B measured at 0.1 Hz and 50 Hz.

G. Typical cross sections with voids and delaminations

More than 100 cross-sections from the tested bars were made. From visual inspection in an optical microscope, it was found that many cross-sections did not have observable voids, while others had visible defects, which are presented in this section. The observed voids in the Group A bars were situated in the wedges between the conductor strands, several millimeters in order of magnitude. The observed voids in Group B bars were smaller and located on the corners with an approximate dimension of 0.1 mm. Both Group A and B had delaminations, whose widths in the cross-section were of several millimeters and heights were typically of 0.1-0.2 mm. Typical voids are illustrated in the micrographs in Fig. 9 for Group A and in Fig. 10 for Group B.



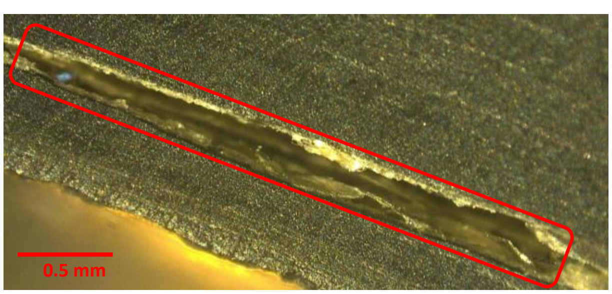
a) Most frequent void in a Group A bar: Voids between the copper conductor strands and mainwall insulation. Height: 0.2 mm and width = 1 mm.



b) Delamination in the mainwall insulation. Height: 0.6 mm and width: 5 mm.

Fig. 9: Selected parts of cross sections from Group A.

a) Small voids in Group B in the mainwall insulation. Height: 0.07 mm and width = 0.2 mm.



b) Delamination in the mainwall insulation. Height: 0.2 mm and width: 3 mm.

Fig. 10: Selected parts of cross sections from Group B.

V. DISCUSSION

A. The PDIV

The measured PDIV is a measure of the voltage distribution for the void with the lowest breakdown voltage. Equation (2) describes a general relation between the void voltage and the applied voltage if the geometry is known. All involved material and geometry parameters are, in fact, temperature dependent. The void breakdown voltage U_s is, by the Paschen law and the ideal gas law, temperature dependent, and a higher breakdown voltage is expected at higher temperatures in enclosed voids. The measured dielectric response ε_b^* increases with temperature, as shown in Fig. 3. Similarly, it is expected that the involved conductivities increase with temperature, according to Arrhenius law. The temperature dependence of such parameter variance on PDIV is shown in Fig. 11. From this figure, it is reasonable that the reduced PDIV at higher temperatures at 0.1 Hz and 1 Hz for the Group A bars is governed by the complex permittivity presented in Fig. 3 used in (2). The complex permittivities for both Group A and B samples are comparable. It is, therefore, interesting to observe a totally different temperature-dependent PDIV as the Group A samples follow the expected temperature dependencies based on dielectric response and (2), while the Group B samples do not follow the same trend.

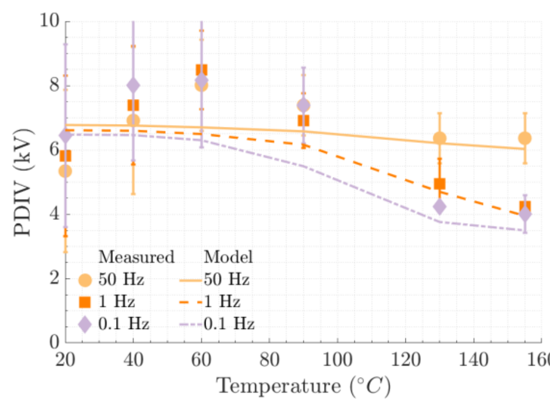


Fig. 11: PDIV according to (2) for Group A with measured complex permittivity. The void gap distance is set to 0.5 mm.

Several different mechanisms may have led to the observed different trends in PDIV. First of all, the voids in Group A are larger than for Group B, as seen in the micrographs in Fig. 9 and Fig. 10. The voids are located within the mainwall insulation for Group B samples but adjacent to the copper conductor strands for Group A. The latter is likely because of poorer resin impregnation in Group A. Delaminations are seen in both groups in the mainwall insulation. The smaller voids can also be assumed enclosed, in which the pressure rises with temperature, according to ideal gas law (resulting in about 1-2 kV increase in PDIV at 155 °C). This is not sufficient to explain the increased PDIV, as a smaller void gap distance is required for sufficiently increasing the PDIV, as shown in Fig. 12. For a sufficient fit, the void gap distances must decrease by 5 % at 90 °C, 20 % at 130 °C, and 35 % at 155 °C to be able to fit measured values, which doesn't seem reasonable because a much higher thermal expansion than what is for copper and insulation on a macroscopic level (< 1 %) is needed. It is therefore not possible to claim any single mechanism responsible for the increase in PDIV for Group B, but the correlating observed and estimated trends indicate that there is a decreasing void resistance with temperature, in accordance with Arrhenius, and a quenching of the voids as the temperature increases.

Another possibility is that some voids are quenched by a low resistance at different voltage levels. This can result in an increased PDIV as new voids with a higher PDIV act as PD sources and thus govern PDIV for the complete insulation system. Then the main difference between the groups is that the voids in Group A are not short-circuited at increasing temperatures, whereas the voids in Group B are gradually short-circuited with a distribution of voids with different PDIV. The voids with the lowest PDIV seem to be short-circuited before the voids with higher PDIV.

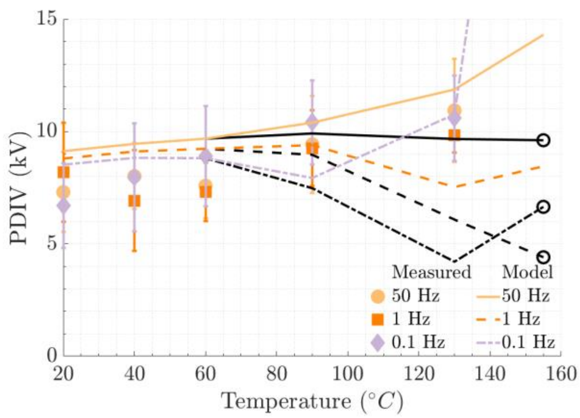


Fig. 12: PDIV according to (2) for Group B with complex permittivity. The void gap distance is 0.1 mm. Here, the pressure increased with temperature in line with ideal gas law. The void conductivity was chosen to be $3 \cdot 10^{-16}$ S/m at 20 °C with an activation energy of 0.9 eV, black curves with a circle at 155 °C. The colored curves include a reduction in void gap distance of 5 % at 90 °C, 20 % at 130 °C, and 35 % at 155 °C.

B. The measured apparent charge magnitude

The cross sections in Fig. 9 and Fig. 10 illustrate that there are many small voids inside the mainwall insulation of the stator bars. The observed apparent charge magnitude distribution in Fig. 6 seems, therefore, reasonable. However, the total apparent charge is linear with voltage above the PDIV. This is not expected, as this requires that the voids inside the insulation have the same PDIV and a constant void capacitance discharge as a function of voltage. This is not in line with the extended abc-model as the maximum apparent charge as a function of voltage is strictly increasing, thus indicating larger and larger voids are activated when the voltage increases – and would require further work to prove.

The temperature dependence of the maximum apparent charge (Fig. 7) and total apparent charge per period-volume (Fig. 8) are inversely proportional to the PDIV, thus dependent on the void voltage and available electrical energy stored in the voids, as described in (7) and (8). The frequency-independent total apparent charge per period volume for the Group B bars indicates that voids must decrease in size, either physically or by means of short-circuiting, due to sufficiently higher surface conductivity at higher temperatures. For the Group A bars, the total apparent charge per period volume is frequency independent between 1 Hz and 50 Hz below 90 °C. The apparent charge magnitude at 0.1 Hz is much lower than at higher frequencies. The low apparent charge magnitude at 0.1 Hz might originate from a relatively low void resistance that partly short-circuits the voids but is not sufficient to completely avoid ignition in some voids. The high increase in apparent charge magnitude at 1 Hz can be explained by the strong increase in dielectric losses, in which a larger portion of the applied voltage is across the void.

The significant increase can be related to the increase in complex permittivity; thus, a higher fraction of the applied voltage is across the void. This enables more PDs to occur within the same period. If this were the case, then the total apparent charge at 0.1 Hz would be very high, which is not the case. This might be explained by using (2) for the idealized void by a decreased non-measurable void resistance at higher temperatures that, to a larger extent, quenches the void voltage, which is then more influential at 0.1 Hz than at 1 Hz.

C. Implications for condition assessment

The objective of this work is to investigate if off-line VLF PD measurements are applicable as a condition assessment method probing PD-activity for hydro generators since this will make PD measurements easier to perform and more cost-effective. The measured PD activity at VLF must be representative and/or translatable to PD activity during service for accurate assessment. It is here found that PD parameters relevant for condition assessment vary with voltage frequency and temperature. Further, the temperature dependencies are also the opposite for the two insulation systems tested. Many samples from each group have been tested, and trends are consistent within the group.

PDIV:

- For Group B, PDIV increases with temperature, as expected. There is little difference between 0.1, 1, and 50 Hz, and VLF is thus representative at all temperatures.
- For Group A, PDIV decreases with temperature. For temperatures above 90 °C, the decrease is significantly larger for 0.1 and 1 Hz compared to 50 Hz. VLF is representative below 90 °C.

Apparent charge and derived quantities

- For Group B, the maximum and total apparent charge per period decrease with temperature, and there is no significant frequency dependency. VLF is representative.
- For Group A, there is a slight increase in maximum and total apparent charge per period with temperature. VLF is representative of the maximum apparent charge up to 60 °C but not the total apparent charge per period volume, which has a much lower value at VLF.

Global dielectric properties, such as complex permittivity (tan δ) and DC conductivity, are similar for both bar groups. It is, therefore, not likely that global dielectric properties can explain the differences in the PD activity.

From a study of load-cycling of RR and VPI bars from the seventies, it was found that RR bars had more delaminations than VPI bars [23]. A difference in void size/shape and how temperature affects these dimensions as a function of temperature can thus be an explanation for the opposite temperature dependencies seen between Group A and Group B.

VLF is representative for Group B bars, but care must be taken for the Group A bars according to the results in this work. More work is thus needed on representative insulation systems, both production process and manufacturer, as much development has been done in the last decades. One way forward is by performing load cycling studies to investigate the dynamics of temperature change in a larger group.

VI. Conclusions

The tests revealed that the two tested bar groups have the opposite frequency dependency of PD behavior in some cases. While the PDIV of tested Group A bars at 0.1 Hz decrease with temperature and at 50 Hz is temperature independent, PDIV for all frequencies for tested Group B bars increase with temperature. For the maximum and total apparent charge per period, the opposite temperature dependency was seen. The implication of this is that a direct comparison of PD parameters at VLF and PLF cannot be made for all machines without considering temperature when measurements are performed on insulation systems. If a new regime of condition assessment is implemented by applying VLF PD measurements, trending of relevant parameters could be undertaken as for conventional PLF PD measurements. The strength of condition assessment by VLF PD measurements is the compact measurement setup and affordability, which should make it possible to extend the use of PD measurements as a low-cost alternative on hydro generators and other rotating machines. An improved condition assessment can also be performed at an extended frequency range and at different temperatures to extract more information from PD measurements. Also, further research on characterizing voltage-frequency dependency on other common defects in stator bars is needed.

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