Condition Assessment of Hydrogenerator Stator Bar Insulation using Partial Discharge Measurements

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***Abstract*—This paper presents results from laboratory measurements of partial discharge (PD) activity in 50 cm long samples cut from the mainwall section of old hydrogenerator stator bars. All stator bars were manufactured in 1976 and samples were taken after 35 years in service from both the low and high voltage sections of the generator, as well as non-energized back-up bars. The PD activity, using a phase resolved (PRPDA) measuring system, was investigated at different test voltages up to 9.6 kV (1.5 U_0), frequencies and temperatures in the range 20-155 °C and 0.1-50 Hz, respectively. The service-aged and the unaged reference samples showed a clear difference in voltage frequency dependence. It was, however, not possible to distinguish between service-aged bars from high and low electric stress. The observed frequency and temperature dependences are discussed with respect to theoretical assumptions regarding possible void degradation and surface conductivity.**

Keywords— Hydropower, partial discharges, variable voltage frequency

I. Introduction

Condition assessment of hydrogenerator stator bars, based on detection of changes in partial discharge (PD) activity are performed either as online or offline measurements. During PD-testing of installed generators, the temperature varies with the current load or time after shutdown. It is usually beneficial to perform offline PD tests at low frequency (0.1 Hz) due to the large capacitance in the generator windings, keeping the test equipment small. Although, several standardized test procedures are available [1-3] it is unclear how PD results obtained at 0.1 Hz relate to results measured at 50 Hz, see e.g. [4, 5].

One example of results from trend analysis of online PD monitoring is given by Bélec et al. [6]. In case of large change in PD characteristics, a more detailed examination of the generator revealed the presence of slot discharges. Based upon this, it was decided to rewind the generator. In case of considering and comparing the quality of large number of generators, statistical analysis of PD measurements are used to locate the critical generators suggested for further more detailed investigations [7]. An alternative approach is to use measured phase resolved PD signatures (PRPDA) to build a database of possible PD sources, for example Hudon et al. [8].

The main purpose of this paper is to examine experimentally, how PD features change with applied voltage frequency and temperature and examine if the variable voltage frequency PD technique can be used as a diagnostic tool for stator bars.

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II. Theory regarding Void Discharges

PDs occur when the voltage across voids exceeds its threshold value and a starting electron is available. This means that the PD inception voltage strongly depends on void shape, size and availability of starting electron. Charge is deposited during a PD, opposing the applied field.

The apparent PD charge q_a, which can be measured by an external circuit, can approximately be expressed as

$$q_a = b \cdot \Delta U \qquad (1)$$

where b according to the well-known abc equivalent of the test object is the insulation capacitance in series with the void. It is assumed that the test object capacitance, a, is much larger than the void capacitance. ΔU is the voltage change across the void during the PD occurrence.

In order to consider possible effects of testing at low frequencies the deposited charge q_i is here considered to decay exponentially

$$\frac{\mathrm{d}q_i(t)}{\mathrm{d}t} = -\frac{1}{\tau} q_i \qquad (2)$$

where τ is a time constant given by

$$\tau = \frac{\varepsilon}{\sigma} \qquad (3)$$

where σ is the resulting apparent conductivity and ε the permittivity.

A statistical time lag influence the voltage ΔU and is more pronounced at higher frequencies, where a certain delay before initiation gives a PD at a higher voltage. The influence of statistical time lag on frequency behavior is e.g. described in the experimental and numerical work in polycarbonate by Forssén et al. [9]. Here a statistical time lag in the millisecond range was used to describe an increase in PD magnitude with applied voltage frequency.

In case of varying the frequency of the applied voltage, three different cases may occur:

I. The time constant is much smaller than the voltage half cycle. Deposited charge decay fast.

II. The time constant is at the order of the voltage half cycle. Deposited charge decay to some extent and is frequency dependent.

III. The time constant is much larger than the voltage half cycle. Deposited charge do not decay.

The PD repetition rate is limited by how fast the void voltage is restored. This means that a higher PD repetition rate is expected in case I than in case II than in case III. The frequency dependence is however expected to be the same, a decreasing PD repetition rate with increasing frequency.

The PD magnitude is, according to equation (1), dependent on a voltage difference and a capacitance. If the complete void participates in the PD, i.e. b constant, then the only factor influencing the PD magnitude is the voltage ΔU. This means that all three cases should have PD magnitude increasing with increasing frequency that are at the same level.

According to equation (3), the time constant is inversely proportional to the resulting conductivity, which is commonly assumed to increase with temperature following Arrhenius law

$$\sigma \propto e^{-\frac{E_\mathrm{a}}{k_\mathrm{B}T}} \quad (4)$$

where E_a is the activation energy, k_B the Boltzmann constant and T the temperature in Kelvin.

It is reasonable to assume that the rate of degradation caused by PD activity is proportional to the PD energy dissipated. Therefore, the PD power P is here presented to facilitate comparing results from test objects differently aged; calculated according to

$$P = \frac{1}{\Delta t}\sum_{\mathrm{i}} U_\mathrm{i} \cdot q_{\mathrm{a,i}} \quad (5)$$

where Δt is a reference time creating either per period or per time unit and U_i is the momentary voltage at the time instant the PD of apparent measured charge $q_{\mathrm{a,i}}$.

III. Methodology

A. Test samples

All 50 cm long test samples were cut from the main-wall insulation of old hydrogenerator stator bars (U_0 = 6.4 kV), manufactured in 1976 and taken after 35 years in service. Three samples were taken close to HV terminal, three samples close to neutral terminal and three samples were non-energized back-up bars.

The bars were insulated by mica paper tape with non-woven glass reinforcement, PET film and polyester binder. The 50 cm long test objects had a resulting capacitance of about 400 pF. The surface of 12 cm at each end was painted with end corona protection, CoronaShield P8001, to reduce the electric field and prevent external PDs at the terminations.

B. Measuring principle and test procedure

The test setup consisted of a standard PD detection circuit, schematically shown in Fig. 1, consisting of a measurement impedance, Z, Omicron CPL 542A in series with a coupling capacitance, C_C, of 3.4 nF. The samples were clamped between grounded copper plates to simulate the stator slot.

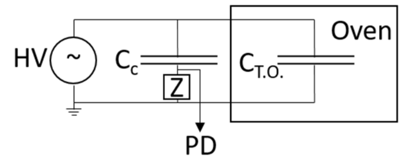


Fig. 1: Test setup. The circuit is fed by a high voltage variable frequency generator, TREK. The coupling capacitance is in series with the measurment impdence Z. The test object $C_{\mathrm{T.O.}}$ is placed within an oven.

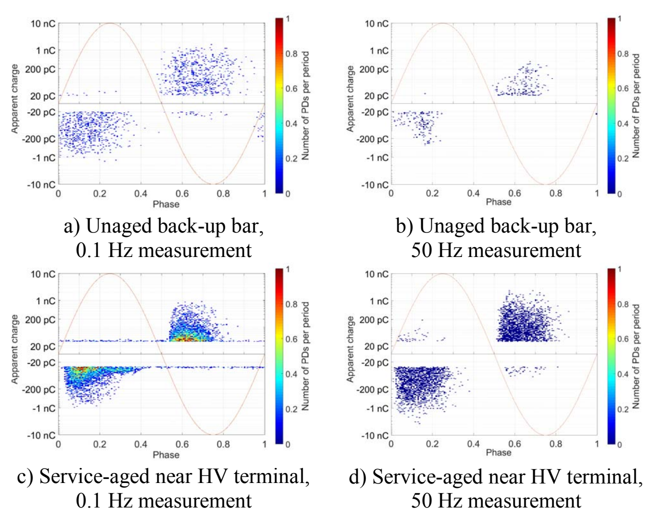
The bars were initially electrically stressed at the maximum test voltage of 9.6 kV (1.5 U_0, where U_0 is the line voltage of 6.4 $\mathrm{kV_{RMS}}$) for 5 minutes at power frequency (50 Hz) as suggested in IEEE std 1434 [3]. During PD testing the voltage was increased from zero voltage to 1.5 U_0 in voltage steps of 0.15 U_0. The voltage was kept constant at each step for the longest of either 10 s or 10 periods. This procedure was immediately repeated for all frequencies, in decreasing order to 0.1 Hz, with the conditioning period reduced to 5 s. The conditioning period also served as a test to control if results from 50 Hz energizing changed during the frequency sweep.

An automated computer controlled test equipment was developed to facilitate PD measurements as a function of voltage magnitude, applied frequency in the range 50 - 0.1 Hz and temperature in the range 20 - 155 ˚C.

During a voltage step, the average of the 10 largest apparent discharges, above a threshold of 20 pC, was noted as the maximum apparent charge. This was done to reduce the influence of noise and large single-occurring PDs. Mean values and error bars in the figures are based on three similar samples per data point.

IV. Results and Discussion

All tested stator bars were produced for the same hydropower generator and it is reasonable to assume that they



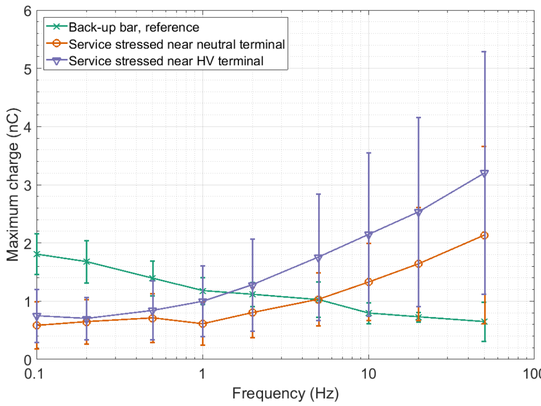
a) Unaged back-up bar, 0.1 Hz measurement

b) Unaged back-up bar, 50 Hz measurement

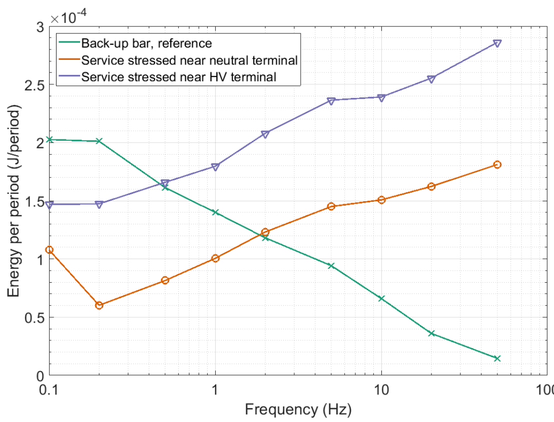
c) Service-aged near HV terminal, 0.1 Hz measurement

d) Service-aged near HV terminal, 50 Hz measurement

Fig. 2: PRPDA for 10 periods for back-up bars and in-service-aged bars from near HV terminal measured at U_0. Measured at both 0.1 Hz and 50 Hz. Normalization of PD numbers to PDs per period. The integration settings are in the time domain. ±100ns.

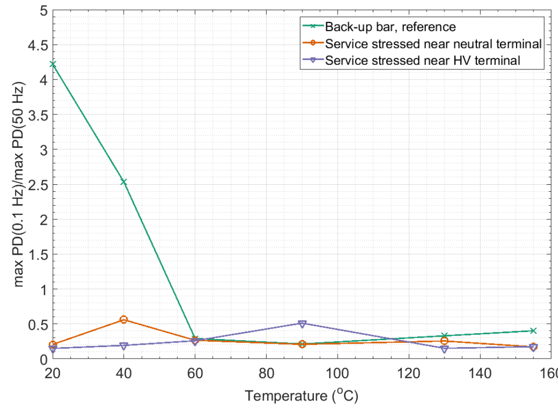


a) Maximum charge

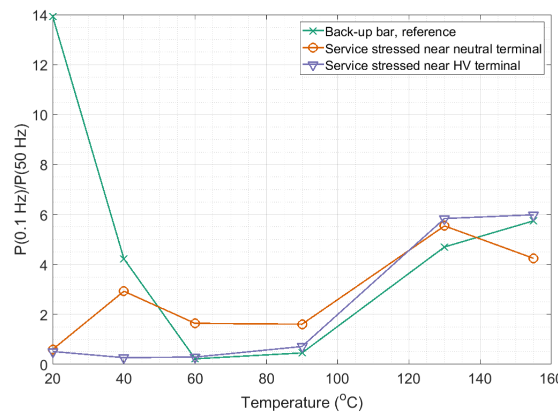


b) Average dissipated energy per period. ERRORBARS are not included because the standard deviation for service aged bars are 100 % and 20 % for the back-up bars.

Fig. 3: Measurements of maximum charge and dissipated energy per period measured at 20 ˚C at U_0.



a) Ratio of maximum charge at 0.1 Hz and 50 Hz



b) Ratio of dissipated energy (P) per period at 0.1 Hz and 50 Hz

Fig. 4: Ratios of measured dissipated energy and maximum charge versus temperature measured at U_0.

were originally similar. Differences must therefore have been introduced during service. Typical PRPDA figures, measured for 10 periods at U_0 and 0.1 Hz and 50 Hz, are shown in Fig. 2. The PRPDAs are symmetric in the polarity, showing internal PDs, and there are more PDs per period at 0.1 Hz than at 50 Hz, as expected. The service-aged bars have more PDs per period than the back-up bars, indicating a higher conductivity as described in the presented cases in the theory section. This indicates that the conductivity has increased during service.

The overall shape of the PRPDA at both 0.1 Hz and 50 Hz are comparable. Measurements at 0.1 Hz energize a larger area due to the field grading paint at the ends of the bar. This is however considered insignificant. Differences were seen between the service-aged and unaged samples. No significant differences were observed between service-aged samples near neutral or HV terminal.

A. Applied frequency dependence,

Results presented in Fig. 3 show the maximum PD charge and dissipated energy per period as function of frequency. The magnitude of the apparent PD charge for the service-aged samples increase with frequency, in good agreement with the presented theory. The dissipated energy is a combined number, dependent on repetition rate and magnitude. Low frequencies give many small PDs and higher frequencies give larger PDs, but fewer. It is therefore reasonable that the dissipated energy increases with frequency, as seen here with the mean value.

The unaged back-up bars were found to have a decreasing PD magnitude with increasing frequency. The dissipated energy is also decreasing with increasing frequency. This is not in accordance with the presented theory. One important assumption in the theory section was that the capacitance *b* is constant for all frequencies. It seems that the discharging area of the voids in the unaged back-up bars is frequency dependent. A larger area is discharged at lower frequencies than at higher frequencies.

B. Test temperature dependence

The graphs presented in Fig. 4 show the ratio of the maximum charge and dissipated energy per period. The ratio is found by dividing the value at 0.1 Hz by the value at 50 Hz. This is a compact method to describe the trends presented in Fig. 3 as function of temperature.

All samples show the same trend as function of frequency when the temperature is above 60 ˚C. PD magnitudes at 50 Hz are larger than at 0.1 Hz for all samples, but the ratio between them varies. The same is valid for dissipated energy, but with values at 0.1 Hz larger than at 50 Hz. The presented theory is valid for this temperature range. The back-up bars differ significantly from the service-aged bars below 60 ˚C where the values at 0.1 Hz are larger than at 50 Hz and the presented theory cannot explain this.

The dissipated energy per period above 90 ˚C is significantly larger at 0.1 Hz than at 50 Hz. This might be related to a very high conductivity at high temperatures, as described in equation (4). This gives a low time constant that allows deposited charges to decay almost instantaneously and a high PD repetition rate occurs.

The service-aged bars close to neutral terminal have a higher mean dissipated energy per period at 0.1 Hz than at 50 Hz at all temperatures. The bars close to HV terminal have a higher dissipated energy per period at 50 Hz than at 0.1 Hz below 100 ˚C, indicating a possible difference between service aging with and without voltage stress.

C. Applied voltage dependence

Maximum PD magnitude as function of applied voltage at 20 ˚C and 60 ˚C for the back-up bars is presented in Fig. 5. Which frequency that gives the highest PD magnitude is dependent on the applied voltage. There is no difference between PD magnitude at 0.1 Hz and 50 Hz below 4 kV. This statement is also valid for the service-aged bars.

Above 7 kV, the PD magnitude at 0.1 Hz becomes temperature independent, whereas the 50 Hz values differ significantly as function of temperature. The PDIV is lower at 20 ˚C than at 60 ˚C, indicating that the void conditions are changed at different temperatures.

D. Sample differences

The observed difference in maximum PD magnitude and dissipated energy indicate that the void conditions of the unaged and service-aged samples are different. These differences could originate in various void types or void degradation due to service ageing. The large spread (up to 100 %) for the service-aged bars makes it difficult to distinguish between samples from high and low voltage. This might however indicate that thermal ageing is more dominant than electrical ageing.

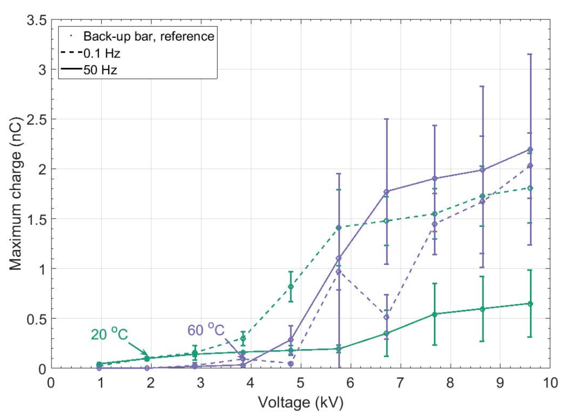


Fig. 5: Maximum charge for the back-up bar as function of applied voltage, measured at 20 ˚C and 60 ˚C at both 0.1 Hz and 50 Hz.

The back-up bars show a lower spread in the results than the service-aged bars. This might indicate that the service ageing of the insulation is not the same in the whole generator. It is however possible to distinguish between the service-aged bars if neglecting the spread in the results. Then, the bars from close to HV terminal produce higher PD magnitude and dissipates more energy per period. This might be a possible difference between the service-aged bars, but a much larger population than three samples must then be tested to reduce the spread and make a conclusion.

V. Conclusion

1. Based upon PD-measurements, it is possible to distinguish the service-aged bars from the back-up bars using their maximum apparent charge and dissipated energy as function of voltage frequency and magnitude.
2. No significant difference in PRPDA was observed between service-aged bars exposed to low and high voltage for 35 years.
3. Frequency sweeps give valuable information that is not revealed testing at one voltage frequency only.

Acknowledgment

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References

[1] IEC TS 60034-27:2006, Off-line partial discharge measurements on the stator winding insulation of rotating electrical machines, 2006.

[2] IEEE Std 433-2009 (Revision of IEEE Std 433-1974), IEEE Recommended Practice for Insulation Testing of AC Electric Machinery with High Voltage at Very Low Frequency, 2009.

[3] IEEE Std 1434-2014 (Revision of IEEE Std 1434-2000), IEEE Guide for the Measurement of Partial Discharges in AC Electric Machinery, 2014.

[4] C. Forssen and H. Edin, "Partial discharges in a cavity at variable applied frequency part 1: measurements," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 15, no. 6, pp. 1601-1609, 2008.

[5] A. Cavallini and G. C. Montanari, "Effect of supply voltage frequency on testing of insulation system," IEEE Transactions on Dielectrics and Electrical Insulation, Conference Paper vol. 13, no. 1, pp. 111-121, 2006.

[6] M. Bélec, C. Hudon, C. Guddemi, and D. N. Nguyen, "A case study of condition-based maintenance of a 202-MVA hydro-generator," in Proceedings of 2008 International Conference on Condition Monitoring and Diagnosis, CMD 2008, 2008, pp. 163-166, 2008.

[7] C. Hudon, N. Amyot, M. Levesque, M. Essalihi, and C. Millet, "Using integrated generator diagnosis to perform condition based maintenance," in 33rd Electrical Insulation Conference, EIC 2015, pp. 341-345, 2015.

[8] C. Hudon and M. Bélec, "Partial discharge signal interpretation for generator diagnostics," IEEE Transactions on Dielectrics and Electrical Insulation, Article vol. 12, no. 2, pp. 297-319, 2005.

[9] C. Forssen and H. Edin, "Partial discharges in a cavity at variable applied frequency part 2: measurements and modeling," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 15, no. 6, pp. 1610-1616, 2008.