Comparison of Offline VLF PD Measurements and Online PD Measurements on a 50-year-old Hydrogenerator stator in Norway

Espen Eberg
Dept. of Electric Power Tecnology
SINTEF Energy Research
Trondheim, Norway
espen.eberg@sintef.no

Torstein Grav Aakre
Dept. of of Electric Power Engineering
Norwegian University of Science and Technology
Trondheim, Norway
torstein.aakre@ntnu.no

Gunnar Berg
Dept. of Electric Power Tecnology
SINTEF Energy Research
Trondheim, Norway
gunnar.berg@sintef.no

Sverre Hvidsten
Dept. of Electric Power Tecnology
SINTEF Energy Research
Trondheim, Norway
sverre.hvidsten@sintef.no

***Abstract*— Stator winding insulation is the part of the hydrogenerator experiencing the highest number and the most damaging failures. Partial discharge (PD) measurement, both offline and online, are commonly used for condition assessment and monitoring of electrical machines. The main concern of using very low frequency (VLF) methods is the changed electrical field distributions compared to that at power frequency. Hence, PD measurements performed at VLF should be carefully assessed and compared to PD measurements at power frequencies. In this work, offline PD measurement at VLF are presented and compared to power frequency online measurements of a 50-year-old hydrogenerator in Norway, using statistical analysis of phase resolved PD recordings. It is found that both offline VLF and online assessment can identify unnormal PD activity in a specific phase, although the phase resolved PD patterns are not similar for VLF offline and online assessment.**

Keywords — Hydrogenerator, stator insulation, condition assessment, partial discharges, very low frequency (VLF)

I. Introduction

The total installed capacity of larger hydrogenerators in Norway is more than 32 000 MVA. Most of the hydrogenerators was installed from 1955 to 1995. Generally, the technical lifetime of such generators is expected to be more than 50 years dependent on type of loading and operation. A significant percentage of the population has therefore likely reached its expected lifetime. It is determined that stator insulation damages are the significantly most frequent failures and those that produce the greatest extent of damage [1]. There is therefore a need for reliable diagnostic methods to detect degradation of the insulation system of the stator bars. The development and use of reliable diagnostic techniques will likely reduce assessment uncertainty and make the condition estimate more accurate.

On-line partial discharge (PD) monitoring and testing has been performed for many decades. Recently it has also been proposed to use variable voltage frequency PD techniques to improve the on-site degradation assessment of hydrogenator stator insulation systems [2]. Very low frequency (VLF) techniques are mainly based on using 0.1 Hz, but also other frequencies can be applied in the same range (0.001-1 Hz). The technique is very attractive as only a relatively small-sized voltage source is needed to energize the complete generator during the off-line PD measurements. However, it is important to keep in mind that the voltage distribution is different at off-line measurements as the stator bars in each phase are energized at the same voltage level simultaneously, and that also the voltage distributions can be different at endwinding sections, but also close to defects where the partial discharge occurs.

The main purpose of this paper is to compare online and offline VLF PD measurements on a hydrogenerator stator winding in Norway being more than 50 years in service. The measured data at 0.1 Hz and 50 Hz are compared using statistical shape analysis of resulting phase resolved PD (PRPD) patterns. Such analysis can be useful to determine the type of PD source [3].

II. Methodology

A. Test object

In this work a U_N = 13 kV line voltage (U_0 = 7.5 kV phase to ground), 95 MVA hydrogenerator installed in 1965 have been assessed. The stator bar high voltage insulation system is *Micadur*, which is a mica paper tape with glass-fibre backing [4].

B. Offline condition assessment

Offline PD measurements were performed in compliance with standards IEC 60034-27-1 and 60270 [5, 6]. A 0.1 Hz VLF source, connected in series with a lowpass filter, was used to generate the 0.1 Hz sine wave. The VLF source was connected to the LV terminal at the neutral point side, whereas PD data was recorded using a 5 nF coupling capacitor and PD monitoring system connected to the HV terminal. The pulse amplitude was normalized applying a 500 pC pulse at the HV terminal. The amplitude-spectrum was integrated with centre frequency f_c = 250 kHz and bandwidth δf = 300 kHz. The

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stator windings were tested separately, with the two other windings grounded in one end during testing.

C. Online condition assesment

For online monitoring 1 nF coupling capacitors were connected to the HV buses after the circuit breakers close to the transformer. Otherwise, online PD monitoring followed IEC TS 60034-2 [7]. A three phase PD monitoring system was used for recording PD data. Integration of the amplitude-spectrum was alternated between f_c = 5 MHz, δf = 1.5 MHz and f_c = 250 kHz, δf = 300 kHz using the same normalization factor.

The stator temperature was logged during both offline and online assessment.

D. Shape analysis of partial discharges

Two phase distributions were calculated based on the recorded PRPD patterns:

a) $H_n(\varphi)$: phase distribution of number of discharges

b) $H_{qn}(\varphi)$: phase distribution of mean discharge amplitude

The shape of these distributions has been found to be characteristic for the type of PD source [3]. To quantify the shape of the distributions, skewness (*Sk*) and kurtosis (*Ku*) have been calculated, which are the third and fourth statistical moments of the distributions, respectively. *Sk* is positive (negative) for a leftward (rightward) shift of a Gaussian distribution, and *Ku* is positive (negative) for a pointier (flatter) distribution compared to a Gaussian distribution. These parameters have been used for quantitative classification of PD sources in e.g. artificial defects [3, 8] and turbogenerators [9, 10].

In addition, qualitative comparison of obtained PRPD patterns with literature [11], which contains PRPD patterns recorded from artificial PD sources relevant to hydrogenerators, have been performed.

III. RESULTS

A. Offline assessment

PD inception voltage (PDIV) was found to be 6 kV for all three phases. The normalized trend of maximum apparent charge and repetition rate are shown in Fig. 1 (a) and (b), respectively. The maximum charge for L2 is higher for all voltage levels compared to L1 and L3. For L3, both maximum charge and repetition rate is more sensitive to the voltage, compared to L1 and L2. The stator temperature during offline assessment was 40 ºC.

In Fig. 2, unipolar PRPD patterns are shown for all phases at U_0 (7.5 kV) and 1.5 U_0 (11.3 kV). L1 and L3 have similar characteristics, whereas in L2 there are additional discharges with high amplitude in both half cycles, marked with red circles. The additional discharge activity is especially pronounced at U_0, since these additional discharges have significantly higher magnitude than the main group of discharges common in all three phases.

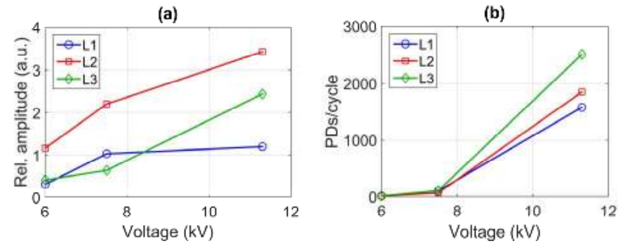

Figure 1: (a) Relative charge amplitude and repetition rate as function of applied voltage for offline assessment.

Ku and *Sk* as function of applied voltage for $H_n(\varphi)$ and $H_{qn}(\varphi)$ are shown in Fig. 3. The distributions have superscript (+) for the positive half cycle, and (–) for the negative half cycle. *Ku* and *Sk* for phase L2 deviate from L1 and L3 with a knee at U_0 for $H_n^+(\varphi)$ and have peaks at U_0 for both half cycles in $H_n(\varphi)$ and $H_{qn}(\varphi)$. This is in correspondence with the PRPD pattern for phase L2 in Fig. 2: Additional discharges near the zero crossings gives an leftward asymmetry and more pointy shape.

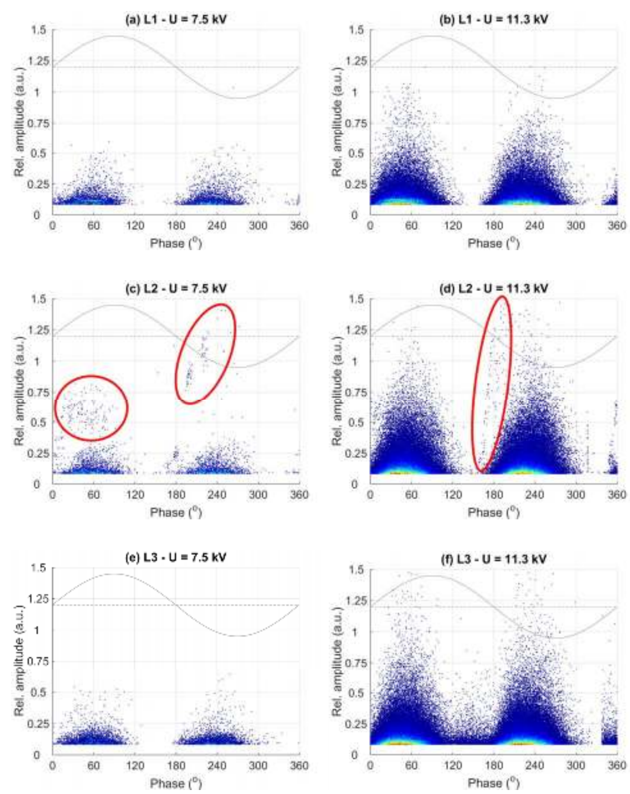

Figure 2: VLF PRPD patterns for (a-b) L1, (c-d) L2 and (e-f) L3.

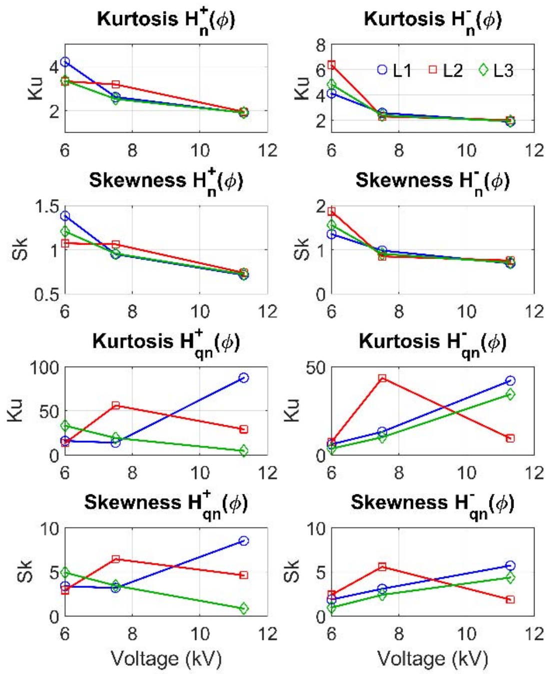

Figure 3: Skewness and kurtosis as function of voltage for offline assessment.

B. Online assessment

PRPD patterns for online PD monitoring is shown in Fig. 4. For measurements acquired within the kHz (IEC) range, Fig. 4 (a, c, e,), the power electronic switching interference originating from the generator excitation system is gated out, marked as grey regions. No electrical interference from the generator excitation system was detected using the MHz-band for PD recording, as seen in Fig. 4 (b, d, f). The stator temperature during online assessment was in the range 68 °C to 72 °C.

Since all three phases are excited during online assessment, there will be crosstalk of the PD-signals between phases, and PRPD patterns for a specific phase will contain PD from the other phases. It is observed that the more peaks are present in the PRPD patterns recorded in the kHz range compared to MHz range. To separate contributions to the separate phases, the 3PARD cluster separation function in the PD recording system was used [12]. The algorithm assigns a PD signal to the phase with highest amplitude. Due to the interference in the kHz range from power electronic switching, it was not feasible to extract PD signals related to specific phases, and further results using 3PARD are concentrated on PD data recorded with MHz bandwidth.

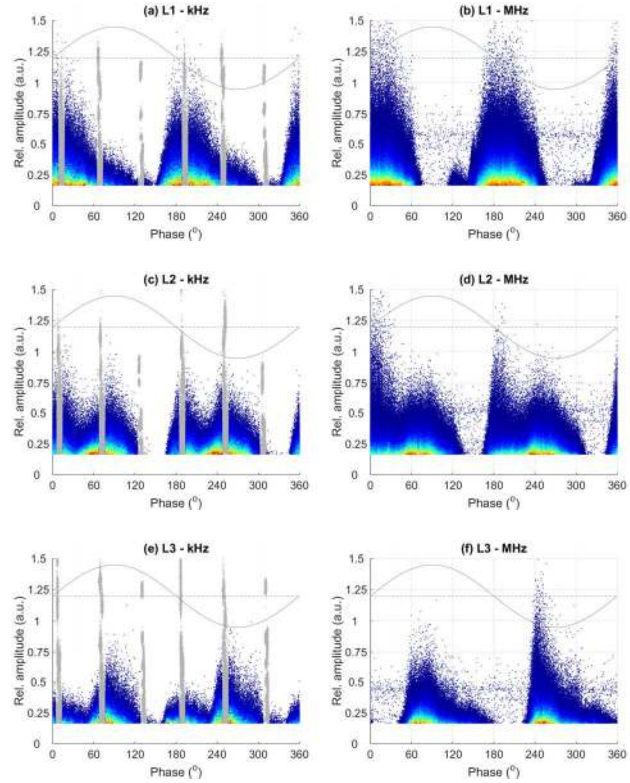

Figure 4: PRPD patterns for online monitoring. For integration bandwidth in the (a, c, e) kHz range and (b, d, f) MHz range.

In Fig. 5 (a), the axes correspond to the phases, and clusters near an axis is correlated to this phase. According to this figure, cluster 1 is correlated to phase L1, whereas cluster 2 is mainly correlated to L3, but also have a component from L2. Likewise, clusters 3 and 4 are correlated to L1 and L2. The region near the origin is attributed to noise. In Fig. 5 (b-h) the PRPD pattern for cluster 1 (L1), cluster 2 (L2 and L3) and cluster 3 and 4 (L1 and L2) are shown.

Ku and *Sk* for $H_n(\varphi)$ and $H_{qn}(\varphi)$ under operation is shown in Fig. 6 for both the unprocessed PRPD patterns in Fig. 4 (b, d, f) and processed PRPD patterns in Fig. 5 (b-h). For $H_n(\varphi)$, *Ku* and *Sk* generally have larger values for the processed PRPD patterns compared to the unprocessed PRPD patterns. There are no consistent trend for *Ku* and *Sk* in $H_{qn}(\varphi)$ in any phases.

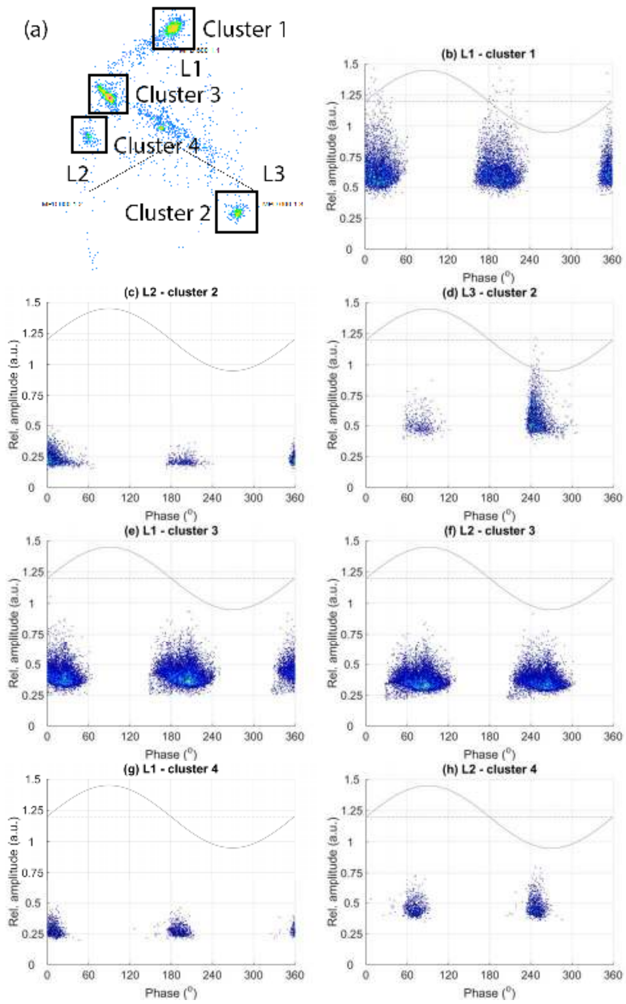

Figure 5: (a) Separation of clusters using 3PARD. PRPD patterns: (b) L1 – cluster 1, (c) L2 – cluster 2, (d) L3 – cluster 2, (e) L1 – cluster 3, (f) 2 – cluster 3, (g) L1 – cluster 4, and (h) L2 – cluster 4.

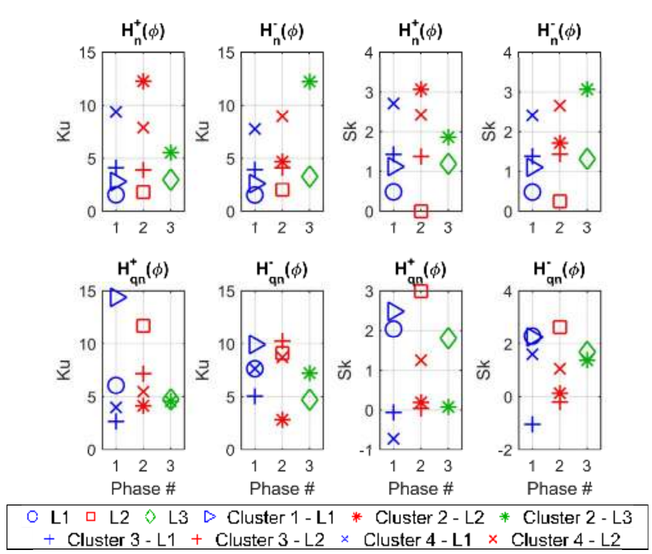

Figure 6: *Sk* and *Ku* for online assessment in the MHz region.

IV. Discussion

A. Offline assessment

Phases L1 and L3 have symmetric PRPD patterns in the positive and negative half cycles, resembling PRPD patterns of PD activity from internal voids measured at power frequency [11]. From Fig. 1, L2 has a significantly higher PD level than L1 and L3. This is also seen for U_0 in Fig 2., where large discharges are found on the leading edge of the voltage. At 1.5 U_0 the effect is less pronounced, since the additional PD activity in L2 is less voltage dependent than the common PD activity seen in all three phases. The increasing charge magnitude with voltage, and presence on both half cycles, indicate that these discharges are likely to be internal.

The *Ku* and *Sk* of $H_n(\varphi)$ and $H_{qn}(\varphi)$ in Fig. 3 show that the additional discharges in L2 are more pronounced at operating voltage than at lower and higher stresses, demonstrating higher stress not necessarily provides more information about the PD source as long as PDIV is reached. As the voltage is increased, the main discharge activity increases relatively more than the additional discharge activity in L2.

B. Online assessment

In Fig. 4, the double peaks in the PRPD patterns for each half cycle can be ascribed to crosstalk between phases for the PD signals. By comparing the PRPD patterns in the kHz and MHz region for each phase individually, the amount of crosstalk is frequency dependent. E.g. for L2, the ratio of the major peaks in the PRPD pattern are different for kHz bandwidth in Fig. 4 (c), and MHz bandwidth in Fig. 4 (d). This can indicate that the PD-sources have different location in the winding [13].

The 3PARD cluster separation function provides three distinguishable PRPD patterns for L1 to L3, as shown in Fig. 5 (b-h). By comparing to the PRPD patterns for L1 to L3 in Fig. 4 (b, d, f), and considering the 120° phase shift between phases, the amount of crosstalk between phases can be identified. The PRPD pattern of L2 is likely to be a superposition with comparable contributions from L1 and L3. Less crosstalk into L1 and L3 is observed.

The shape analysis using *Ku* and *Sk* will be less accurate, as contributions from all phases are likely to be present in each PRPD pattern. This is confirmed by the similar levels for *Ku* and *Sk* in $H_n(\varphi)$, for all phases in Fig. 6. For the processed PRPD patterns, *Ku* and *Sk* are largest for cluster 2: for $H^+_n(\varphi)$ in L2, and for $H^-_n(\varphi)$ in L3. Due to PD activity on the leading edges in L2 and the 120° phase shift between L2 and L3, the PRPD pattern for L3 is likely to be interference from L2. This indicates that L2 have a diverging PRPD pattern, in accordance with the offline VLF assessment. *Sk* in $H_n(\varphi)$ is however only slightly smaller for cluster 4 compared to cluster

2, hence care should be taken when interpreting the shape of processed PRPD patterns.

C. *Offline 0.1 Hz vs. online 50 Hz*

There are several factors that can give differences in observed PD-activity between VLF offline and power frequency online assessment:

- Offline assessment is here performed with a VLF source, compared to power frequency when in service. By applying VLF voltage, the potential distribution of the field grading materials is changed, potentially incepting PD in the end winding not present during service [14]. Also, the activity of the PD source itself can be frequency dependent, due to decay of surface of charges in the defect, and stochastic time lag for PD inception [15].
- Normally, different integration bandwidths are used for offline and online assessment, due to interference from other electrical apparatuses during online assessment. This can affect the PD signal level, and thus charge distribution in the PRPD patterns [13]. Due to electric interference in the online assessment in the kHz range, direct comparison can be challenging to perform.
- The full winding is stressed by HV during offline assessment, whereas only the part near the HV terminals are fully stressed during online assessment. For offline assessment it is thus likely that additional PD sources, if existent, are active compared to online assessment. The offline assessment may therefore activate PD activity that is not present during operation.
- In offline assessment, one phase is energized, while the other two are grounded. For online assessment, all phases are energized, and there will be crosstalk of PD signals between the phases, which alters the shape of the PRPD patterns. This complicates a direct, qualitative analysis of PRPD patterns.

CONCLUSIONS AND OUTLOOK

1. Both offline VLF and 50 Hz online PD assessment can identify unnormal PD-activity in the PRPD patterns.
2. VLF PD assessment is a valuable means for identifying the phase with diverging PD-activity, which is not intuitive due to crosstalk and PD signal damping along the winding in online assessment.
3. The effect of integration bandwidth should be further investigated for VLF PD assessment, both for probing the frequency response of the PD sources themselves – and frequency response of the winding.

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