Standardization of On-line VHF PD Measurements on Turbo Generators

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ABSTRACT

Based on field experiences on a number of different turbo-generators in the Netherlands, several fundamental and applied aspects of on-line very high frequency (VHF) partial discharge (PD) diagnostics are discussed. In particular the systematic results presented in this paper contribute to: 1. the characteristics of different on-line detection using suitable VHF sensors, 2. the methods to suppress disturbances and to distinguish between different types of discharges and 3. the interpretation of measured results to obtain knowledge about the insulation condition.

1 INTRODUCTION

The purpose of performing on-line partial discharge (PD) measurements on turbo generators is to detect possible defects in the stator insulation system, for example slot discharges and end-winding discharges. On-line very high frequency (VHF) partial discharge measurements have been performed on large generators by KEMA for several years now. The measurements have been standardized and an interpretation method has been developed.

Presently an expert is needed to interpret the results of an on-line VHF PD measurement on a turbo generator. Due to the complexity of the measured data even different experts may interpret the same results differently. Therefore standardization of on-line VHF measurements and their interpretation is needed to a certain degree before the results of on-line VHF PD measurements can be used in the maintenance program of a generator unit.

In this paper an overview is given of on-line VHF PD measurements, their complexity and their interpretation. First, the basic concept of an on-line VHF PD measurement is given and the differences between an on-line PD measurement and an off-line classic PD measurement is summarized. To perform an on-line VHF PD measurement specially designed sensors have to be installed into the insulated phase bus of the generator. There are different type of sensors, each type with its own characteristics. It will be shown that the sensitivity of different sensors highly depends on the electrical environment.

The standardized on-line VHF PD measurement and interpretation consist of a number of steps. There is the measurement itself, the identification of the partial discharges and the interpretation of the generator phase partial discharges.

3 ON-LINE VHF PD MEASUREMENT

Disturbances and noise dominate partial discharge measurements on turbo generators, when measured on-line. Kurtz et al. [1] developed the on-line VHF PD measurement technique to detect PD in hydro generators. To perform on-line VHF PD measurements a circuit is used as shown in Figure 1.
The main difference between an on-line VHF PD and an off-line PD measurements is the use of a spectrum analyzer (SA). The SA is used as an AM-demodulator at the specified frequency. Using the SA it is possible to measure the PD pattern at certain frequencies (Figure 2).

In the case of the generator in Figure 2 it is possible to detect PD at 10 MHz, whereas disturbances make it impossible to do the same at 4 MHz. There are three basic differences between interpreting the results of off-line PD and of on-line VHF PD measurements:

1. An on-line VHF PD measurement detects partial discharges in mV. It can not be used to determine the charge of the PD in nC.

2. Like an off-line PD measurement, an on-line VHF PD measurement has a lower sensitivity for PD occurring deep in the measured winding. This sensitivity dependency on PD location is higher for on-line VHF PD than it is for off-line PD measurements. The reason for this can be found in the attenuation of the PD signal while traveling through the windings of the generator. The higher the frequency, the higher the signal attenuation and the less deep the measurement technique "probes" the insulation system.

3. An on-line VHF PD measurement is performed under normal operating conditions of the generator, in which case there is a voltage gradient over the windings. This voltage gradient is not present during a normally performed off-line measurement because such a measurement is performed with the entire phase or winding at the specified voltage.

4 TYPE OF COUPLERS

On-line VHF PD measurements are performed using couplers installed in the insulated phase bus (IPB) connecting the generator with the step-up transformer. To detect PD signals three types of couplers are in use: (a) Capacitive couplers (C couplers), (b) Rogowski coils and (c) current transformers. Each type of coupler has its own characteristics. In this paper an example is given in which the differences between Rogowski coils and C couplers are investigated.

Figure 3. Location of the different on-line VHF PD couplers on the generator tested. Phase U is equipped with a C coupler, consisting of a 80 pF capacitor in series with a 50 Ω impedance. Phase V is equipped with a Rogowski coil and phase W is equipped with a Rogowski coil as well as a C coupler.
To test the difference in behavior of a C coupler and a Rogowski coil, a generator was equipped with both types of couplers. Both types were installed on an 11 kV, 55 MVA four pole generator on the outside of the generator casing, see Figure 3. To test the performance of the sensors, the following set-up was chosen: phase U was equipped with a C coupler, phase V with a Rogowski coil and phase W was equipped with both a Rogowski coil and a C coupler. This set-up was chosen to investigate the influence of coupler type and electrical geometry on the sensitivity for PD measurements.

The result of this experiment is shown in Figure 4. The C coupler allowed detection of PD in phases U and W. This was not true for the Rogowski coil. Using the Rogowski coil it was possible to detect the PD in phase W, but not in phase V. To understand why it was possible to detect the PD on phase W and not on phase V using the Rogowski coil the propagation path of the PD has been investigated. The equivalent electrical circuit for the PD propagation path for phase V is shown in Figure 5.

The shield of the cable connecting the generator with its load is not directly connected with the generator casing. Since the measurements are made at relatively high frequencies, there is an air coupling between the generator and the cable, represented by $Z_{ghk}$. This impedance $Z_{ghk}$ is very large compared to $Z_g$ and causes the current $I_h$ to be small.

<table>
<thead>
<tr>
<th>Phase</th>
<th>C coupler</th>
<th>Rogowski coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>Not present</td>
<td>Partial Discharges</td>
</tr>
<tr>
<td>V</td>
<td>Not present</td>
<td>No partial discharges detected</td>
</tr>
<tr>
<td>W</td>
<td>Partial Discharges</td>
<td>No partial discharges detected</td>
</tr>
</tbody>
</table>

Figure 4. Partial discharge patterns as measured on the C couplers and Rogowski coils on phases U, V and W. Due to the presence of the C coupler on phase W it was possible to detect partial discharges in that phase.

Figure 5. Equivalent circuit for a partial discharge. $Z_g$ is the transmission line represents the generator, $Z_{ghk}$ is the far-field coupling between generator and high voltage cable, $Z_{hk}$ is the transmission line representing the high voltage cable and $Z_L$ is the load.

Figure 6. Equivalent circuit for the propagation path of a partial discharge. $Z_g$ is the transmission line representing the generator, $Z_{ghk}$ is the far-field coupling between C coupler and high voltage cable, $Z_{hk}$ represents the high voltage cable and $Z_L$ the load of the generator.
Table 1. The five steps to perform an on-line VHF PD measurement.

<table>
<thead>
<tr>
<th>Step</th>
<th>Title</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Check Sensor</td>
<td>Check if the sensors are in working properly.</td>
</tr>
<tr>
<td>2</td>
<td>Phase reference</td>
<td>Determine the power frequency phase difference between the phase on which is measured and the power supply of the PD detector.</td>
</tr>
<tr>
<td>3</td>
<td>Frequency Spectra</td>
<td>The frequency spectra are measured on the sensor.</td>
</tr>
<tr>
<td>4</td>
<td>Selection of measuring frequencies</td>
<td>The measuring frequencies are determined.</td>
</tr>
<tr>
<td>5</td>
<td>PD Pattern measurement</td>
<td>The partial discharges are recorded and stored to provide full 3D phase reference pattern images.</td>
</tr>
</tbody>
</table>

through the Rogowski coil to be very small compared to the original PD current inside the generator. The C coupler is placed between the generator and the cable and is connected to ground at the nearest points on the generator casing. The equivalent circuit changes into that of Figure 6.

The impedance of the C coupler is much smaller than the impedance $Z_{ph}$ of the far-field coupling between the generator and the cable. Consequently the PD current through the Rogowski coil increases significantly. The PD pulse is now detectable with the Rogowski coil.

This experiment shows that, when deciding which type of coupler to use, comparing C couplers and Rogowski coils cannot be done without investigating the propagation path(s) of the PD signals. In some cases Rogowski coil couplers will have a higher sensitivity and in other situations C couplers will. Selection of the type of coupler should be done after a thorough investigation of the propagation properties of the PD in that particular setup.

Table 2. The two methods to determine the measuring frequency.

<table>
<thead>
<tr>
<th>Step</th>
<th>“Disturbance-free” environment</th>
<th>“Heavy-disturbance” environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Determine the maximums in the measured frequency spectra.</td>
<td>Measure the frequency spectrum of the background noise with an antenna.</td>
</tr>
<tr>
<td>2</td>
<td>Select the maximums occurring in all three phases.</td>
<td>Calculate the “division spectra” of the three phases.</td>
</tr>
<tr>
<td>3</td>
<td>Check if the values of the maximums are equal to each other.</td>
<td>Determine the maximums in the division spectra.</td>
</tr>
<tr>
<td>4</td>
<td>Check if the selected frequencies are caused by partial discharges or by noise.</td>
<td>Select the maximums occurring in all three phases.</td>
</tr>
<tr>
<td>5</td>
<td>Compare the selected frequencies with the frequencies of earlier measurements.</td>
<td>Check if the values of the maximums are equal to each other.</td>
</tr>
<tr>
<td>6</td>
<td>Check if the selected frequencies are caused by partial discharges or by noise.</td>
<td>Compare the selected frequencies with the frequencies of earlier measurements.</td>
</tr>
</tbody>
</table>

5 MEASUREMENT STEPS

An on-line VHF PD measurement can be split up into five steps, shown in Table 1.

1. A fraction of the power frequency voltage on the measured phases passes through the sensor. If this fraction is the same as earlier measurements, then the sensor is working appropriately.

2. Since there is a phase difference between the ac power supply and the three phases of the generator, the obtained PD pattern is phase shifted. To determine the
amount of shift, the difference in phase is determined
using an oscilloscope.

3. The frequency spectra of the sensors are measured using a spectrum analyzer.

4. To detect PD signals with a high sensitivity, the measuring frequency with the optimum signal to noise ratio has to be chosen. In some power stations the disturbance spectrum is higher than the signal spectrum. This doesn't necessarily mean that an on-line VHF measurement cannot be done. In a 3D phase-resolved PD pattern noise pulses can sometimes be identified and discarded. For selection of the measuring frequencies two methods are used. If the noise-pulses are relatively small in comparison with the PD signals the “disturbance-free” method is used. If the disturbance-pulses cannot be neglected the “heavy-disturbance” method is used. Each method can be sub-divided into several steps, see (Table 2).

The “heavy-disturbance” environment measuring selection method uses a high frequency (HF) antenna to determine the frequency spectrum of the background noise. By dividing the frequency spectra of the three phases by the spectrum measured with the antenna the division spectrum is obtained. This division spectrum could be seen as a kind of signal to noise ratio spectrum. An example of a division spectrum is given in Figure 7.

When selecting the measuring frequencies in a “heavy-noise” environment one has to remember that this method makes an incorrect assumption that there is a linear relationship between the noise pulses measured on the phases of the generator and the noise pulses measured using the antenna. The frequency selection methods shown in Table 2 do not always select the optimum measuring frequencies. Cycling through the frequency spectra by hand on the spectrum analyzer is advisable as well.

5. After the measuring frequencies are selected PD measurements are performed on the selected frequencies. The bandwidth of these measurements depends on the generator, insulated phase bus (IPB) and transformer. The bandwidth for the measurements presented in this paper is 300 kHz around the center frequency.

6 IDENTIFICATION OF PD PULSES

Compared to off-line PD measurements identifying PD from the pattern of an on-line PD measurement is relatively hard. Next to the phases own partial discharges an on-line measured PD pattern can contain more severe disturbances. Only three out of the eleven generators,
which are tested regularly, have an almost disturbance free PD pattern. The disturbances on the other nine can be divided into six groups: thyristor pulses, radio signals, corona, cross-talk, partial discharges from other HV equipment and random pulses of which the source is unknown. The interpreter of an on-line PD measurement should be able to distinguish the phase PD from these disturbances.

6.1 THYRISTOR PULSES

Figure 10 shows a thyristor distorted PD pattern, which was measured on a 300 MVA generator. The thyristor pulses shown in Figure 10 are caused by the ac/dc conversion of the rotor current. They can be thus identified because the number of pulses is identical to the number of thyristors switched during a power cycle. In our experience thyristor pulses tend to have their largest influence on VHF PD measurements below 4 MHz.

6.2 RADIO SIGNALS

At three from the eleven power plants an AM-radio signal couples into the IPB and can be received at the VHF sensors. The resulting “PD Pattern” is very distinguishable from PD, because it shows up as a band of PD in the PD pattern, see Figure 12.

6.3 CORONA

Corona has a unique PD pattern, which differs from that of generator produced PD’s. A corona pattern shows PD around the minimum and/or maximum of the power cycle and tends to have a fixed level. Corona can be identified and neglected prior to the interpretation of the generator’s own PD. An example of corona disturbance is shown in Figure 10.

6.4 CROSS-TALK

Cross talk from PD of other phases on the PD pattern of the measured phase can be recognized using the power frequency phase-shift of the cross talk. Cross talk from phase U to phase V will have a phase shift of 120°. Normally the cross talk is smaller than the phase PD. If the cross talk larger than the phases own PD level, then the start of the search should be whether propagation effects could be the cause. An example of cross talk is given in Figure 15.

Figure 10. Corona on a measured PD pattern of a 125 MVA generator with Fc = 12 MHz and BW = 300 kHz.

Figure 11. Cross-talk of partial discharges of another phase on the PD pattern of the measured phase of a 750 MVA generator with Fc = 20 MHz and BW = 300 kHz.
6.5 PD FROM OTHER EQUIPMENT

If PD are detected with an on-line PD measurement, it does not necessarily mean that they originated in the generator. In one of the eleven regular measured locations, the measured PD do not originate in the generator. It was found that the PD occur in the generator circuit breaker, which resides in the insulated phase bus between generator and step-up transformer. The measured PD pattern is shown in Figure 12.

In this case it was possible to determine the cause of the PD, was due to a loose contact.

7 REMOVAL OF NOISE FROM THE PD PATTERN

Removal of the noise from the PD pattern can be done using a filter method. The most common methods to filter out the disturbance signals from the PD pattern are: (a) an antenna measured the disturbance signals and (b) two PD couplers are used to determine if the measured pulse originated in the generator or from the net. More information about de-noising techniques may be found in [5,6,7].

8 INTERPRETATION METHOD

After identifying the generator own PD they are interpreted. The interpretation method developed classifies a generator as being in one of the following four categories:

1. Insulation is ok: No defects are detected.
2. Insulation ok? There might be a defect present in the stator insulation
3. Insulation not ok? There is a probable defect present in the stator insulation
4. Insulation not ok There is a defect present in the stator insulation

The interpretation method makes a statement about the possible presence of a defect or not. With a defect any
Degradation process is possible, which lead to a premature breakdown of the insulation system and is detectable using on-line VHF PD measurements.

If a defect is detected, further investigation has to be done to identify the defect. In some cases the type of defect can be determined using on-line PD measurement [2]. Even if the defect can be identified using the on-line PD measurements it is advisable to perform different kind of tests (off-line PD, tan δ, polarization grade, etc.) on the generator to confirm the result. This “second opinion” is needed to make sure that the normally very costly preventive action is not done in vain.

To classify the stator insulation system into one of the four categories, the decision tree shown in Figure 13 is used. This decision tree is based on three tests: pattern shape, trend analysis and phase comparison. Each test gives a “pass” (OK) or “no pass” (fails) result, which is used in the decision tree.

**8.1 PATTERN SHAPE**

Figure 14 shows the PD pattern of a stator in a healthy condition and the same stator with a defect present. The shape of the PD pattern clearly changes due to this particular kind of defect. Different kinds of defects have different kinds of PD pattern shapes [4].

The interpreter of the measurement has to decide if the PD pattern is that of a healthy insulation system or not. This test is the most important of the three tests and also the most subjective. Different interpreters interpret the PD pattern shape differently. Several algorithms are available, which predict on the basis of the PD pattern shape what kind of defect is present. These algorithms work well under controlled laboratory experiments, where no disturbances are present. Using them on generator field measurements is less successful, due to disturbances and the sometimes low signal to noise ratio.

**8.2 TREND ANALYSIS**

Performing on-line VHF PD measurements on a regular basis makes it possible to perform trend-analysis of the PD level. A sudden and permanent change in PD level could indicate a defect is present or a “sleeping” failure mechanism has become active. Trend analysis of the level of off-line measured partial discharges has been used successfully for the past decades.

The load and temperature of a generator influence the measured PD level, an example of the load influence on the PD activity was given by Binder et al. [3]. For optimum results the on-line VHF PD measurement should be carried out under equal circumstances. In reality this is hard to obtain, since it could be very costly to adjust the power generated.

An example of a trend analysis is shown in Figure 15. The figure shows the VHF PD-level at 30 MHz and 50 MHz on a 170 MVA generator from 1995 until 2000. This figure shows the characteristic behavior of the VHF PD-level due to changes in operating conditions. To determine if a defect is present, the PD-level should be outside the standard deviation of the average PD-level. For this stator winding, these calculations are given in Table 3. If the PD-level is outside the standard deviation interval for more than 50% of the frequencies without a known cause, then the generator fails this test. A known cause could be that the generator is operating under very different operating conditions compared to earlier measurements, for example under zero load conditions.

**8.3 PHASE COMPARISON**

For off-line PD measurements the PD levels and patterns of the three phases are often compared. This is done based on the assumption that most defects occur on a single phase of the generator and not on all three at the same time or to the same extent. An example of this is given in [14].

To illustrate how a phase comparison test is performed the measurements on a 125 MVA generator are used as an example. The PD-levels of the three phases of this generator are shown in Table 4. It is expected that a generator in a good condition has an equal PD level for each phase. Normalizing the PD-Level of each phase per frequency gives the following results:

<table>
<thead>
<tr>
<th>Frequency</th>
<th>PD-Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 MHz</td>
<td>38 dBm</td>
</tr>
<tr>
<td>50 MHz</td>
<td>44 dBm</td>
</tr>
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<td>44 dBm</td>
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</table>

# Table 3: Average PD-level, the standard deviation and the relative measurement error of the VHF PD-Level of the generator.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>Relative Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 MHz</td>
<td>-38 dBm</td>
<td>5 dBm</td>
<td>13%</td>
</tr>
<tr>
<td>50 MHz</td>
<td>-44 dBm</td>
<td>4 dBm</td>
<td>9%</td>
</tr>
</tbody>
</table>
Table 4. PD-Level as measured on different frequencies and phases of a 125 MVA generator.

<table>
<thead>
<tr>
<th>Freq</th>
<th>Phase U</th>
<th>Phase V</th>
<th>Phase W</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 MHz</td>
<td>1.2 mV</td>
<td>1.3 mV</td>
<td>1.8 mV</td>
</tr>
<tr>
<td>30 MHz</td>
<td>300 µV</td>
<td>250 µV</td>
<td>430 µV</td>
</tr>
<tr>
<td>50 MHz</td>
<td>130 µV</td>
<td>110 µV</td>
<td>90 µV</td>
</tr>
</tbody>
</table>

Frequency will show a 33% contribution of each phase to the total amount of PD. By averaging the contribution of the phases for different frequencies the error in the measurements is considerably improved. For the measurement shown in Table 4 this will result in Table 5. If the deviation of the average of one of the three phases is larger than 8%, then the generator does not pass this test. Using the values from Table 4, normalizing the PD-Levels and consequently calculating the averages over the three phases provides Table 5. No phases have a larger difference than 8%, the largest is 5%, and thus this generator passes this test.

9 INFLUENCE OF PROPAGATION ON INTERPRETATION

Propagation effects have a major influence on VHF PD measurements [5]. They are the main cause for an incorrect result for the third test, phase comparison. If the geometry of the three phases of a generator is not identical, the pulse propagation and accompanying oscillation frequencies in the three phases is not the same. i.e. if the propagation is not the same for each phase, than the measured PD pattern can not be compared in a direct manner. An example of this phenomenon was found on a 170 MVA generator.

This particular 170 MVA generator failed the phase comparison test because phase 3 has a significantly different PD level than the other two phases (see Figure 17). The cross talk was for some frequencies even higher than the phase own PD-level. To check if propagation effects could be responsible for these results, time-domain measurements were performed on sensors on different locations in the IPB.

Table 5. Phase comparison test of the example generator.

<table>
<thead>
<tr>
<th>Freq</th>
<th>Phase U</th>
<th>Phase V</th>
<th>Phase W</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 MHz</td>
<td>28%</td>
<td>30%</td>
<td>42%</td>
</tr>
<tr>
<td>30 MHz</td>
<td>30%</td>
<td>26%</td>
<td>44%</td>
</tr>
<tr>
<td>50 MHz</td>
<td>39%</td>
<td>33%</td>
<td>28%</td>
</tr>
<tr>
<td>Average</td>
<td>32%</td>
<td>30%</td>
<td>38%</td>
</tr>
<tr>
<td>Deviation from 1/3</td>
<td>-1%</td>
<td>-4%</td>
<td>5%</td>
</tr>
</tbody>
</table>

Figure 17. Influence of propagation on the PD pattern. The PD patterns are shown on the left and the transfer function of the sensors are shown on the right. From top to bottom are shown phase 1, phase 2 and phase 3.
The IPB of this generator was equipped with two C couplers per phase. On each phase a C coupler was located at the generator side of the IPB and one was located at the transformer side of the IPB (Figure 16). If the propagation path between the two sensors is identical for each phase, then the transfer function of a signal traveling from the generator to the transformer between the transformer and generator sensor should be identical as well. The transfer function between the two sensors was determined using Equation 1.

\[ H(f) = \frac{U_2(f)}{U_1(f)} \] (1)

In this formula \( U_1(f) \) is the fast fourier transform (FFT) of the PD signal measured at the transformer sensor and \( U_2(f) \) the FFT of the same signal measured at the generator sensor. The transfer function \( H(f) \) should be the same for each phase for the phase comparison method to work well.

Figure 17 contains the PD patterns, which were measured on the three phases as well as the transfer functions of the sensors on the three phases. The figure clearly shows that the transfer function of phase three differs significantly from the transfer functions of phase one and two. This confirms that propagation effects are the cause of the generator failing the phase comparison test. In this case the difference in propagation can be attributed to the physical shape of the IPB itself. The IPB of phase three is shorter and contains fewer corners than the IPB of phases one and two.

CONCLUSIONS

1. Before deciding on the type of coupler an investigation of the PD signal propagation has to be performed. Based on this investigation a choice can be made on the type of coupler, where they should be installed and what kind of further adjustments should be made to allow the PD to exit the generator. Installing couplers without a thorough investigation could very well result in disappointing measuring results.

2. Great care has to be taken with the selection of the measurement frequencies. Disturbance signals might fool the operator into selection of inappropriate measuring frequencies.

3. For identification of the phase own partial discharges, the operator should be able to distinguish the phase PD from the different type of disturbances. Sometimes it is not possible to detect the phase PD, due to disturbances.

4. The presented interpretation methodology is aimed at detecting possible defects in the stator insulation systems. If a defect is present in the insulation system, the three-step interpretation will classify the generator other than "insulation ok." The paper shows that the interpretation methodology could also lead to false results owing to propagation effects. The results of the interpretation method do not detect PD detectable defects beyond a reasonable amount of doubt.

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