CIGRE-324
2020 CIGRE Canada Conference
Toronto, Ontario, October 19-22, 2020

The Use of Absolute Limits for PD Measurements on Stator Windings

MATHIEU LACHANCE
OMICRON electronics Canada Corp.
Canada

SUMMARY

Partial discharge (PD) measurement is a widely accepted method to access the insulation of stator windings of rotating electrical machinery. Even though it has been extensively used for decades, there is still no complete consensus on how it should be performed. Sensors, measured quantities and measuring frequencies are among the most debated parameters. This publication summarizes the results of three experiments that were performed on different types of machines in order to gain a better understanding of the propagation behaviour of PD pulses in stator windings. Every machine had different geometries, rated power and rated voltages. The results are then used to expose the limitations of using absolute limits to assess PD measurements on complete stator windings.

For each machine, the insulation of the winding was drilled at different locations on one phase, at regular intervals, between the neutral and the line terminal. A PD calibrator was used to inject artificial impulses at these locations. The PD apparent charge and the impulse in the time domain were then measured at the line terminal using respectively a quasi-integrating, frequency variable PD detector and a wide-band digital oscilloscope. The results are summarized using attenuation matrices where the normalized apparent charge and the peak value are plotted as a function of distance from the sensor.

Even though the experiments were performed on three different types of machines, the outcomes are very similar. The results confirm the known fact that PD acceptance criteria for complete stator windings cannot be established unless many precautions are taken. In practice, those are rarely met.

Apart from this, the results also confirmed that measuring PD by using filters settings with a lower cut off frequency offers a better coverage than measuring at high frequencies.

KEYWORDS

Rotating machines, Stator windings, Partial discharges, PD

mathieu.lachance@omicronenergy.com

1. INTRODUCTION

Partial discharge measurement is a valuable tool to assess the insulation of rotating electrical machines. The PD impulses, resulting from insulation defects or anomalies, can often be measured several years before these defects cause a complete failure of a machine. Thus, it is a powerful tool to provide an early warning to the operator who can plan countermeasures accordingly. However, unlike many other apparatus, there are no globally accepted absolute values to decide if a PD level is deemed acceptable or unacceptable for complete stator windings. Relevant standards such as IEC60034-27-1 and IEC60034-27-2 explicitly warn the reader against the use of such limits. This can often complicate the work of machine operators because they must either, develop their own expertise on the topic or to contract the task of analyzing the data to another company.

Some organizations publish or provide absolute values for their customers. Even though this can seem useful and straightforward, operators must be careful when using those values. To understand why, one must be aware of the propagation phenomena that occur when a PD impulse, travels from the defect site, to the sensors.

Throughout the years, there have been several publications regarding the PD impulse propagation behavior in generator stator windings [1-5]. The purpose of this contribution isn't to revisit in detail this topic, but rather to use the available data to provide the reader with a better understanding of what using those absolute values imply. The data from three studies [3-5] that were performed on different types of machines is reviewed and used to expose the limitations from using absolute limits for complete stator windings.

2. BACKGROUND THEORY

The theory of partial discharges applicable to rotating machines is very comprehensive. A detailed description is beyond the scope of this publication. However, a basic understanding of the phenomenon is helpful from this point onward.

Partial discharges are localized electrical breakdowns in the insulation system that only partially bridge the insulation [6]. They occur when the local electric field is exceeding the local dielectric strength. Root causes often are defects in the insulation or deterioration of the insulation system by different ageing mechanisms. Each partial discharge generates a current pulse which propagates from the discontinuity in the insulation through the winding. At its origin the unipolar pulse includes a broad frequency spectrum. However, it is practically impossible to measure the PD impulses at its origin. The most common method therefore is to use coupling capacitors with a series connected impedance at the terminals of the machine. As examples, Figure 1 shows a picture of a typical installation and Figure 2 shows a sketch of a typical single-phase PD measurement circuit.

Figure 1 : Installation of coupling capacitors

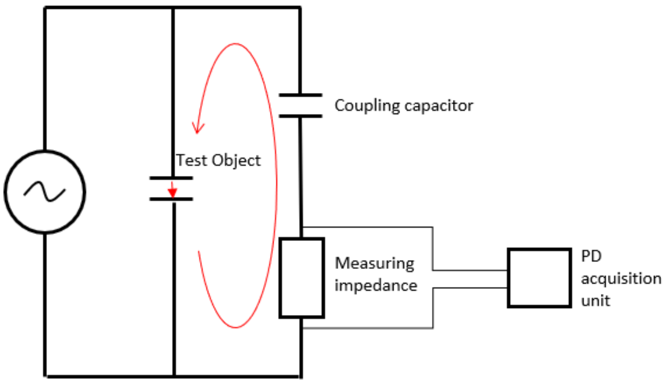

Figure 2 : Typical PD measurement circuit

The most commonly used measured quantity is the apparent charge in Coulomb (C). Simplified, the apparent charge can be summarized as the integration of the area under the PD pulse as measured from the terminal of a test object (Figure 3). For rotating machines, the measured charge is usually in the range of nanocoulombs (nC). Another common measured quantity is the impulse peak value in millivolts (mV). The latter is simply the magnitude of the first peak of the PD pulse.

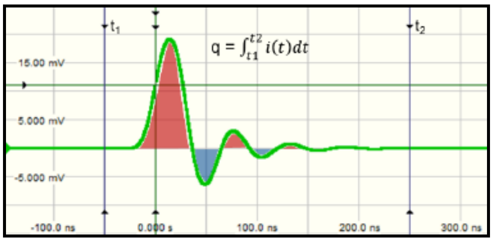

Figure 3 : Calculation of apparent charge of a PD impulse

Stator windings can be represented as a very complex distributed electrical circuit, with several series-connected reactors and parallel capacitances. When a PD event occurs in the winding, the impulse propagates from its origin, through the winding, to the sensor. The propagation path includes a complex network of partly conductively connected and partly electromagnetically coupled elements. The short, unipolar PD pulse is transformed as it travels by attenuation, reflections, dispersion and electromagnetic coupling effects into a greater or lesser extended, oscillating signal. Therefore, the PD impulse available at the sensors can be highly distorted compared to its original shape. The frequency response of the chosen PD system, including sensors and digital filters, will also influence the characteristics of the recorded PD impulses. Different frequency components of the impulses are damped differently. The higher frequency content is the most rapidly and strongly attenuated as the impulse stretches and shrinks when it travels through the winding. Figure 4 shows a measured PD impulse, at different locations, as it travels through a stator bar to the sensor.

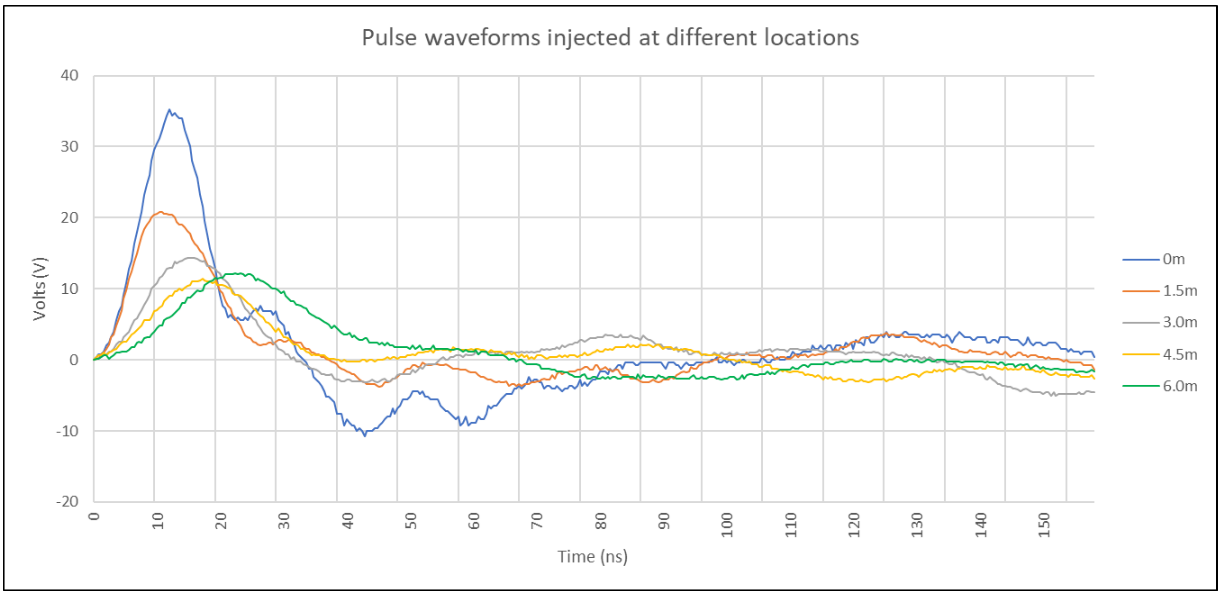

Figure 4 : PD impulses measured at different distances from the sensor

3. REVIEW OF PREVIOUS EXPERIMENTS

This section summarizes the results of three experiments. Those were performed on three different types of machines; a) a 102 MVA hydro generator [3], b) a 5,6 MVA hydro generator [4] and c) a 234 MW turbo generator [5]. The experiments were very similar in all three cases. The insulation was drilled a different location between the line and the neutral terminals of a single phase of the windings.

A PD calibrator was used to inject artificial PD impulses at those various locations. The PD impulses were then measured at the line terminal, using a quasi-integrating PD measuring system and a digital wide-band oscilloscope. For the measurement of the apparent charge, different frequency settings were used. For reference, Figure 5 shows a sketch of a typical setup.

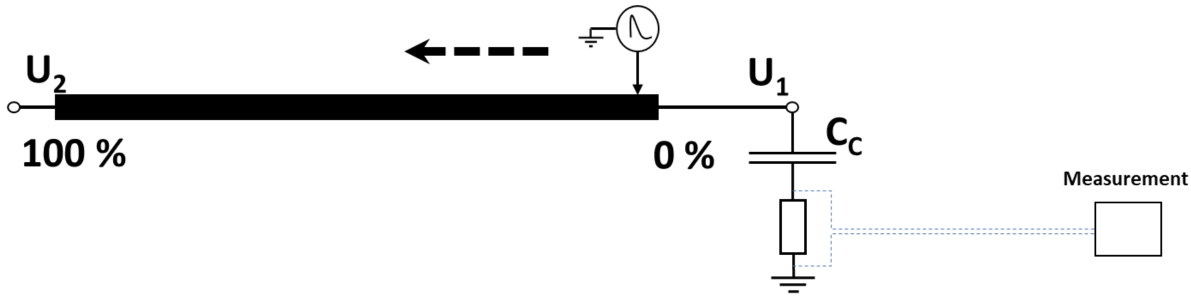

Figure 5 : Typical setup used during the experiments

3.1. 102 MVA HYDRO GENERATOR

The stator winding of a 102 MVA Hydro generator was used for this experiment. The rated voltage of the stator winding is 12.5 kV and each phase have two parallel windings of 48 bars. Holes were drilled in every end turn for the first 10% of the winding. Thenceforth, holes were drilled at every second or third bar. A coupling capacitor of 1.1 nF was used to decouple the PD impulse. Figure 6 shows the results of the apparent charge measured at the line terminal using different frequency filters.

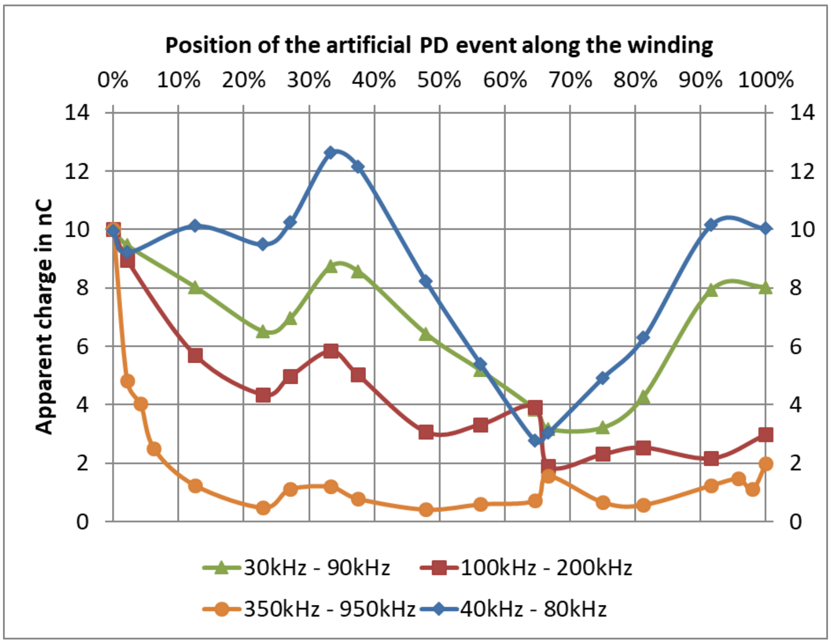

Figure 6 : Attenuation matrix for the measurements of the apparent charge of the 102MVA Hydro Generator

In addition to this experiment, the authors of this study also verified the attenuation within one single bar. A wideband oscilloscope was connected at the star point of the machine. The artificial pulses were then injected at three locations into the second bar from the star point. Figure 7 shows a sketch of the setup and Figure 8 shows the measured impulse for each location.

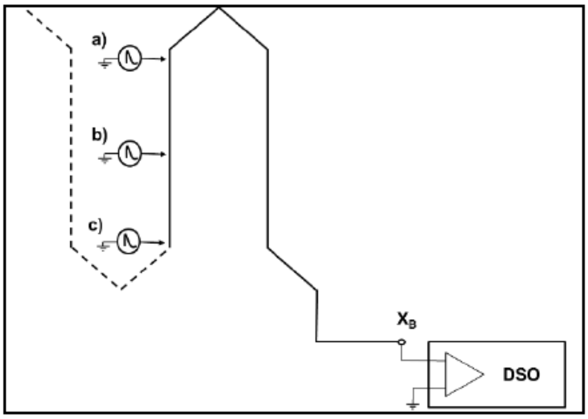

Figure 7 : Schematic of the setup for the peak value measurement of one single bar

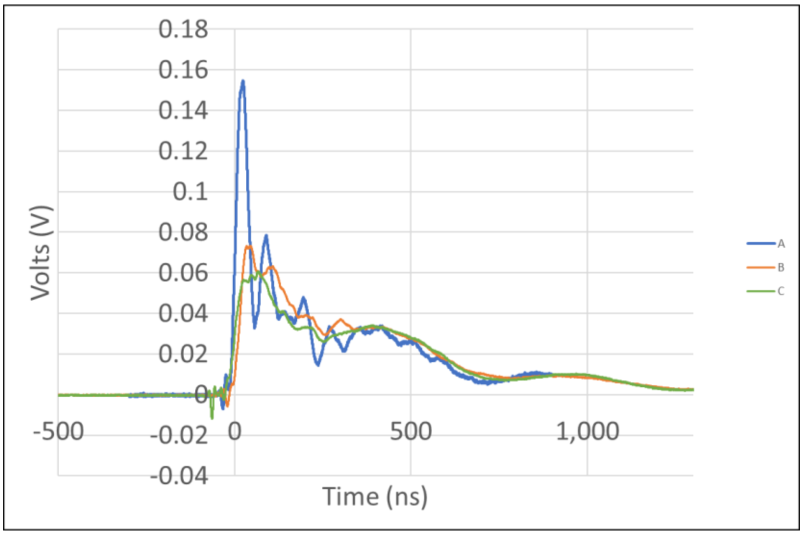

Figure 8 : Measured pulses at X_b

3.2. 5.6 MVA HYDRO GENERATOR

This experiment was performed on a 5.6 MVA hydro generator taken out of service. The rated voltage of the machine is 6.4 kV and each phase consist of a single circuit made of multi-turn coils (two turns per coil) distributed over 156 slots. The stator has an inner diameter of 2.3 m and a core length of 0.57 m. The authors of this publication did not specify the value of their coupling capacitor, even though it is mentioned to have a value higher than 1 nF.

In addition to the injection of the artificial PD impulses using a calibrator, the authors also created real PD activity at different locations within the winding. The results between these real PD impulses and the artificial PD impulses are very similar. The measurements were both recorded using a quasi-peak PD acquisition system, for the measurement of the apparent charge, and with a wideband digital oscilloscope, for the measurement of the impulse peak value.

The attenuation matrix of Figure 9 shows the results of the apparent charge measurement at the line terminal. Figure 10 shows the normalized measured peak value at the line terminal as a function of the injection site.

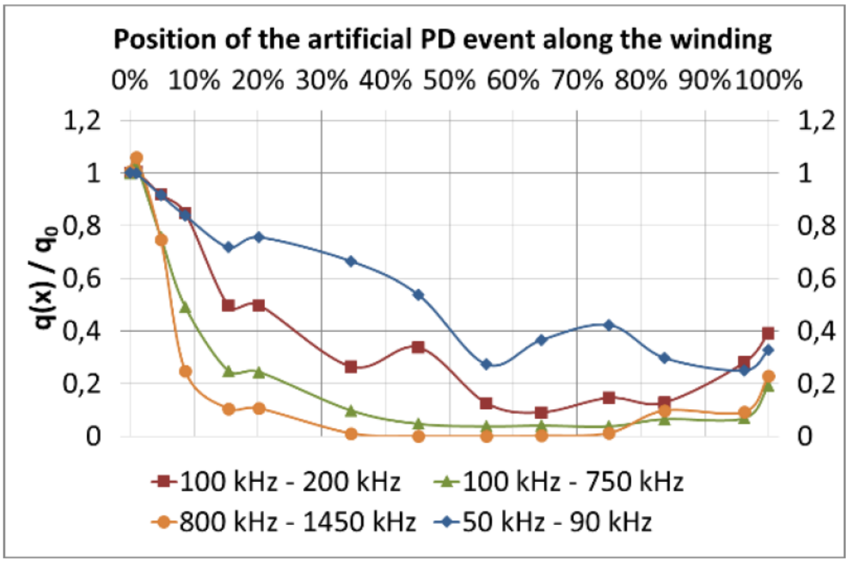

Figure 9 : Attenuation matrix for the complete winding

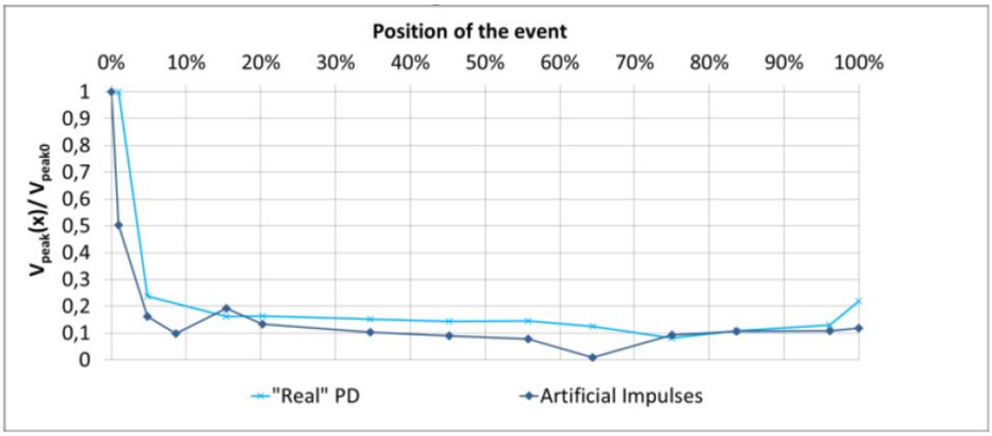

Figure 10 : Normalized peak value depending on the position of the PD source

3.3. 234 MW TURBO GENERATOR

This experiment was performed on a 234 MW turbo generator. The rated voltage of the machine is 15 kV and each phase consist of two parallel circuits of 16 bars. The stator has an inner diameter of 1.25 m and the core length is 4.5 m. The overhand area of this generator is approximately 1.5 m. The insulation was drilled at every turn of phase B in the end winding area. For this experiment, a 1.2 nF capacitor was used to decouple the signal.

The impulses were recorded using a quasi-peak PD acquisition system. The attenuation matrix of Figure 11 shows the normalized measured apparent charge at the line terminal as a function of the injection site.

In addition, the attenuation within one single bar was also verified. Figure 12 shows a schematic of the setup, Figure 13 illustrates the dependency of the measured peak value on the distance between the sensor and the PD site and Figure 14 shows the attenuation matrix for the measurement of the apparent charge.

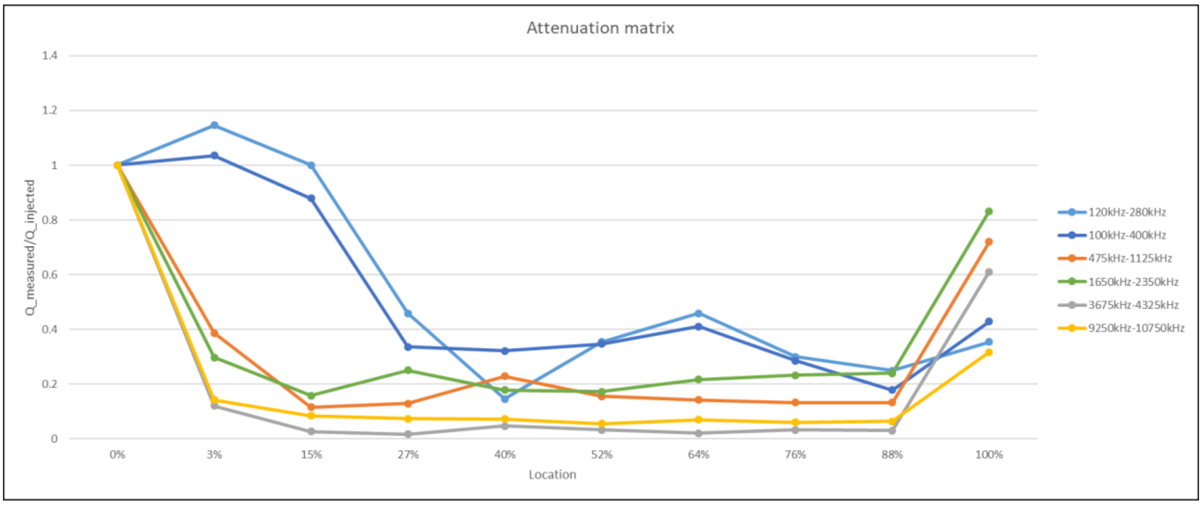

Figure 11 : Attenuation matrix for the complete winding

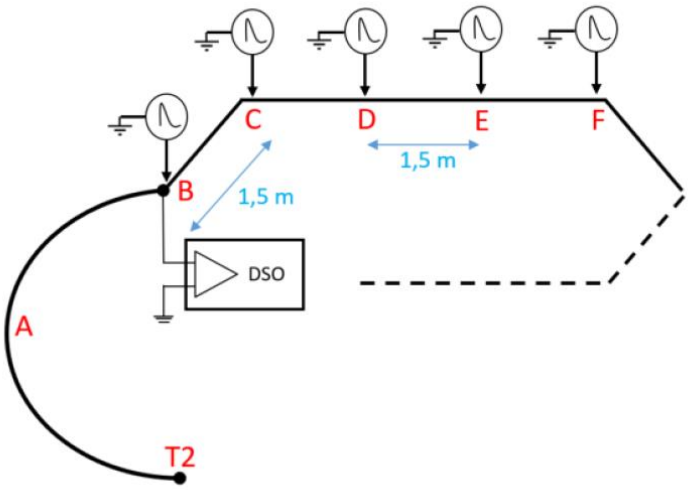

Figure 12 : Schematic of the setup used for the measurement of the peak value

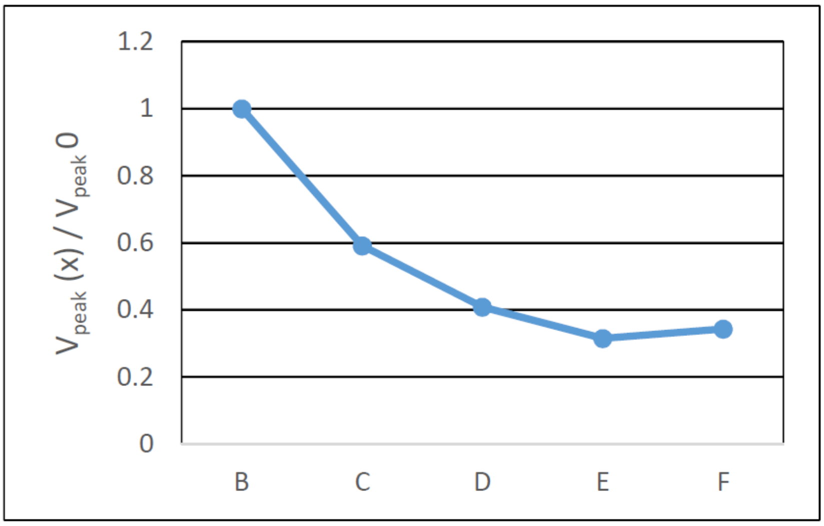

Figure 13 : Attenuation of the peak value for along one single bar

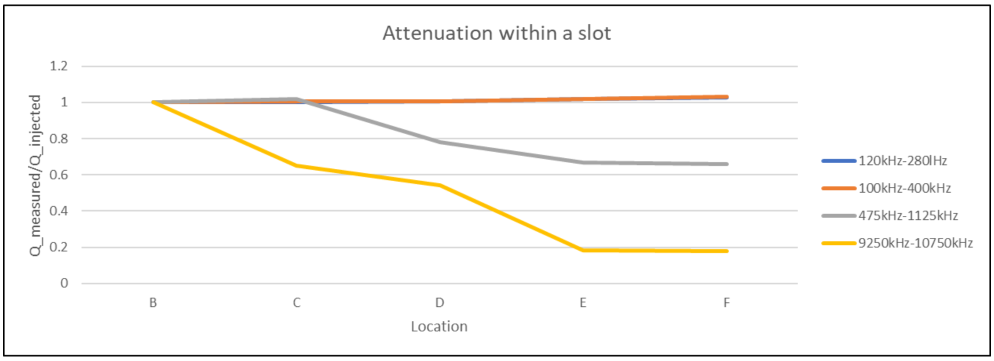

Figure 14 : Attenuation matrix for the measurement of the apparent charge

4. INTERPRETATION

As mentioned in the introduction, relevant documents which cover PD measurement for stator windings, such as IEC60034-27-1 and IEC60034-27-2 explicitly warn the reader against the use of absolute limits. For example, IEC60034-27-2 clearly points out that On-line PD tests on stator windings produce comparative, rather than absolute measurements. This creates a fundamental limitation for the interpretation of PD data and implies that simple limits for allowable PD cannot be established unless many precautions are taken [7]. IEC60034-27-1 mentions that a direct comparison of different types of machine in terms of absolute values is not possible [8].

The results of all three experiments clearly show that several factors can influence the measured quantities at the PD sensors. Some of those factors will be discussed in the following section; a) measurement filter frequencies, b) location of the defect and c) construction of the machine.

4.1. Measurement filter frequencies

When looking at Figure 6, Figure 9 and Figure 11, it is obvious that measuring frequencies have a significant impact on the recorded apparent charge. For every machine, an artificial PD impulse with a known apparent charge was injected at a given location. The recorded apparent charge at the sensor was highly affected by the different measured frequencies regardless of the type of machine.

For example, in Figure 11, when a PD impulse was injected at approximately 5 m from the sensor (3% of the winding length), the normalized apparent charge measured at different frequencies ranged from 0.12 to 1.15. In this case, an assessment solely based on the absolute limit would lead to an erroneous diagnosis. Similar results were recorded for all three machines and for all locations along the winding. This means that the same defect measured at different frequencies will give different results.

If resonances are not considered, increasing the filter frequencies of the measurement device results in lower measured values at the sensor. This means that as the measuring frequencies are increased, the coverage zone of the winding decreases. Therefore, measuring at low frequencies offers the possibility to identify defects that could otherwise be undetected.

Nevertheless, measurements shall be performed using the same measuring frequencies in order to be comparable. To meet this condition, the frequency response of the complete system must be considered. In addition to the digital filter settings, the frequency responses of the sensor, the measuring impedance and the PD system inputs must be the same.

In practice, this condition can often be met if the compared measurements were performed using the same PD instrument, sensors and filter settings.

4.2. Location of the defect

The distance between where the artificial impulses were injected, and the sensor also had a significant influence on the recorded PD levels. Figure 10 shows that after traveling approximately 5% of the winding, the measured impulse peak value is approximately 20% of its original value. It is obvious that, in this case, measuring the peak value results in a poor coverage of the winding. A similar behavior is visible on Figure 13. After traveling one bar, which is equivalent to approximately 6% of the total length of the winding, the measured impulse peak value is approximately 35% of its original value. This shows that even relatively short distances can have a significant influence on the measured quantity recorded by the peak detecting PD instrument. Similar results were also reported for the measurement of the apparent charge at high frequencies (figure 14).

As it was mentioned before, PD impulses are distorted when traveling from their origin to the sensor. Due to attenuation, this usually means that PD not occurring in the vicinity of the sensor are measured with a smaller quantity (pC or mV) than the ones occurring at the sensor. This creates an obvious problematic if one wishes to establish absolute limit levels for any PD measured quantities. Using any given limit could result in overestimating or underestimating the severity of a defect, depending on where it is located.

4.3. Construction of the machine

Construction of stator windings can differ greatly from one machine to another. Those differences include the length of the core, whether the winding uses multi-turn coils or half-turn Roebel bars, the end arm geometry, the circuit ring bus layout, the insulating system, etc. [9]. All those parameters will have an important impact on the measured PD impulse at the sensor.

The experiments described in sections 3.2 and 3.3 were performed on two different types of machine. The first machine was a 102 MVA hydrogenerator with a rated voltage of 12.5 kV while the second machine was a 234 MW turbogenerator with a rated voltage of 15 kV. To expose the effect of the parameters that are specific to each machine, the measurements were performed using the same frequency filter settings (100 kHz – 400 kHz) and the same PD instrument. Figure 14 shows the normalized apparent charge for both machines as a function of distance between the injection of the artificial PD impulse and the sensor.

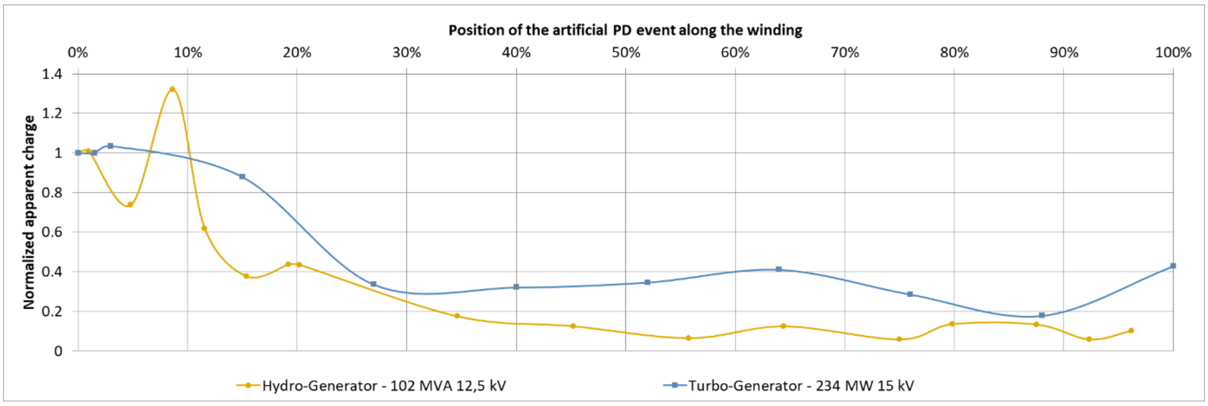

Figure 15 : Comparison of the attenuation in two generators

As it is expected, both machines exhibit different responses to the impulses injected along their respective winding. At any given locations, the same injected impulse was measured differently depending on if the measurement was taking place on the hydrogenerator or on the turbogenerator. This means that an accurate diagnostic could not be performed by comparing the measured PD values of those two machines.

5. DISCUSSION

PD is often the result of anomalies within an insulation system. Yet, PD is usually present even in healthy medium voltage stator windings. Because of their construction, small voids, often called « microvoids », are introduced during the manufacturing process. This leads to a localized high electric field within the insulation. However, stator winding insulation system, which is mainly made with mica, is highly resistant to PD and should be able to withstand this type of discharge without a significant decrease of its expected lifetime.

Nevertheless, several other types of PD can shorter the lifetime of stator windings. They can be the results of numerous issues including, poor manufacturing process, bad installation, operation under abnormal stress or simply ageing. Due to the different factors described in section 4, it is generally not possible to specify PD levels that are proportional to the risk of insulation failure. Furthermore, the degree of deterioration, and hence the risk of insulation failure, depends considerably on the specific type of partial discharges [7]. It is therefore crucial to isolate and identify the different sources of any significant PD activity. An analysis of the phase resolved partial discharge (PRPD) diagram using a high-resolution display is a well-established method to identify the types of defects that are present in the machine.

Some relevant documents mention that empirical limits verified in practice could be used as a basis for evaluating test results [7, 8]. Those should be used carefully and applied only between very similar machines. The limits provided by some organizations are usually divided in categories based on the machine-rated voltages. As it is shown in this publication and demonstrated by others [10, 11], there are numerous other factors to consider when comparing PD magnitude between different machines. Not considering those factors could lead to an inaccurate diagnostic.

In order to control as many factors as possible, a comparison between measurements can be done on the same machine over time (trending), between the phases of a given machine or between machines of very similar construction. This approach is valid for both offline and online measurements. The test conditions shall be the same in order to enable an accurate comparison. It has been proven by others that environmental conditions (for offline measurements) and operating parameters (for online measurements) will highly affect the recorded PD [12-15]. For instance, several documents provide guidance in order to help the tester to determine if two measurements can be comparable or not. Those generally include the test voltage, the winding temperature, the stator current, the relative humidity and the gas pressure in case of hydrogen cooled machines.

6. CONCLUSION

This paper summarizes the findings of three experiments on the topic of PD pulse propagation in stator windings. It uses the results to expose the limitations of using absolute limits to assess PD measurements on rotating machine stator windings. It has been shown that such limits of magnitude cannot be accurately and simply used as acceptance criteria except if several conditions are respected. Those are in practice rarely met.

Comparing PD levels from one measurement to a database cannot be done easily. The PD instrument, the sensors, and the construction of the machines all have a significant influence on the measured quantities. Even if the same PD instrument is used on very similar machines, the location of the defect, the types of defects, the environment and the operating parameters of the machines during the measurements will also significantly affect the results. Those findings are in concordance with relevant standards applicable for PD measurements of stator windings.

All the parameters mentioned above will also affect the coverage zone of the measurement. Generally, PD occurring close from the sensors will have a stronger response. However, this response will decrease when PD occur from a given distance of the sensor. When measuring at high frequencies, PD occurring outside the vicinity of the sensors can go undetected. Measuring at low frequency generally enhance the capability of detecting PD across a wider area of the winding.

BIBLIOGRAPHY

[1] A. Wilson, R. J. Jackson and N. Wang, "Discharge detection techniques for stator windings," in IEE Proceedings B - Electric Power Applications, vol. 132, no. 5, pp. 234-244, September 1985

[2] A. J. M. Pemen, P. C. T. van der Laan and Wout de Leeuw, "Propagation of partial discharge signals in stator windings of turbine generators," in IEEE Transactions on Energy Conversion, vol. 21, no. 1, pp. 155-161, March 2006

[3] F. Oettl and C. Engelen, "An investigation regarding the impulse propagation of partial discharges in a small hydro generator," CIGRE Colloqium Rotating electrical machines for power generation, Vienna, Austria, September 2017

[4] F. Oettl, C. Engelen, E. Binder and T. Kessler, "A study of the propagation behavior of partial discharge pulses in the high-voltage winding of hydro generators," 2017 IEEE International Electric Machines and Drives Conference (IEMDC), Miami, FL, 2017, pp. 1-5

[5] M. Lachance, F. Oettl, "A Study of the Pulse Propagation Behavior in a Large Turbo Generator," 2020 IEEE Electrical Insulation Conference (EIC), Virtual Event 2020

[6] IEC 60270, High-voltage test techniques – Partial discharge measurements

[7] IEC/TS 60034-27-2, Rotating electrical machines – Part 27: On-line partial discharge measurements on stator winding insulation of rotating electrical machines

[8] IEC/TS 60034-27-1, Rotating electrical machines – Part 27: Offline partial discharge measurements on stator winding insulation of rotating electrical machines

[9] IEEE Guide for the Measurement of Partial Discharges in AC Electric Machinery," in IEEE Std 1434-2014 (Revision of IEEE Std 1434-2000), vol., no., pp.1-89, 4 Dec. 2014

[10] M. Lévesque, M. Bélec, C. Hudon and C. Guddemi, "The need for PD quantification based on the type of discharge sources," 2017 IEEE Electrical Insulation Conference (EIC), Baltimore, MD, 2017, pp. 380-383

[11] H. Zhu, V. Green, M. Sasic and A. Jakubik, "Partial discharge database: its benefits and limitations on assessment of stator insulation deterioration," Proceedings: Electrical Insulation Conference and Electrical Manufacturing and Coil Winding Conference, Cincinnati, OH, USA, 2001, pp. 405-409

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

[13] C. Hudon, M. Belec and M. Levesque, "Study of slot partial discharges in air-cooled generators," in IEEE Transactions on Dielectrics and Electrical Insulation, vol. 15, no. 6, pp. 1675-1690, December 2008

[14] R. P. Nair, B. V. Sumangala, B. N. Rao and Thirumurthy, "Effect of temperature on slot discharge pattern measured in stator coils at variable frequency sinusoidal voltage excitation," 2018 12th International Conference on the Properties and Applications of Dielectric Materials (ICPADM), Xi'an, 2018, pp. 257-261

[15] M. Farahani, E. Gockenbach, H. Borsi and M. Kaufhold, "A method for the evaluation of insulation systems for high voltage rotating machines," Proceedings of the 7th International Conference on Properties and Applications of Dielectric Materials (Cat. No.03CH37417), Nagoya, Japan, 2003, pp. 1108-1111 vol.3.