Guidelines for PD measurement according to IEC 60270

Mraz, Petr; Abdul Madhar, Saliha; Treyer, Patrick; Hammer, Urs

Publication date
2019

Document Version
Accepted author manuscript

Published in
21st International Symposium on High Voltage Engineering, Budapest, Hungary, August 26-30, 2019

Citation (APA)
Mraz, P., Abdul Madhar, S., Treyer, P., & Hammer, U. (2019). Guidelines for PD measurement according to IEC 60270. In *21st International Symposium on High Voltage Engineering, Budapest, Hungary, August 26-30, 2019*

GUIDELINES FOR PD MEASUREMENT ACCORDING TO IEC 60270

P. Mráz[1*], S. A. Madhar[1,2], P. Treyer[1], U. Hammer[1]
[1]Haefely Test AG, Birsstrasse 300, Basel, 4052, Switzerland
[2]Delft University of Technology, Delft, the Netherlands
*Email: pmraz@haefely.com

Abstract: Partial discharge measurements performed according to IEC 60270 has become an essential tool for the quality assurance of HV equipment. The main goal of IEC 60270 is to standardize and unify PD measurements to get comparable results for tests performed at various locations, using different equipment and by different operators. This paper aims at providing clear and unambiguous guidelines on how to perform repeatable and comparable PD measurements in compliance with one of the most popular international testing standards in Europe, the IEC 60270. This paper also discusses the functionality of the various components in the measuring setup. In addition, it makes some invaluable recommendations based on scientific knowledge regarding the selection of proper PD test and evaluation parameters to ensure correctness of obtained test results. The main focus is on the selection of a suitable frequency measurement range, which is a key step in the quasi-integration process involved in the charge estimation of the PD pulse.

1 INTRODUCTION

Partial Discharge (PD) measurement performed according to IEC 60270 has become an essential tool for a product's quality assurance. The main goal of IEC 60270 is to standardize and unify PD measurement to get comparable results for tests performed at various locations, with different equipment and by different operators. To achieve this goal IEC 60270 has defined a complex set of processes and key parameters, which are essential to be followed carefully. The original IEC 270 standard (1980's) has been designed for testing lumped capacitive test objects. Nevertheless, from long-term experience, it has been found that good and plausible results can be obtained for test objects with windings such as transformers and electrical machines as well. However, especially in case of testing more complex RLC systems certain rules need to be followed and particular limitations should be considered.

The purpose of this article is to provide clear and unambiguous guidelines on how to perform repeatable, plausible and comparable PD measurement according to the IEC 60270. It describes briefly the differences between the definition of the so called induced and apparent charge. It also discusses in detail functionality and suitability of the commonly used measuring test setup and its components including the coupling capacitor, measuring impedance, PD calibrator, PD detector and potential filtering elements. In addition to this, the selection and explanation of proper test evaluation parameters and PD detector settings are described including selection of a suitable frequency measurement range, which is a key factor when it comes to PD testing. Last but not least, a robust but simple performance and verification procedure for the test setup and PD detector settings is introduced and explained.

2 INDUCED AND APPARENT CHARGE

Since the 1930's several models have been developed to represent the partial discharge phenomenon accurately [1]. The most popular and widely accepted among them is the 3-capacitor model also referred to as the a-b-c model. Its simplicity enables the easy comprehension of discharge scenarios by representing the defect as a lumped capacitor. Though several other models (more complex) were proposed through the years, namely the 5-capacitor model in the 1960's [2] and later the dipole model in the 1980's [3], the a-b-c model remained the most popular. Based on this model, IEC 60270 defines the term 'Apparent charge' which is the charge measurable at the terminals of the test object. The message that the IEC conveys through the term apparent charge is that the value of the measured charge is not exactly equal to the charge involved at the site of discharge. That is, if C_c is the capacitance of the defect, C_b is the capacitance of the healthy dielectric in series with the defect and q_c is the charge at the defect location then the charge measured at the terminals (q_a) is given by

$$q_a = q_c\,(C_b/C_c) \tag{1}$$

under the assumption that $C_c >> C_b$, $q_a << q_c$. Due to this reason this term has been misconstrued to be an arbitrary value which has no relation to the value of the real discharge. However, this is not true, the value of the measured charge is directly representative of the charge involved at the discharge site as confirmed by E. Lemke in the 2010's [4-5] based on Pedersen's Dipole model [3]. He introduced the term 'Induced charge' in an attempt to redefine the value of the measured PD at the test terminals and dismiss the delusion involved with the usage of the term apparent charge. According to this theory the measured charge is proportional to the real charge through a continuous dimensionless positive scalar function λ which differs based on the geometry and location of the defect

$$dq = -\lambda \cdot dQ \qquad (2)$$

where dq is the measurable charge and dQ is the charge involved at the defect location.

Henceforth, the charge value measured in pC as prescribed by the IEC is a quantity that is well correlated to the PD severity. Presently, there have been discussions on ‘calibration’ and ‘sensitivity checks’ for PD measurements using unconventional techniques. Though the term sensitivity check is still acceptable in these cases, the process of calibration is rather complex and does not seem to be meaningful. Unconventional PD measurement techniques depend on the response between the sensor position and the failure location and not just the response of the HV test object as is in the case of the IEC measurements. The results of such measurements (HF above IEC range, VHF, UHF, acoustic and other radiated field measurements) change dramatically based on the PD test system configuration. For instance, neglecting all the errors from external factors and considering an acoustic measurement of a transformer, a single defect can generate signals of several different amplitudes. Depending on the propagation path and sensor position, the generated signal might be completely damped/reflected, i.e. no signal reception. In addition, it is impossible to define this 3-D space in which the radiated waves are measured.

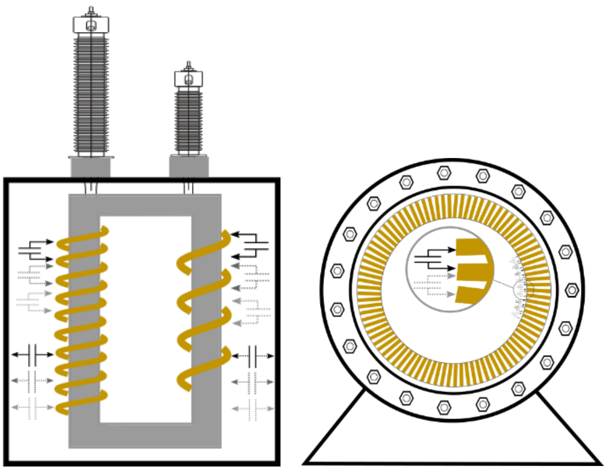

Figure 1: The stray capacitances in a transformer and a rotating machines stator winding.

It can be argued that the case is similar to the electrical measurement on a large test object or a test object with windings where the PD calibration over the test leads is unlike the real PD event, and the measured value is arbitrary and does not correlate to the real discharge. However, for instance, in case of conventional electrical PD measurement on a large transformer, the Low Frequency (LF) components of the PD source located anywhere deep in its winding partially ‘by-passes’ the LC filtering effect of the winding inductance and the inter-winding and tank stray capacitance as shown in Figure 1. Similarly, in the case of rotating machines, the stray capacitance in between stator bars at the stator end-winding provides good cross-coupling of the LF components enabling the location of faults deep inside the windings. This has been explained in detail through simulation and measurement in [6], showing the frequency response of several large test objects with complex RLC configurations.

The study published in [7] simulated a PD source at different locations on a transformer winding and measured the pulse spectrum of a real PD pulse as shown in Figure 2. From this plot one can notice the better stability of the spectrum at frequencies lower than 300 kHz. This will ensure the stability of measured PD values and preserve the validity of the quasi-integration process (discussed in Section 4.2.2). The displayed PD pulse spectra indicate that in case of correct and IEC 60270 compliant settings, charge reading would be consistent thru the complete winding. This confirms the recommendation of IEC 60270, Section 4.3.4, Note 2 which states that for test objects with windings the upper cut-off frequency f_2 shall be reduced to a few 100 kHz or even below.

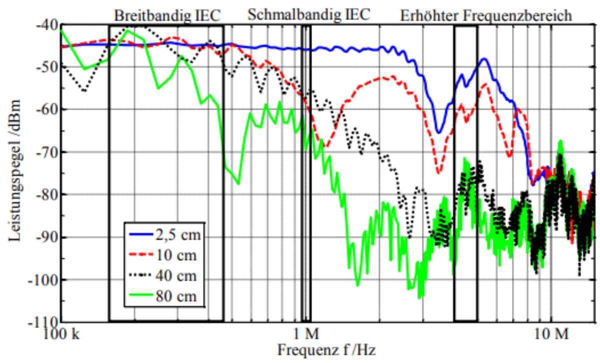

Figure 2: The pulse spectrum of a PD source simulated at different winding positions [7].

3 PD MEASUREMENT PROCEDURE

Partial discharge measurements for high voltage AC equipment have been defined by the IEC 60270 standard which specifies the general requirements of the measuring and calibration system. The partial discharge measuring system is divided into two major subsystems, the coupling unit and the measuring instrument. This section describes the preliminary step towards performing the PD test by describing the selection of the circuit components and their functionality.

3.1 Measurement circuit

The PD measurement circuit is shown in Figure 3 and the various components of the measurement circuit are described in the following sections.

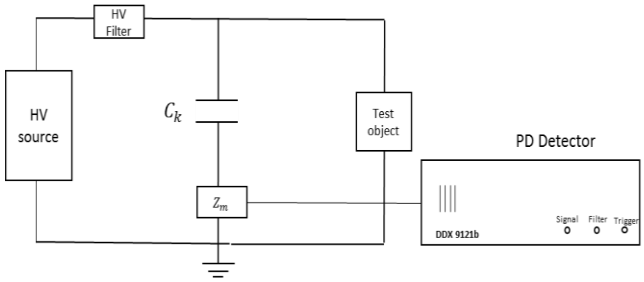

Figure 3: Schematic of the PD measurement setup.

3.1.1. HV Filter

The use of a blocking impedance (HV filter) is strongly advised. The correct choice of a blocking inductance is imperative to the outcome of the partial discharge test. The functionality of the HV filter can be listed as follows:

- Noise and interference originating from the power supply side will be blocked and will not interfere with the PD measuring loop.
- The HV filter is also called blocking impedance because it confines the High Frequency (HF) partial discharge signal coming from the test object in the measuring loop and avoids signal leakage thru the power source capacitance and hence improve the sensitivity of the measurement.

In many cases, while performing PD acceptance tests close to the maximum voltage rating of the supply transformer, discharge from the HV source is very likely. To prevent such errors the PD test system should be tested regularly for discharges from the source. The attenuation of PD from the source increases with increasing filter order.

3.1.2. Coupling Capacitor

The coupling capacitor (C_k or C_c) provides a low-impedance path for the HF discharge current to circulate. The coupling unit needs to be carefully selected considering the following points:

- The ratio of the coupling capacitance (C_k) and the test object capacitance (C_t) determines the sensitivity of PD measurement. The relationship of the measurable charge (Q_m) and the charge at the test object terminals (Q) is depicted in Figure 4. By increasing the value of the coupling capacitance, it is possible to achieve greater measuring sensitivity and SNR (Signal to Noise Ratio).
- However, increasing the size of the capacitance also necessitates a higher power supply to provide increased load current.
- It is also interesting to think in terms of the circuit's time constant. A larger coupling capacitor will increase the time constant thereby increasing the width of the discharge pulses.
- The coupling capacitor commonly serves as the primary of the voltage divider in which case the capacitance should have sufficiently linear voltage characteristics to preserve a constant divider ratio.

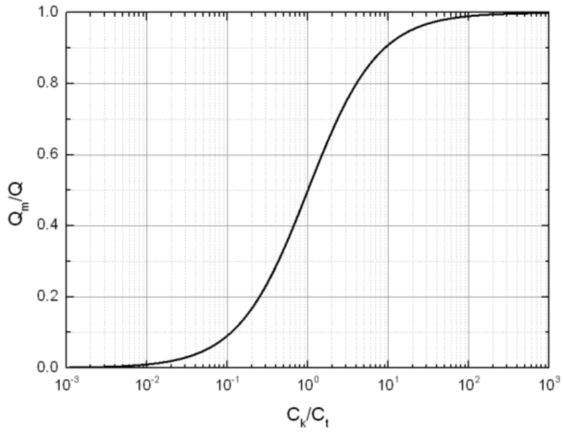

Figure 4: Sensitivity of the measurable charge in dependence of the C_k to C_t ratio.

3.1.3. Measuring Impedance

The measuring impedance converts the input current signal of the partial discharge to an output voltage signal while effectively blocking or separating the power frequency signal. This ensures that there is no power frequency (50/60 Hz) signal or its harmonics in the measured PD voltage signal.

Finally, the measuring impedance has to be equipped with over-voltage or flashover protection in case of breakdown. This is a vital feature for this application.

3.1.4. PD Detector

The PD detector serves as the signal acquisition unit and it has to fulfil the regulations defined by IEC 60270. The permissible filter ranges have to be correctly and precisely implemented in the detector in addition to the PD magnitude calculations (in terms of pC) which are currently defined by the pulse train response. The detailed description of the filter settings of the detector are presented in Section 4.

4 FREQUENCY BAND SELECTION

Selecting the right frequency band for PD measurement is the most important step towards obtaining reliable test results with a high level of reproducibility. In earlier times, obtaining the frequency spectrum of a pulse required special oscilloscopes able to compute the Fast Fourier Transform (FFT) of the acquired pulse or complex spectrum analyzers requiring skillful operators.

However, these days it is possible with a unique single click feature using 'Trigger by level' or 'Trigger by position' enabled on the fully digital state of the art PD detector [8, 9]. The typical frequency spectra of various signal sources are shown in Figure 5. Tips on checking the noise floor and discriminating interference pulses as well as on selecting the correct bandwidth for PD calibration and measurement are described in this section.

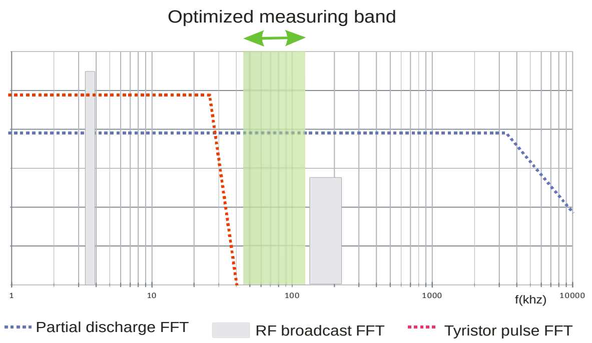

Figure 5: Typical frequency spectrum of various signal sources.

4.1 Step 1: Checking the noise spectrum

When it comes to electrical PD measurements there are three common categories of noise:

- *Random noise* otherwise referred to as 'white noise' is the stochastic noise which randomly varies around its mean value which equals to zero. The FFT/spectrum of such noise is characterized by a constantly low dB level and no prominent peaks at specific frequencies as shown in Figure 6.

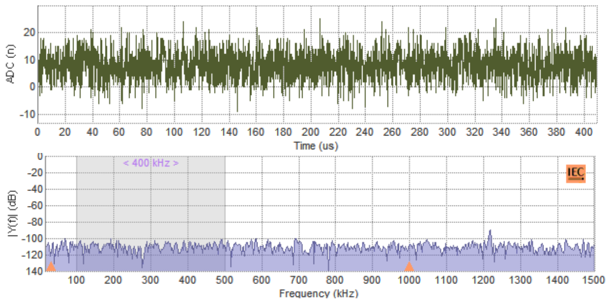

Figure 6: White noise (top) and its FFT (bottom).

- *Switching noise* is a high-frequency radiated noise. The most common sources of this kind of noise are equipment with electronic switching such as frequency converters (HV controls, heating ovens, lifts etc.). The spectrum of an electronic switching pulse looks uneven with prominent resonant peaks. The FFT of a switching pulse is similar to the FFT of a PD event when performing tests on large test objects or test objects with windings such as transformers or rotating machines. These pulses are synchronized to the 50 or 60 Hz power cycle and occur at a specific frequency (typically the switching frequencies of a few kHz). One such example is shown in Figure 7.

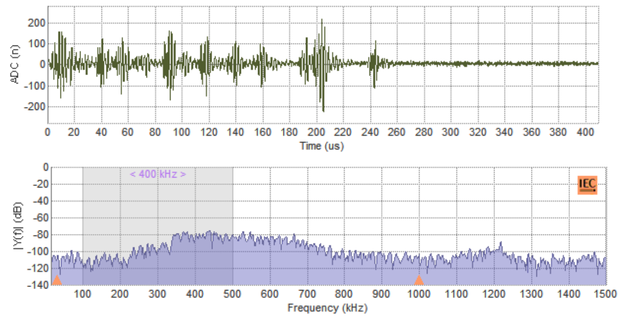

Figure 7: Switching noise (top) and its FFT (bottom).

- *Sinusoidal noise* is one other category which could hinder the PD test. It is a continuous wave which might originate from radiated AM and FM signals or other communication bands. This noise if not recognized can have strongly negative impact on the PD test results. Sinusoidal noise is reflected in the noise spectrum as a narrow peak at a very specific frequency such as shown in Figure 8.

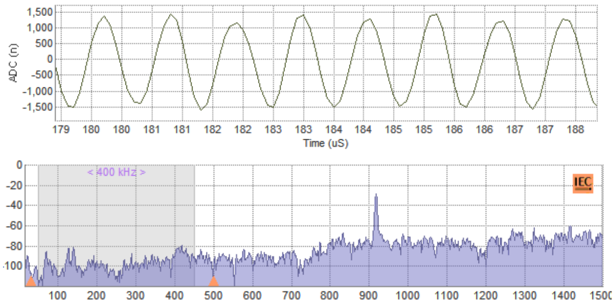

Figure 8: Sinusoidal noise (top) and its FFT (bottom).

Therefore, one of the first and most vital steps while performing PD tests is to check the prevailing noise floor in the testing field/laboratory. Once the operator has complete knowledge of the noise conditions in the test fields he goes on to select a frequency band for PD measurement trying to exclude the noisy peaks. In case of standard (IEC/IEEE/NEN) compliance tests the operator needs to keep in mind the test specifications defined in the respective standards and ensure that the filter settings are within the required range.

4.2 Step 2: Checking the calibration spectrum

The calibrator is connected across the test object and a PD pulse of known charge value is injected. The detector is then calibrated. The following tips on calibration are highly recommended.

4.2.1. General Tips for Calibration

- Always inject the calibration pulse across the leads of the test object and not the coupling capacitor.
- Make sure all circuit components are connected, and the circuit is of the final form before doing the calibration.

- Any alterations made to the circuit after calibration will require recalibration.
- Any alterations made to the PD detector settings (frequency range settings etc.) will require recalibration
- To avoid calibration errors, remove the ground rod from the circuit.
- Always check the noise spectrum before calibration (see Section 4.1).
- Check linearity of the calibration by injecting multiples of the originally injected charge value, e.g. 50% and 200%.

The calibration is invalid in case the frequency spectrum is not flat over the filter band set by the user. In this case the quasi-integration process explained in Section 4.2.2 is invalidated, yielding wrong charge values. Such errors are more likely when testing large test objects or test object with windings, which are comprised of a complex RLC network generating resonances over the prescribed measuring range. One such example is shown in Figure 9 with a resonance at 350 kHz. The correct choice of filter settings for this calibration is to restrict the higher cut-off frequency to < 300 kHz.

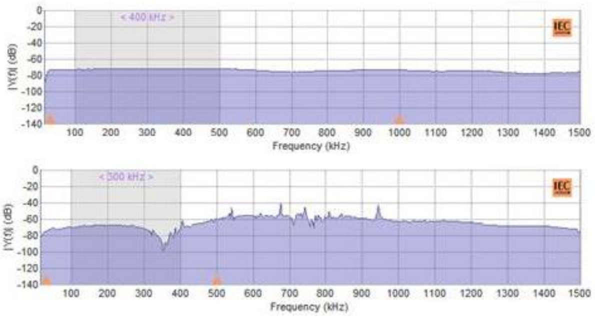

Figure 9: The frequency spectrum of an ideal calibration pulse (top) and with resonance at 350 kHz (bottom).

4.2.2. Quasi-integration

In the time domain methodology of charge estimation, the peak of the filter response is proportional to the value of apparent charge of the PD pulse. During PD measurement the proportionality constant is calculated by first injecting a known value of charge during calibration. However, this proportionality is only valid if the filter extracts the PD pulse energy where the spectral density is constant. This process is known as quasi-integration. In case of resonances in the measuring setup/test object, the selected frequency spectrum can sometimes fall on non-flat regions making the charge estimation invalid.

4.3 Step 3: Analyzing the real PD pulse spectrum

The final confirmation check that is recommended for advanced users in order to ensure the correctness of the measured charge value is to acquire a real PD pulse and check its spectrum. In case of large test objects or test objects with windings this becomes crucial. It is possible that the frequency response of the test object during calibration is different from that during a real PD event as shown in Figure 10. This is because the frequency response depends on the pulse travelling path.

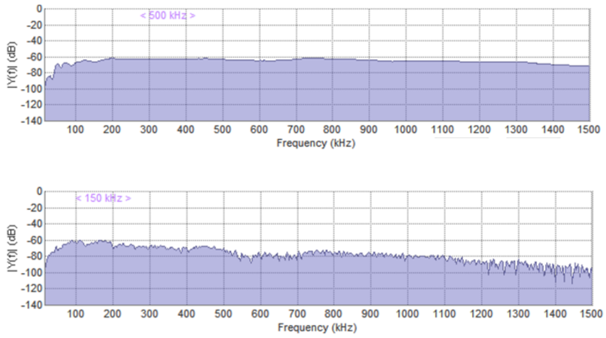

Figure 10: The calibration pulse spectrum (top) and spectrum of the real PD (bottom) measured on a stator winding.

In the case of the stator presented in Figure 10. The setup had to be recalibrated placing the filter between 100 and 400 kHz instead of the initial 100 to 700 kHz.

The purpose of checking the spectrum of the discharge pulse is to confirm the validity of the calibration. However, this matter shall rather be taken care of by the vertical standards of the IEC which have been developed to deal with specific test objects and define more specific criteria for those objects. It is a precautionary measure that can be exercised in order to improve the reliability of test results. The PD test standards, IEC 60270 defines the basic allowable measuring bands up to 1 MHz. However, e.g. the vertical standard IEEE Std. C57.113-2010 which deals with PD measurements on power transformers recommends a maximum upper frequency limit of 300 kHz in order to perform a charge estimation (integration) with sufficient accuracy. The PD event recorded from one such PD test performed on a power transformer rated for 80 kV is shown in Figure 11. It clearly shows that the energy of the PD pulse is confined to the lower frequencies and there is no apparent reason to measure at higher frequencies.

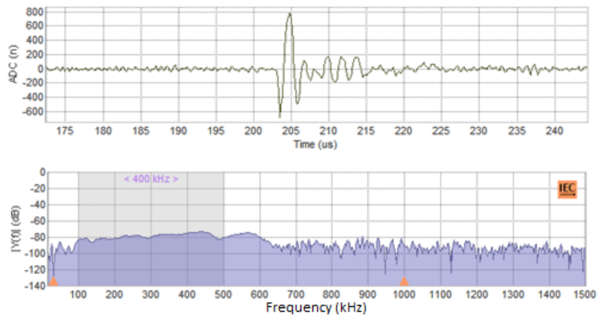

Figure 11: The real PD pulse (top) and its frequency spectrum (bottom) measured on a power transformer.

In case of cable measurements ‘artificial resonance’ peaks appear in the frequency spectrum due to the reflected pulses from the cable end. However, this effect can be neglected. A more detailed study on the frequency spectrum of cable networks is described in [10]. The latter investigates the drastic attenuation of the PD pulse at frequencies above 1 MHz and shows an error of 28% for the estimated charge value when using a filter in the frequency band of 1 to 20 MHz while it is only a meager 4% when measured over the prescribed IEC band (50 to 500 kHz). Hence, selecting a low frequency range prevents measurement errors due to increased cable attenuation at higher frequencies resulting in more stable and accurate PD level measurement.

In case any PD activity is detected, the fault location processing needs to take advantage of the full bandwidth (unfiltered signal). To properly check the pulse spectrum and filter settings, it is recommended to connect the calibrator at the cable end and to record a single pulse. In this way, any resonance in the path from the cable termination thru the coupling capacitor and to the measuring impedance can be detected. The pulse shape recorded during calibration can be used for comparison with the pulse shape recorded from real PD activity.

Multiple pulse reflections along the cable can make it difficult to check the pulse spectrum when PD activity arises because one single pulse should be considered for spectrum verification. Anyway, in the worst case the recorded real PD events are supposed to exhibit the same limited spectrum and pulse shape like the PD calibrator pulses injected at the cable end.

Therefore, it is always recommended to remain in the lower frequency range, especially for large test objects and test objects with windings and for advanced users to take the opportunity to confirm the correctness of the measured charge values by cross-checking the spectrum of the real PD event.

5 CONCLUSION

The general conclusions of this paper can be summarized as follows.

- Especially for large test objects and test objects with windings it is recommended to measure in the lower frequency range (upper cut-off frequency < 200 to 300 kHz).
- The nature/geometry of the test objects creates shunt-paths and by-passes caused by the stray capacitances across conductive parts which allows the LF components of the PD pulse to appear at the test object terminals with the least attenuation possible.
- Non-conventional PD measuring techniques are strongly influenced by the nature of the connection pathway between the location of the sensor and the defect itself.
- Conventional PD measurement at higher frequencies is less meaningful since the frequency response of the test connections and the measuring loop curtail the maximum frequency of the PD pulse to less than a few MHz (~ 2 MHz).
- Resonances in the PD measuring band invalidate the calibration based on quasi-integration.
- The main purpose of the IEC standardization process is to define test procedures that provide repeatability and inter-comparison.
- Measuring at frequency ranges outside the IEC spectrum brings risk of greater error and defeats the purpose of standardization.
- Checking the frequency spectrum of the real-PD pulse is highly recommended as it increases the reliability of the measurements.
- The term ‘apparent charge’ defined by IEC 60270 well reflects the strong relationship between the real charge (at the PD origin) and the measured charge (at the test object terminals). Renaming the term ‘apparent charge’ to ‘induced charge’ might be considered as proposed in [4, 5].

REFERENCES

[1] A. Gemant, W. Philippoff, "Die Funkenstrecke mit Vorkondensator," Zeitschrift für Technische Physik, vol. 13, no. 9, pp. 425-430, 1932.

[2] Böning, W.: Luftgehalt und Luftspaltverteilung geschichteter Dielektrika I. Untersuchung der Entladungen in einzelnen Luftspalten bei äußerem Wechselfeld, Electrical Engineering (Archiv für Elektrotechnik), Springer Berlin / Heidelberg, ISSN 0948-7921 (Print) 1432-0487 (Online), vol. 48, no. 1, 1963

[3] A. Pedersen, "Partial discharges in voids in solid dielectrics. An alternative approach, "*Conference on Electrical Insulation & Dielectric Phenomena"*, Gaithersburg, MD, USA, 1987

[4] E. Lemke, "A critical review of partial-discharge models" *IEEE Electrical Insulation Magazine*, vol. 28, no. 6, pp. 11-16, Nov-Dec 2012.

[5] E. Lemke, "Analysis of the partial discharge charge transfer in extruded power cables" *IEEE Electrical Insulation Magazine*, vol. 29, no. 1, pp. 24-28, Jan-Feb 2013.

[6] P. Mraz, et al, "Innovative application of frequency response analysis for Partial Discharge measurement," in *19th International Symposium on High Voltage Engineering*, ISH, Pilsen, Czech Republic, August 23 – 28, 2015.

[7] CIGRE TB 676, D1.29: Partial Discharges in Transformers, Feb. 2017

[8] Haefely Test AG, “DDX 9121b Partial Discharge Detector”, Operating Manual, V7.1

[9] Haefely Test AG, “DDX 9121b – PD Frequency range settings”, FAQ 118 document, 2018

[10] S. Abdul Madhar, et al, "Frequency Response of a Real Cable Network and its Impact on Field PD Measurements," *25th International Conference on Electricity Distribution,* Madrid, Spain, June 2019.