Technical Document

Evaluation and Limitations of Corona Discharge Measurements – An Application Point of View

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Evaluation and Limitations of Corona Discharge Measurements – An Application Point of View

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Abstract—**The phenomenon of corona discharge has been extensively discussed in numerous publications. However, those studies mostly focused on physical and chemical processes or the comparison of the corona effect for different isolation materials such as air, oil, etc. In this paper the effect of corona partial discharges is investigated from an application point of view. Corona characteristics and discharge patterns are explained and discussed starting from an initial phase which is dominated by Trichel pulses up to the onset of breakdown (pre-breakdown streamers). The limitations of electrical partial discharge measurements for the evaluation of corona discharges are examined.**

Keywords—partial discharge; corona; Trichel pulses; pulse-free zone; corona discharge fingerprints

I. INTRODUCTION

Partial Discharge (PD) measurement is an important part of modern and progressive diagnostic methods in high-voltage (HV) testing. The topic of PD measurement and evaluation has been investigated in numerous publications but only few have focused on an application point of view to particular PD effects. This paper deals with corona discharge which belongs to the group of external PD discharges. Special emphasis is placed on the evaluation of the voltage dependence of corona discharges. It is shown that, depending on the applied voltage, the cluster characteristics of corona discharges can be divided into four distinct development stages. A total of eight characteristic cluster patterns are identified depending on the location of the corona source (HV or Earth), the position of the measuring impedance and the development stage of the corona process. Based on the polarity of the corona discharge pulses and the cluster position the corona source can be clearly localized. As described in this paper, proper selection of the test setup and proper tuning of the partial discharge detector characteristics is essential to successfully interpret corona discharge patterns.

The occurrence of a “pulse-free” zone in the corona cluster is experimentally verified and discussed. This particular effect can be observed during Phase III of the corona discharge formation process and is characterized by the absence of partial discharge pulses in the center of the corona cluster. This phenomenon is caused by the bandwidth limitations according to IEC 60270 [1] and comparatively high pulse repetition rates observed for corona discharges. In this paper the well-known observation of a “pulse-free” zone (i.e. a drop in PD magnitude) for corona discharge pulses is thoroughly analyzed and verified by practical measurements.

II. CHARACTERISTICS OF CORONA FORMATION

A basic needle-plane test arrangement has been chosen for all measurements. Corona discharge has been simulated with a brass needle tip (∅ 24 µm before electrical stress), a circular lower brass electrode (∅ 75 mm) and a gap distance of 10 mm.

A. Phase I

If high-voltage is applied to the needle, discharge pulses can be observed in the negative half of the AC sine wave (Fig. 1a). These so-called Trichel pulses [2, 3] have relatively small amplitude (depending on the tip shape), high repetition rate and remain stable over time. Trichel pulses are caused by a fast transfer of electrons from the high-voltage electrode (needle) to the ground electrode (plane). The emission of the electrons leads to slow positive ions being generated. A space charge region is developed around the tip which inhibits further electron movement after a certain time. Only when the ions are moved away subsequent pulses can be initiated.

B. Phase II

As shown in Fig. 1b an increase of the test voltage causes the Trichel pulses to spread over a wider area of the AC phase. The number of electrons travelling between the electrodes is raised (avalanching) and a higher PD repetition rate is observed.

C. Phase III

Further increase of the test voltage results in the emergence of a “pulse-free” zone in the PD pattern. This special zone is located in the center of the Trichel pulse cluster (Fig. 1c). Common partial discharge detectors in compliance with IEC 60270 fail to correctly display PD pulses in this particular area. In fact, the repetition rate of pulses in this area is so high, that common PD analyzers are not able to recognize these pulse trains, the reason for this effect being the limited bandwidth settings according to [1], as explained in section V.

D. Phase IV

If the test voltage is further increased (close to the breakdown voltage of the test arrangement) high energy pulses occur in the positive half of the AC sine wave (Fig. 1d). These pre-breakdown or onset streamers exhibit high charge (i.e. energy) levels (significantly higher than Trichel pulses) and a tendency towards instability. The pulses are located in the positive half of the AC sine wave (needle) since this emerging conductive channel consists of positive streamers. Due to their high instability these streamer discharges can easily induce a voltage breakdown during phase IV. In that case onset streamers can be observed in both polarities of the test voltage. Phase IV is characterized by an audible (acoustic) effect.

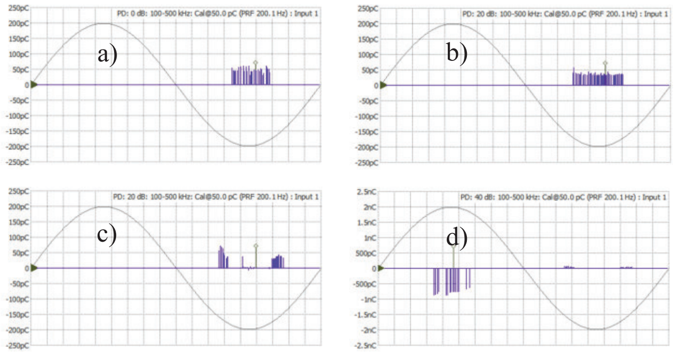

Fig. 1: Corona development phases in the pulse (Φ-q) diagram: a) Phase I, b) Phase II, c) Phase III, d) Phase IV.

The charge-voltage dependency is distinctive for each type of PD failure. Fig. 2 shows the typical characteristics of corona discharges. For lower voltages (phase I—III) a quasi-constant charge level is observed. Therefore, this particular behavior was used like a high-voltage PD calibrator in the past [4]. It should be noted, that the measured charge level is dependent on the tip radius and the described effect is valid only in a certain range of the test voltage. If the voltage is further increased, the stability of the charge value is reduced (see higher dispersion values for elevated voltages in Fig. 2).

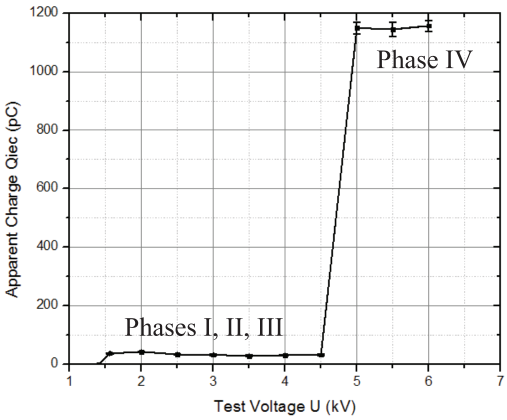

Fig. 2: Charge-voltage dependence of corona discharge

III. PD PULSE POLARITY RECOGNITION

Correct pulse polarity recognition is of major concern for PD measurement and evaluation especially in case of corona discharges. The source of corona discharges can be determined by virtue of the PD cluster position with respect to AC phase, cluster type as well as the pulse polarity.

The shape of the measured PD pulse is mainly determined by the following aspects [5]:

- PD failure type
- Impedance characteristics of the test object
- PD travelling path
- PD measurement system available bandwidth

Pulse polarity recognition is influenced by the aspects mentioned above together with the respective pulse recognition technique implemented inside the PD instrument. One of the main parameters for pulse recognition is the so-called “dead time” parameter used in common PD instruments. Some PD detectors use a fixed dead time value which can be adjusted if needed. Another approach is to calculate the dead time value based on PD instrument settings without access for the user to tune the value. Several PD detectors allow prolonging of the dead time value.

A constant value for the dead time parameter can lead to ambiguous recognition of the pulse polarity as shown in Fig. 3a. Pulse shape and duration can differ during normal PD testing depending on the voltage level which affects the character of the PD behavior or which can trigger an additional PD failure source with different pulse characteristics. Dead time is only one part of the pulse recognition algorithm and in particular cases usage of a fixed dead time parameter can lead to wrong polarity recognition. This is irrespective of the PD failure type and occurs for all type of PD, independent of the repetition rate. For correct polarity detection separate signal processing is required for PD detection and PD level measurement. Successful pulse detection requires the full PD detector bandwidth in addition to a dedicated pulse recognition algorithm as implemented e.g. in the DDX 9121b PD measuring instrument [6].

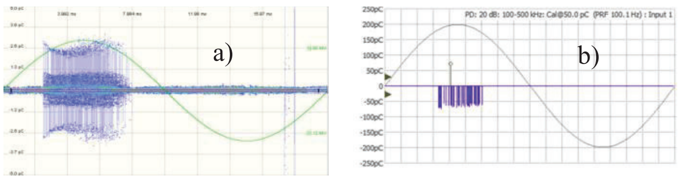

Fig. 3: Pulse polarity: a) ambiguous recognition due to fixed dead time, b) distinct recognition without ambiguity.

As previously discussed correct pulse recognition is essential to determine the origin of PD failures under AC stress. Correct pulse recognition becomes even more critical under DC stress since the number of PD pulses is one of the acceptance criteria for HVDC equipment. Using a fixed dead time parameter can cause tremendous measurement errors and acceptance problems for the device under test (DUT). For example, if the dead time parameter is selected too short oscillations caused by the PD filter settings will be recognized as additional PD events, hence the number of PD pulses is over-estimated. On the other hand, if a long dead time is selected the amount of pulses will be under-estimated in case of increased repetition rates [5].

IV. CORONA PULSE POLARITY EVALUATION

As previously shown in Fig. 1 corona discharge formation can be separated into two main cluster characteristics which are visually very similar: the “Trichel pulse cluster” (Fig. 4) and the “pre-breakdown streamer cluster” (Fig. 5). The location of the origin of corona can be easily determined based on the occurrence of either one of these clusters and considering the external voltage phase and pulse polarity.

In Fig. 4a positive pulses can be observed in the negative half of the AC sine wave. This is in contradiction to the assumption that Trichel pulses are caused by electrons flowing between the electrodes which would implicate negative polarity of the pulses. This observation is caused by the measuring circuit, i.e. by the position of the measuring impedance.

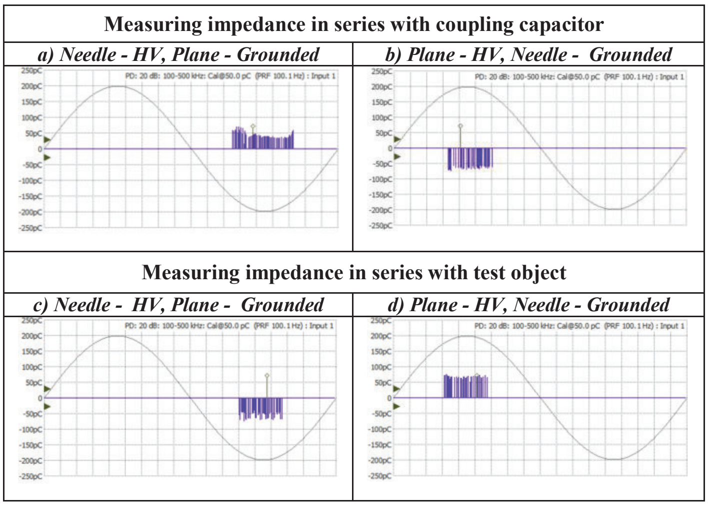

Fig. 4: Influence of the measuring impedance and HV source location – Trichel pulses – Phases I – III

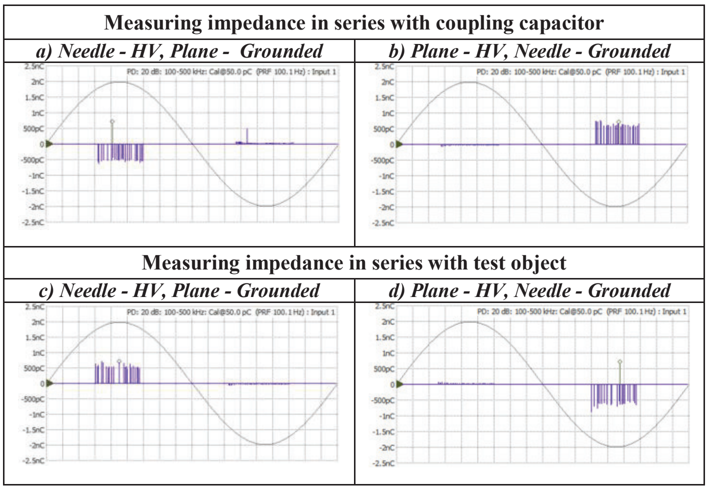

Fig. 5: Influence of the measuring impedance and HV source location – Pre-breakdown streamers – Phase IV

Fig. 6a shows the current flowing in the standardized PD measuring setup, where the measuring impedance (AKV) is in series with the coupling capacitor (note that this is the most common setup for PD testing). In the case of Trichel pulses the electron particle current is directed towards the grounded plane (needle is at HV). On the other hand, the corresponding electrical current results in a positive current flow and hence positive pulse polarity at the measuring impedance (see Figs. 4a and 6b).

Correct pulse polarity in accordance with the physical origin of the PD pulses can be obtained when the measuring impedance is connected in series with the test object (Fig. 4c). However, depending on the test object this configuration may not be feasible and can be dangerous in case of DUT breakdown.

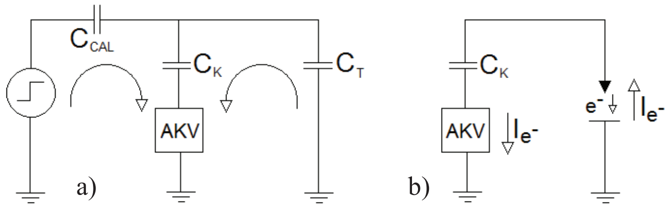

Fig. 6: Influence of the measuring circuit to the pulse polarity.

V. IMPACT OF FILTER BANDWIDTH SETTINGS ON PD MEASUREMENTS

This chapter deals with PD filter settings and their impact on PD recognition and pulse shape. Corona discharge behavior has been used for experimental verification. Special emphasis has been placed on the phenomenon of the "pulse-free" zone, which is located in the center of the Trichel pulse cluster and which occurs in the third phase of the corona development process described in Section II. PD pulses in the mentioned zone cannot be observed with common partial discharge detectors. In fact, their repetition rate is so high, that common PD analyzers fail to recognize those pulses.

It is easiest to explore the theoretical background of this phenomenon in the frequency domain of the PD signals. Fig. 7 illustrates how the continuous frequency spectrum of a single PD pulse event is transformed to the discrete spectrum (Fourier series) of repetitive/periodic pulses with a pulse repetition frequency PRF. A burst of PD pulses (corona) spaced in time at 1/PRF will have a continuous spectrum with peaks regularly spaced at PRF.

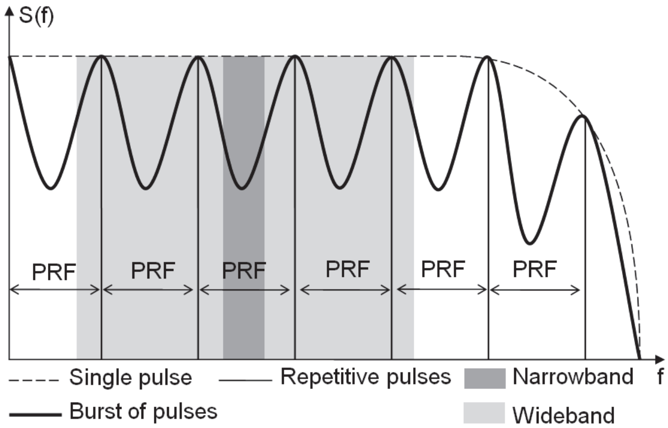

Fig. 7: PD spectrum formation

As previously shown corona behavior is characterized by a "burst" cluster with very high PRF which can reach the limit of 1 MHz for particular cases [7]. The frequency response magnitude of such a burst of pulses exhibits characteristic peaks and troughs defined by the PRF as shown in Fig. 7. For correct quasi-integration of the corresponding PD events the applied PD filter bandwidth must cover one or more peaks of the frequency response. Thus, narrow-band measurements (as indicated by the dark grey bar in Fig. 7) can lead to incorrect and unstable measurement results. The PRF of real PD activity is inherently unstable and therefore narrow-band PD filters will be randomly applied to the peaks and troughs of the measured PD spectrum. In addition, narrow-band measurements suffer from superposition errors of the time-domain signal, which can cause unstable PD readings as well.

The interaction of the PD filter bandwidth and the PRF of PD events has been experimentally verified. In the experimental setup a standard oscilloscope (500 MHz bandwidth) was used to record the raw signal data of corona discharges. The raw data is post-processed by a 4th order Butterworth low-pass filter with various cut-off frequencies. A standard needle-plane test arrangement with a 10 mm air-gap was applied.

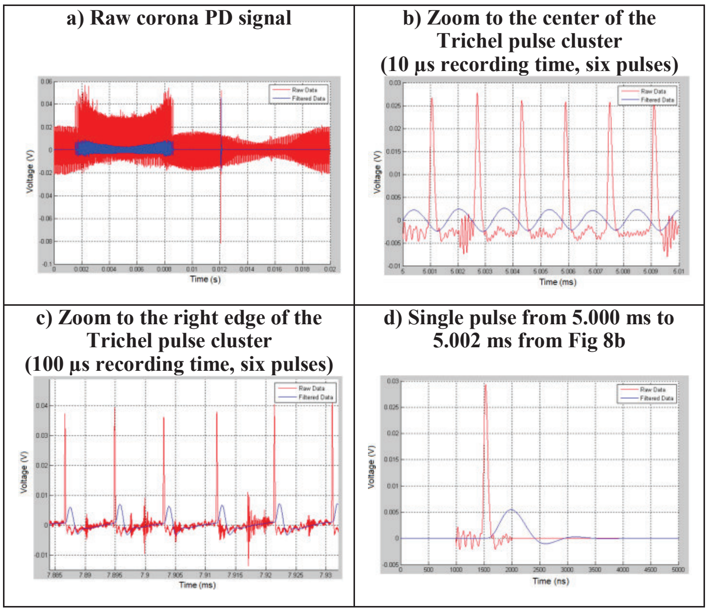

Fig. 8: Oscilloscope measurements (0.5 MHz low-pass filter)

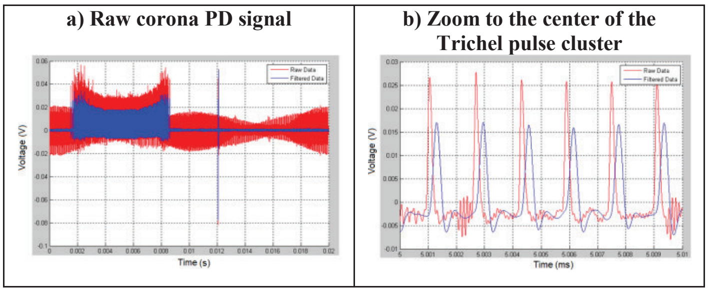

Fig. 9: Oscilloscope measurements (2 MHz low-pass filter)

A clear difference is observed between the repetition rate in the center and at the edges of the Trichel pulse cluster. The repetition rate in the center of the Trichel pulse cluster (see Fig. 8b) is ten times higher than at the edge (see Fig. 8c). Hence, PD pulses at the edges of the Trichel pulse cluster pulses are further spaced apart and the oscillations of the filtered output signal are less pronounced (Fig. 8c) than for the case of high repetition rates in the center of the Trichel pulse cluster (Fig. 8b). If the pulse repetition rate is higher than the PD filter bandwidth (i.e. the time lag between single pulses is too small), the filter output is mainly a pure sine wave. This effect prevents correct recognition of the PD pulses.

As shown in Fig. 8b the filtered output signal in the center of the Trichel pulse cluster is basically a sine wave with a frequency of 1 MHz. On the other hand, if a single pulse is processed by the filter, the filtered output preserves the general PD pulse shape which enables correct PD pulse recognition by the PD detector. The initial assumption that common PD detectors are unable to observe PD events in the “pulse-free” zone (as stated at the beginning of this section) must therefore be revised. The occurrence of a “pulse- free” zone in the center of the Trichel pulse cluster is caused by the PD filter limits imposed by IEC 60270:2000, which requires a maximum low-pass cut-off frequency of 500 kHz. As shown in Fig. 9, if the cut-off frequency is increased to 2 MHz the correct PD pulse level can be determined. The latest amendment to IEC 60270 [1] adapts the permitted PD filter settings for wide-band measurements by increasing the maximum low-pass frequency limit to 1 MHz and allowing a maximum measurement bandwidth of up to 900 kHz. This modification enhances correct pulse recognition and fulfills the general requirement that the system bandwidth should be higher than the pulse repetition frequency of the recorded PD activity.

VI. Conclusion

The formation and development of corona PD from an initial phase up to the onset of HV breakdown has been explained and described in this paper. Corona PD activity has a distinctive charge-voltage behavior, which is characterized by an initial stage governed by Trichel pulses up to a final stage with its pre-breakdown onset streamers. The origin of corona discharges can be readily determined from the PD pattern formation (burst cluster position) and pulse polarity. The phenomenon of a “pulse-free” zone in the PD pattern has been explained together with the proper tuning of the partial discharge detector characteristics. The experimental results reveal that narrow-band PD measurements suffer from many limitations when applied to corona discharges. A sufficiently wide bandwidth with respect to the pulse repetition frequency is essential for reproducible and plausible corona PD measurement and evaluation. For reliable and consistent measurement results it is strongly recommended to consider and verify both the time domain signal as well as the frequency response of PD events. The PD detector could even display a warning message when the PRF is too high.

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