Effect of High Voltage Impulses on Partial Discharge Characteristics of Oil-Impregnated Paper for Online Diagnostics

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***Abstract*—The onset of Partial Discharge (PD) activity within an insulation system is often an important signature of degradation. Changes in the PD pattern aid assessment of the insulation degradation level. High voltage transients such as lightning and switching impulses are inevitable phenomena in power systems. They can impose electrical stresses on the insulation system of power components such as power transformers and their bushings which may lead to their failure. After the arrival of a transient the AC PD pattern may change, in a way that is influenced by the type of PD source. In this paper, the effect of HV impulses on the change of surface and cavity discharges of oil-impregnated paper has been investigated. With resemblance to the real situation, insulation samples have been subjected to an impulse voltage superimposed on the AC voltage. The behavior of PDs before and after the impulse for different defects and moisture content levels in oil-impregnated paper has been studied. The results show a distinctive behavior of PD due to the impulse for each defect and insulation condition, either by change in the PD rate and magnitude or by causing PD inception or extinction. Recording the voltage signals and associated PD measurements during and after the incident of high voltage transients can be used for assessing the insulation condition of power transformers and their bushings and interpretation of the recorded signals can be used for online diagnostics.**

***Keywords*—cavity discharge, surface discharge, PD pattern, oil-impregnated paper, superimposed impulse.**

I. Introduction

Partial discharge measurement and analysis can provide information at an early stage of insulation degradation, before insulation failure. They can improve the reliability of the system through the estimation of the failure probability of the components. Physical understanding of PD behavior and interpretation of the results has a significant role in exploiting the PD measurements as a powerful tool in diagnostics. There are many parameters involved in the PD behavior which need to be considered for the interpretations. Power system equipment mostly works at power frequency 50/60 Hz and their insulation requires working in that frequency for a long life cycle without failure. However, various stress factors such as inevitable transients happening in power system will unpredictably affect the insulation parts. Partial discharges are known for the defect indication [1] and their prolonged activity can lead to the failure of the insulation system.

Other than AC voltages, PD activity of insulation systems under DC voltages has also been investigated to characterize different defects in HVDC systems [2], [3]. There are some works that have been done on the effect of impulses on the insulation system. Breakdown strength and impulse-inception stress of polyethylene under several impulses has been investigated in [4]. PD inception and breakdown strength of oil-impregnated paper (OIP) with lightning impulse superimposed on the AC has been studied in [5], [6]. However; PD mechanisms under the superimposed impulse on the AC voltage are less investigated [7]. Transients of different origins like lightning discharges and switching operations of circuit breakers are inevitable phenomena that occur in electrical power systems. Transients usually can occur during the operation of the component and they will get superimposed on the AC operating voltages. Although power components are protected from the transients whose magnitude gets limited through the surge arresters, they can still be stressed by overvoltages.

Other stress and aging factors such as high temperature and manufacturing issues can lead to defects in the insulation. The aged insulation is prone to further damage and in this situation the effect of impulses on the insulation gets more important. Equipment in operation may have defects above the PD inception level and there is a maximum acceptable partial discharge activity for a power component. As long as the PD activity doesn't exceed the critical level, its deterioration effect will be considered trivial. Therefore it is of interest to know how the impulses can affect the partial discharge characteristics above the PD inception voltage.

The aim of this work is to investigate the effect of transients such as lightning impulses on the AC partial discharge behavior of OIP for surface or cavity defects. Pressboard as another major insulation of power transformers was also investigated for surface discharges. Moisture, which is an aging product of oil-paper insulation, can change the electrical property of the paper. Therefore, its effect on partial discharge behavior of the paper with applied impulse also has been investigated. This whole study shows how the PD activities get influenced by the impulses and how those behaviors can be valuable for online diagnostics and the defect identification in power transformers and their bushings.

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II. EXPERIMENTAL SETUP

A. AC with superimposed impulse

To investigate the effect of impulses on partial discharge characteristics of oil-impregnated paper, AC and impulse generator system was used together to be able to superimpose the impulse on the AC voltage at a controlled point in the AC cycle. Fig 1 shows the circuit of the superimposed standard lightning impulse (1.2/50 µs) on the 50 Hz AC voltage.

For the measurements shown in this paper, the impulse was positive and was triggered at the positive peak of the AC voltage. Triggering of the impulse generator at a specific phase position of the AC voltage is done with a phase-triggering circuit consisting of a microcontroller (Arduino) and a solid state relay.

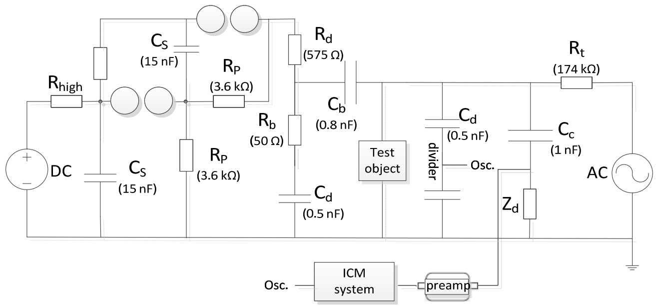

Fig. 1. Test circuit for PD measurement with impulse superimposed on AC voltage

B. PD measurement

For partial discharge measurement, a series connected coupling capacitor (C_c) of 1 nF and detection impedance (Z_d) of 1 kΩ were connected in parallel with the test object. The voltage over the detection impedance was measured by an Insulation Condition Monitoring (ICM) system from Power Diagnostix, through its preamplifier (preamp), Fig. 1. This PD measurement system can be used to record the PD patterns with respect to time or to the phase of the AC voltage. For capturing time-resolved signals in a shorter time period around the occurrence of an impulse, the PD signal after low-pass filtering and amplification in the PD measurement system was also recorded on one channel of a Tektronix DPO4102B oscilloscope.

C. Recorded data

In the Results Section, some plots show the signals captured on the two channels of the oscilloscope, representing the voltage at the test object and the PD activity. They only indicate the timing of the impulse relative to the AC voltage and the PD activity, and the phase and relative magnitude of PD activity within each AC cycle. Due to the loading effect from the phase-triggering circuit and change in PD system filtering and amplification between measurements, they don't show the actual values. However, the correct AC peak value and impulse voltage magnitudes measured by the meters connected to the voltage divider are written below each figure. PD patterns in phase or time, recorded from the PD measurement system instead of the oscilloscope, are calibrated in terms of apparent charge.

D. Sample setup

A setup with a needle electrode on high potential and a grounded bar on the surface of the insulation was used for the surface discharge study, as shown in Fig. 2. The needle had a tip radius of 3 µm. The distance between the needle tip and the ground bar was set to be 3 cm. 10 layers of Munksjö Thermo 70 oil-impregnated paper (each 100 µm thick) and 2 mm thick pressboard immersed in the oil were used for the studies. The papers and pressboard were dried and impregnated in Nytro 10XN transformer oil. After the impregnation process [8], the moisture content of the samples is less than 0.5%. Both paper and pressboard samples were immersed in the transformer oil for the experiments.

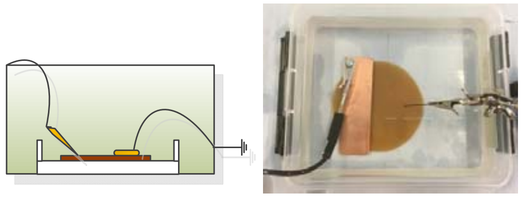

Fig. 2. Test setup for surface discharge measurements

To study the cavity discharges, only oil-impregnated paper samples were used. Each sample had 16 layers of oil-impregnated Munksjö Thermo 70 with a total thickness of 1.6-mm, Fig. 3. A cylindrical cavity with 8 mm diameter and thickness of 0.4 mm was made by punching discs out of the 4 central layers of paper. The whole set-up of electrodes and paper layers was assembled and clamped before immersion in the oil, to form a gas filled cavity [8].

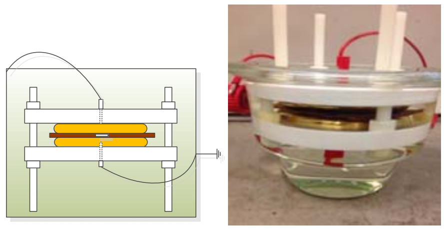

Fig. 3. Test setup for cavity discharge measurements

The effect of moisture content was studied by using saturated salt solution, as a closed chemical system [9], to control the Relative Humidity (RH) of the air surrounding the oil-impregnated paper. By using two different salts, two different moisture levels (3% and 5.5%) were obtained in the paper samples. Table 1 shows the relative air humidity and equilibrium moisture content of oil-impregnated paper, for the two salts, based on Rockland [9] and Cheng [10]. Permittivity and loss tangent of each material were measured as a function of frequency at 200 V using a Megger IDAX 300 from 0.01 Hz to 10 kHz.

Several samples of each material were used for each study, to have a better understanding of their PD behavior under the superimposed impulses and each displayed figure shows results from one sample that was seen to be a typical of similar samples.

TABLE I. RELATIVE AIR HUMIDITY OF SATURATED SALTS AND CORRESPONDING MOISTURE CONTENT OF OIL-IMPREGNATED PAPER AT ROOM TEMPERATURE (20ºC) [10]

Salt	Relative air humidity (%) at 20ºC	Moisture content of paper (%)
Potassium acetate	23	3.0
Sodium bromide	57	5.5

III. RESULTS FOR SURFACE PD

The effect of impulses on the AC surface PD characteristics of oil-impregnated paper and pressboard was investigated for voltage levels, below and above the PD inception voltage. Although pressboard and paper are made of almost the same material, the surface and bulk of pressboard has a different structure from the paper. This difference can also lead to their different PD behavior affected by the impulse.

A. *Surface PD on Oil-impregnated Pressboard*

Surface PD behavior of oil-pressboard by applied superimposed impulse was studied below and above the surface AC inception voltage. When the AC voltage applied to the samples was kept below their surface PD inception voltage (about 90% of the inception), the applied impulse can initiate surface discharges which decays after few seconds but the continuous surface PD activity cannot be fulfilled. The charge decay can also be affected by several parameters related to the properties of both oil and pressboard and applied AC voltage.

Above the surface PD inception, a positive superimposed impulse was applied at the positive AC peak voltage to the oil-pressboard samples.

Following the applied impulse at the positive AC peak, the surface PD shows a cluster of higher magnitude PD which declines over time, Fig. 4 and 5. For this case, decay of the injected charges from the HV impulse seems to be fast and the charge magnitude decay over time has an exponential-like behavior for the pressboard.

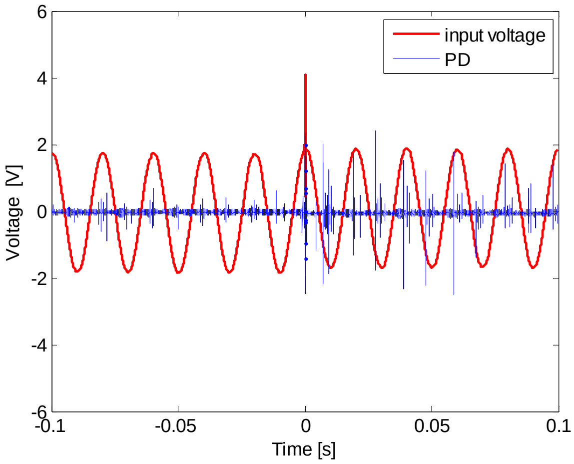

Fig. 4. Oil-pressboard surface PD activity during five cycles before and after the impulse, at 27 kV AC (20% above the inception), with 25 kV superimposed impulse

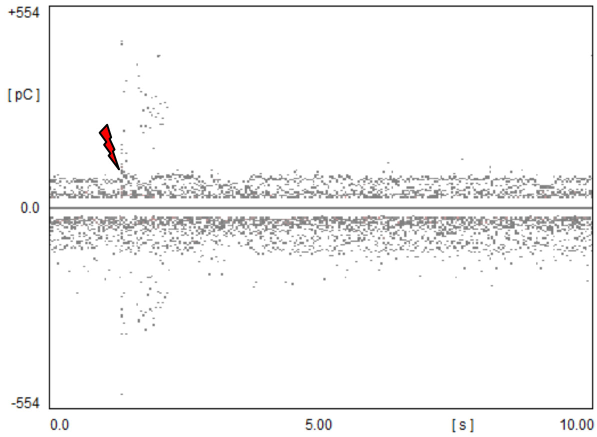

Fig. 5. Oil-pressboard surface PD charges vs time over a 10 s time window, at 27 kV AC (20% above the inception) with 25 kV superimposed impulse

B. *Surface PD on Oil-impregnated Paper*

The superimposed impulse effect on OIP surface PD was also studied at voltages below and above the PD inception voltage. When the AC voltage is below the surface PD inception, the superimposed impulse can initiate a temporary surface PD on the oil-paper interface that decays after several AC cycles. Above the PD inception voltage, a superimposed impulse at the AC peak increases the number of PDs for several AC cycles which can be observed in Fig. 6 and 7.
Ionization due to the applied impulse voltage results in charges being deposited on the surface of the insulation, modifying the local electric field during and after the impulse. This is a way in which the impulse can affect the subsequent AC PD, by affecting the resulting electric field in the region. Drift of charges through the oil and trapping and detrapping of charges from the paper or pressboard surface, can influence the behavior of PD after the impulse.

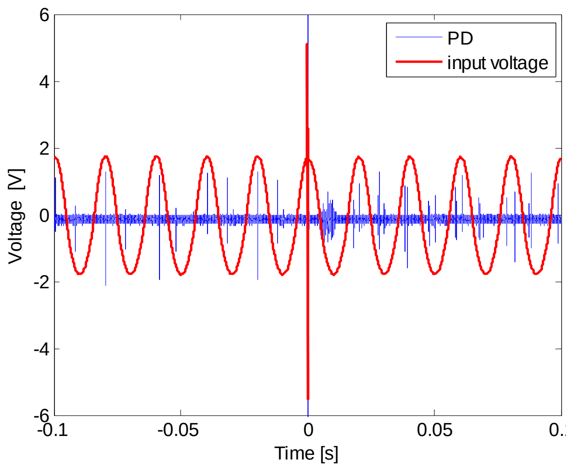

Fig. 6. Oil-paper surface PD activity during five cycles before and after the impulse, at 27.6 kV AC (20% above the inception) with 33 kV superimposed impulse

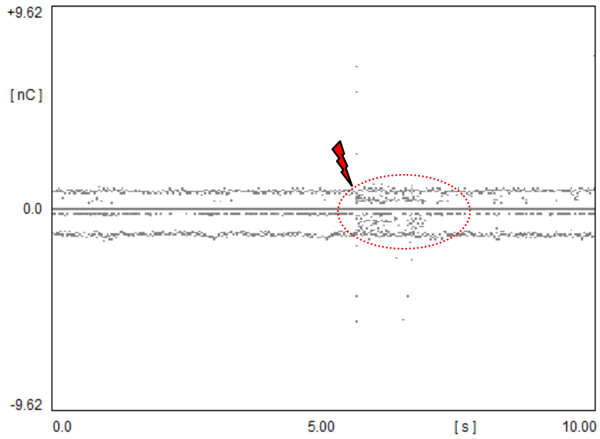

Fig. 7. Oil-paper surface PD charges vs time over a 10 s time window, at 27.6 kV AC (20% above the inception) with 33 kV superimposed impulse

Another potential influence of the impulse voltage is the availability of charges due to the impulse's ionization. Charges will decay depending on their interaction with the AC PD, and on the permittivity and surface conductivity of the insulation. Different behavior of surface PD on oil-impregnated pressboard to the applied impulse compare to the OIP can be valuable for identification of PD sources.

C. *Surface PD on Oil-impregnated Paper with Moisture Content*

The presence of moisture in OIP can significantly affect its surface discharge characteristics [11]. Water is a polar molecule that can align easily in the direction of the electric field, and also increases the presence of positive and negative ions. Therefore, it is expected that the behavior of surface PD for paper with moisture content would be different from the dry paper (with moisture content below 0.5%) and that it shows different characteristic by the impulse. Therefore, the effect of moisture content in surface PD behavior of OIP has been also investigated, using OIP samples with two levels of moisture content, 3% and 5.5 %.

Paper with 3% moisture content shows a prompt decrease in the PD activity after the impulse, but returning to its previous level within a few seconds. Paper with 5.5% moisture content shows the same behavior in the few cycles after the impulse, but after that a considerable increase in the PD apparent-charge magnitudes is seen, Fig.8 and 9. Decrease in the magnitude of discharges after the impulse, followed by an increase in the PD magnitude, may be a sign of moisture content in the paper for the surface discharge defect.

Small gas bubbles were produced by partial discharges and found floating in the oil. The discharges and impulses might force the moisture out of the paper in the region of the surface PD activity and leave the small weak voids in it which can cause bigger partial discharges occurring at the same voltage [12]. Therefore, the effect of impulses on the paper with high moisture content might be considered more seriously.

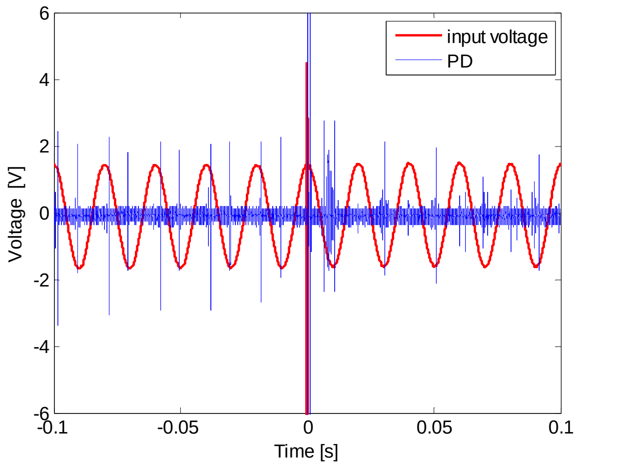

Fig. 8. Surface PD activity of oil-paper with 5.5% moisture content during five cycles before and after the impulse, at 22 kV AC (20% above the inception) with 33 kV superimposed impulse

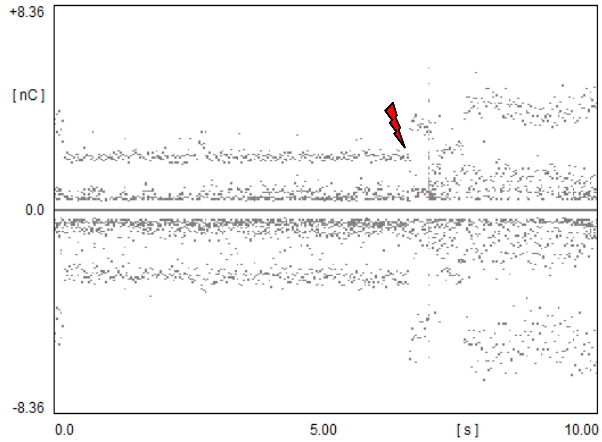

Fig. 9. Surface PD charges vs time over a 10 s time window, for oil-paper with 5.5% moisture content at 22 kV AC (20% above the inception) with 33 kV superimposed impulse

IV. Results for Cavity PD

Cavity PD sources are of practical significance for insulation systems in many types of power equipment, including bushings and transformers with oil-paper insulation. Their continuous activity can lead to deterioration and failure in the insulation. Impulses can provide the initial condition for PD inception in cavities that would otherwise not experience PD with just the AC voltage. This has a practical relevance in that it assists identification of these cavities, but also in that it increases the deterioration. Cavity PD is studied in this Section, using OIP insulation as described in Section 2.

A. *Cavity PD Below the Inception Voltage*

The experiment was done to check whether the impulse can initiate the cavity PD below the inception voltage. The AC voltage was applied to a sample at several voltage levels below the inception voltage, and a superimposed impulse was applied at the positive peak of the AC. The Fig. 10 shows that at voltages close to the cavity inception voltage, the impulse voltage can initiate continuous AC PD activity. If the applied AC voltage level was lower than 80% of the inception, the PD initiation by the impulse had more temporary behavior. The effect of impulse amplitude on PD initiation at voltages close to the inception was also investigated. The results show that at AC voltages close to the inception, the PD can get initiated even with low magnitude impulse. However, there can be more involved parameters such as insulation condition which can participate in the PD behavior. The impulse can provide the ionization and surface charges to facilitate the subsequent AC PD, and the continuity of the PD activity in the cavity can be easily satisfied by the previous PDs. When PD has already occurred in a cavity, electrons from previous discharges may be held in traps near the surface of insulation increasing the supply of starting electrons. The PD extinction for a cavity is typically significantly below the inception, so the PD has a good chance of continuing once initiated.

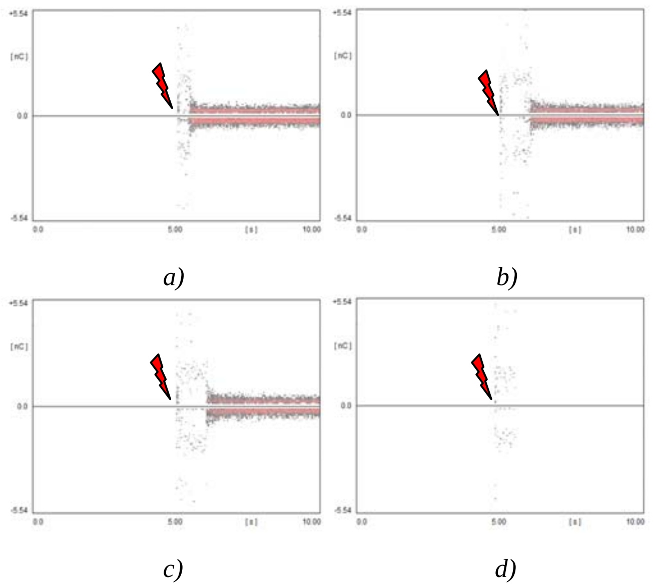

Fig. 10. Cavity PD pattern vs time for 10 s time window with impulse effect, a) with AC at 98% of inception b) with AC at 90% of inception c) with AC at 80% of inception d) with AC at 75% of inception of 6.7 kV, All measured with a 22 kV impulse.

B. *Cavity PD at the Inception Voltage*

Another study was done on the impulse effect at cavity PD inception voltage. An interesting phenomenon was observed on the PD behavior at its inception voltage with applied impulse. When the electric field in the cavity was just at its PD inception level, the applied superimposed impulse could extinguish the PD for several cycles following the impulse, Fig. 11 and 12. There may be several reasons leading to this behavior including reduced electric field, ion neutralization, charge depletion or high conducting void surface that would shield the void interior from the electric field. This pattern was observed on all samples used for this study.

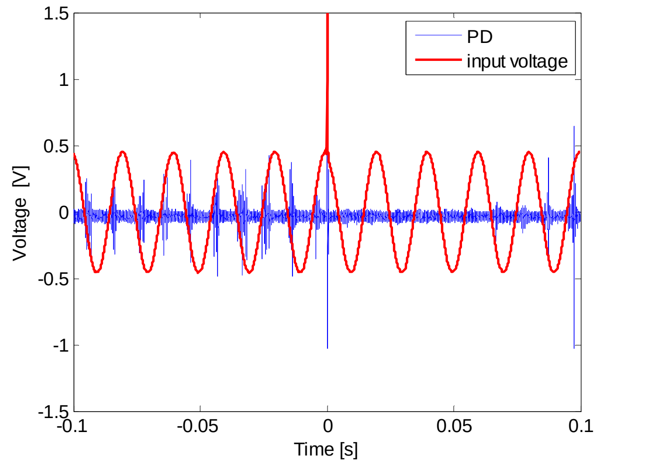

Fig. 11. Oil-paper cavity discharge activity during five cycles before and after the impulse, at 5 kV AC inception with 22 kV superimposed impulse

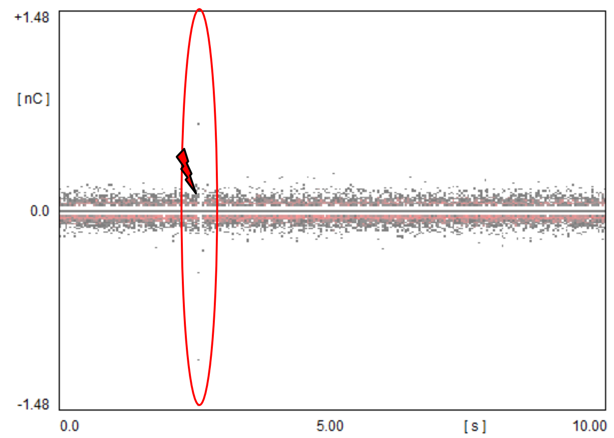

Fig. 12. Oil-paper cavity PD charges vs time over a 10 s time window, at 5 kV AC inception voltage with 22 kV superimposed impulse

C. *Existance of several cavities*

In some situations, there can be several cavities with different sizes within the solid insulation. This can lead to a different PD inception condition for each of them. Another interesting behavior was observed for samples with different cavity sizes imposed to the impulse above the inception voltage. Samples of 16 layers of OIP were used. One 8 mm and four 3 mm diameter disc-shaped cavities were made at the middle layers with a thickness of 400 µm. An AC voltage above the PD inception level was applied, and a superimposed impulse was triggered at the AC positive peak voltage. The result shows that by an applied impulse, a cluster of larger magnitude PD can be observed in the PD pattern for several cycles after the impulse, Fig. 13. Applied impulses superimposed on the AC voltage can excite the smaller cavities even if they would not have had sustained PD at the rated AC voltage; these cavities can then be identified by detection of the changed PD activity.

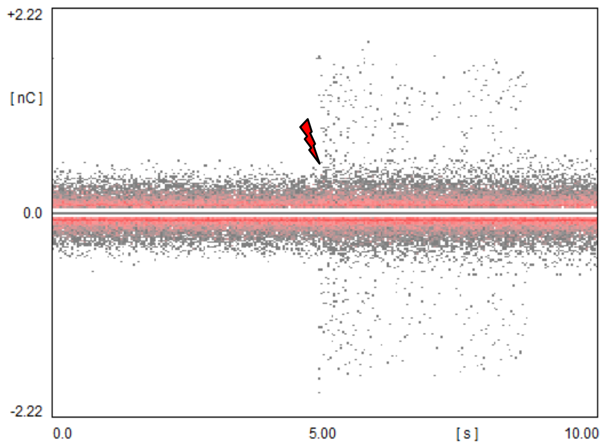

Fig. 13. PD pattern of oil- paper with several cavities vs time over 10 s time window, at 6 kV AC (20% above the inception) with 22 kV superimposed impulse

D. Cavity PD in Oil-impregnated Paper with Moisture Content

The effect of moisture content was also investigated for a cavity in oil-impregnated paper insulation. OIP with 3% and 5.5% moisture content were used for the study. The AC voltages for PD inception in papers with moisture content were lower than the inception level for dry paper (moisture content below 0.5%) [13]. With AC voltage at the cavity PD inception, OIP with 3% moisture content showed the same pattern as the dry OIP, and impulse could extinguish PDs for several following cycles. However, for OIP with 5.5% moisture content, applied impulse could increase the number and magnitude of charges for several following cycles after the impulse, Fig 14.

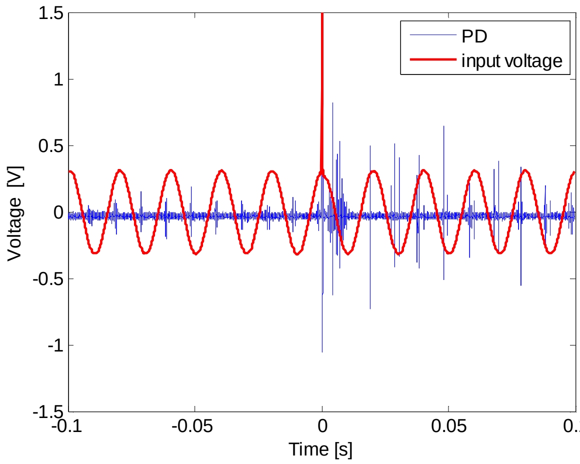

Fig. 14. Cavity discharge activity of oil-paper with 5.5% moisture content, during five cycles before and after the impulse, at 3.8 kV AC inception with 22 kV superimposed impulse

V. CONCLUSION

The effect of an impulse on surface PD behavior has been shown to vary between different insulation interfaces. The AC surface PD at oil-pressboard and oil-paper interface can show either an increase in the magnitude or an increase in the number of PD following the impulse. Insulation condition such as moisture content in the paper can affect the PD behavior after the impulse, e.g. leading to the decrease in the magnitude and number of charges for several AC cycles. Cavity PD with the AC voltage below the inception can be initiated by an applied impulse. When the AC voltage is at the cavity's inception level, the impulse can extinguish the PDs in dry samples for several cycles, whereas in paper with high moisture content, the impulse can increase the PD number and magnitudes for few seconds. In general, the impulse will affect the PD behavior and in practice it is valuable to measure the PD when the transients happen. As the behavior of PD after an impulse is distinctive for each defect and insulation condition, this study may be used for online diagnostics and interpretation of PD activities for defect classification.

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