Partial Discharge Behaviour under Operational and Anomalous Conditions in HVDC Systems

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ABSTRACT

Power cables undergo various types of overstressing conditions during their operation that influence the integrity of their insulation systems. This causes accelerated ageing and might lead to their premature failure in severe cases. This paper presents an investigation of the impacts of various dynamic electric fields including ripples, polarity reversal and transient switching impulses on partial discharge (PD) activity within solid dielectrics with the aim of such considerations in high voltage direct current (HVDC) cable systems. Accordingly, down scaled terminal voltages of a generic HVDC converter were reproduced – of different harmonic contaminations – and applied to the test samples with the aim of PD analysis. The effects of systematic operational polarity reversal and superimposed switching impulses with the possibility of transient polarity reversal were also studied in this investigation. The findings of this investigation will assist in understanding the behaviour of PDs under HVDC conditions and would be of interest to asset managers considering the effects of such conditions on the insulation diagnostics.

Index Terms — Firing angle, Power conversion harmonics, HVDC transmission, Insulation, Polarity reversal, Power system transients, Partial discharge, Ripples.

1 INTRODUCTION

The introduction of polyethylene in the 1940s initiated a revolutionary progress in the cable industry [1], and since then many polymeric materials have been produced and found applications in cable manufacturing owing to their technical and economical advantages. Accordingly, successful deployment of high voltage direct current (HVDC) projects relying on mass impregnated non-draining (MIND) cables motivated the employment of their polymeric counterparts, particularly, of cross-linked polyethylene (XLPE) material in such applications. In addition, the envisaged Supergrid, interlinking different countries within Europe through HVDC cables has the aim of delivering one hundred percent of Europe’s electricity from renewable resources eliminating nearly forty-five to fifty percent of European greenhouse gas emissions at affordable prices [2,3]. Consequently, this accentuates the application of environmentally friendly interconnecting cables. The first application of XLPE DC cable was the Gotland project, Sweden, operating at 80 kV in 1998, and since then significant developments have taken place in terms of material, rating and characteristics. In 2014, ABB announced manufacture of an XLPE DC cable operating at 525 kV [4].

However, it has been reported that polymeric power cables are less resistant to partial discharge activity and electrical treeing [5]. They could even be influenced by the normal polarity reversal operation of Line Commuted Converters (LCC), this might be due to accumulation of space charges under the effect of DC electric fields [6, 7] that result in locally intensified fields within the cable insulation. This affects the electrical strength of the cable insulation leading to its accelerated aging and premature failure. Moreover, the operational nature of HVDC systems introduces another challenge: harmonic injection that appears in the form of ripples in the DC side of the converters influencing cable insulation [8].

Furthermore, transients in electrical systems are inevitable phenomena that happen due to external or internal influences in power systems. The effects of transient overvoltages on insulation, particularly partial discharge behaviour within power cables under AC regimes, has been comprehensively studied and the phenomenon is well understood [9-11]. Nevertheless, less research has been devoted to such effects under DC electric fields, especially DC superimposed with transient overvoltages that can also cause transient polarity reversals.

Partial discharge measurement is a non-destructive insulation diagnostic method that can be performed online or offline. It is a mature technique for AC systems [12], and many partial discharge
diagnostic methods have been proposed and developed [13, 14]. The influences of voltage distortion, harmonics and transients in AC systems have been investigated in [15, 16] and it was reported that these phenomena hasten the insulation degradation. Concerning the principles and the mechanisms of partial discharge under DC fields, thorough investigations have been carried out [17, 18] and, recently, new studies have focused on the insulation behaviour such as partial discharge activity under abnormal conditions that could be imposed by the operational conditions of HVDC equipment through modelling [19, 20] and experimental tests [21, 22]. However, a knowledge gap exists regarding the effects of HVDC ripples, converters’ operational polarity reversal and transient overvoltages in HVDC systems on PD behaviour. To address this, the present study investigated the PD characteristic behaviour under such incidents based on empirical observation in a range of experiments that have been conducted under laboratory conditions on artificially prepared insulation defect test samples.

2 THE OPERATION OF HVDC SYSTEMS

2.1 RIPPLES IN HVDC CONVERTER TERMINALS

Nonlinear operation of high voltage converters generates harmonics that appear as ripples in the DC side and distortions in the AC side. The harmonic currents and voltages cause power losses, overload the transmission lines and give rise to degradation of the insulation systems [23, 24]. In spite of the fact that the rippled currents in the DC side contribute to ohmic losses in the conductor, their overall effects on the insulation is less prominent than that of voltage ripples. This is due to the inductive characteristic of the DC side in LCC [25].

Mostly, two schemes of HVDC systems are currently employed in electricity transmission: Voltage Source Converters (VSC) and line commutated current source converters. Accordingly, the operational principles and the adopted technologies result in distinguished outputs making each suitable for different projects of certain purposes [26]. The LCC schemes are commonly deployed for the purpose of bulk power transmission up to several GW due to availability of highly rated Thyristors [27], and the polarity reversals are adopted for the change of power flow direction, while the VSC schemes are deployed at lower power ratings, with no voltage polarity reversals are required for the redirection of power flow.

In the generic HVDC system illustrated in Figure 1, a three-phase bridge rectifier is the building block of an LCC converter where the switching valves are based on Thyristor technology. These converter valves are turned on by gate firing circuitry and commutated by the AC line voltage alternation. Usually twelve-pulse converter topologies are employed in modern HVDC LCC schemes, where two six-pulse converters are connected in series. One of these six-pulse converters is fed from a star connected transformer and the other from a delta connected transformer on the valve side. The component six-pulse converters might operate symmetrically or asymmetrically [28, 29]. The phase angle of Thyristors is the governing parameter for the control of direction and the amount of power to be exchanged within the operating transmission line. At the same time, the value of firing angle determines the harmonic level, voltage and current, injected into the DC side of the system. As the value of firing angle increases the magnitude of the harmonic components grows [24]. Figure 2 shows terminal voltage of a typical HVDC converter. The magnitude and waveform of the rectified voltage is a function of firing and commutation angle.

Fourier analysis of the converter voltage shows that the orders of the comprising harmonics of the ripples are a function of the converter’s topology. For example, in a six pulse converter the harmonic voltages are obtained using [23]:

\[ V_n = \frac{V_{co}}{\sqrt{2(n^2-1)}} \left[ (n-1)^2 \cos^2(\frac{n+1}{2}) \right] + (n+1)^2 \cos^2(\frac{(n-1)}{2}) \]

\[ -2(n-1)(n+1) \cos((n+1)\frac{\mu}{2}) \cos((n-1)\frac{\mu}{2}) \cos(2\alpha + \mu) \]

and the maximum rectified voltage defined as follows:

\[ V_{r} = \frac{3\sqrt{2}V_{c}}{\pi} \]

where \( V_{r} \) is the line voltage, \( n \) is the harmonic order, \( \alpha \) and \( \mu \) are delay and overlap phase angles, respectively. Figure 3 depicts the magnitude of the dominant sixth harmonic voltage as a function of the firing and commutation angles [23, 30].

![Figure 1. A generic HVDC transmission system.](image1)

![Figure 2. A typical output of a six-pulse LCC converter considering the firing angle \( \alpha \) and the commutation angle \( \mu \).](image2)

![Figure 3.](image3)
operation of the converter is another source of internal transients. A misfiring or fire-through of a switching valve due to malfunctioning of the Thyristor gate firing circuitry, or single/double commutation failure as a result of dynamically changing conditions in the AC side, or the high current flow in the DC side along with the controlling unit are main reasons for transient overvoltages in the DC side. Furthermore, a single pole to ground short circuit occurring in symmetrical monopole HVDC systems or bipolar schemes might give rise to induced transient overvoltages. The grounding topology of HVDC systems also affects the characteristics of the overvoltages [37-39]. The transient overvoltages overlay the DC side voltage either in the same polarity or in the opposite [6]. Depending on the type of the superimposition, the imposed Laplacian electric field could either underpin or weaken the Poisson field of the already built-up space charges within the insulation [17]. Hence, the intensified resultant electric field could critically affect the cable insulation or even lead to its failure [6,40]. In Section 5.3, the experimental results of superposition of standard switching impulses will be discussed.

### 3 Partial Discharge Phenomenon

The localized enhanced electric field that rises beyond the surrounding medium strength could result in partial discharges [41]. PDs appear in different pulse shapes covering a varying frequency spectrum depending on their origins and the path they travel in the medium to the detection point. They are influenced by the driving electric field magnitude, insulation medium, environmental conditions and the defect site geometry [12,42-43].

#### 3.1 PD Mechanisms Under DC Fields

Partial discharges occur in the defect sites, regardless of the type of applied voltage, when the net electric field across the defect rises beyond its electric withstand, providing discharge igniting electrons are present. Under a steady state AC regime, the emitted PD pulses take place repetitively forming specific patterns.

However, under DC voltages there is no such a driving (of AC voltage) for discharge incidence at defect sites and the DC PDs possess an infrequent occurrence due to the effect of non-varying DC fields. The reason underlying this is the behaviour of the dielectric materials when subjected to steady state DC voltages. Under such conditions, the electric field distribution within the dielectric is governed by its conductivity ($\sigma$), where it is mainly a function of the material composition and the temperature. Dielectrics generally behave capacitively under the influence of AC fields, with the permittivity ($\varepsilon$) of the insulating material having the major role in the electric field distribution [6, 44-45]. Figure 4 shows the extended $abc$ [46] model in order to explain the mechanism of discharge at DC fields. In its simplest form, the incorporated conductive elements govern the voltage and hence the electric field distribution according to Ohm’s law. So the modelled defect site is charged through the resistor in series and when the electric field magnitude reaches breakdown, a discharge occurs. Accordingly, as the magnitude of the applied voltage increases the number of the discharges rises due to the increase in the magnitude of the leakage current within the insulation [19, 40]. Generally, the material employed for the insulation systems are of high ohmic properties, so the leakage currents are of low values resulting in a lower level of PD activity at defect sites under DC fields than when compared to AC fields.
Nevertheless, the voltages that HVDC cables experience in the real scenarios are not a purely smooth DC voltage, but contain ripples and are exposed to transient overvoltages of many types as discussed in section 2. In such situations the insulation experiences sudden field changes and it is reported that they behave pseudo-capacitively [6]. The rising front of overvoltages are comparable to a quarter of an AC cycle which influences the state of already accumulated space charge and redistributes them leading to increased probability of PD occurrence at the defect point [47].

3.2 PD DETECTION METHODS

Partial discharge phenomenon is a mechanism of energy conversion. A PD incident is accompanied by light emission, electromagnetic radiation, electromagnetic vibration (sound), chemical transformation and heat generation [13-14, 48]. Therefore, detection of one or many of these phenomena would result in recognition of PD occurrence within the device under test (DUT). Generally, the detection or the measurement method is adopted according to the type of equipment. The electromagnetic methods have proved to be more appropriate for the detection of PD pulses in cable system, and they are, generally, categorized as conventional and nonconventional test techniques [13, 14]. Recently, nonconventional techniques have attracted much attention and various methods have been developed and proposed by researchers. Among the nonconventional methods are high frequency techniques – measuring the PD pulses in the range of 3-30 MHz using high frequency current transformers (HFCTs) [49-51].

4 MEASUREMENT OF PARTIAL DISCHARGE

In this study, partial discharge pulses emanating from artificially made test samples were detected using an HFCT sensor. The sample preparation and the measurement procedures will be discussed in the following subsections.

4.1 TEST SAMPLE PREPARATION

The geometry of the test sample is shown in Figure 5. The bulk material of the sample is epoxy resin of 3 mm in thickness. It is transparent and has insulation properties that make it suitable as a test specimen. In order to produce a gas filled cavity to simulate a discharging defect, a controlled amount of air was injected to the partially-solidified moulded specimen and was left to set forming the gas-filled void. The diameter of the formed air-filled bubble is 1 mm.

4.2 EXPERIMENTAL SETUP

The experimental setup for the PD measurement under laboratory conditions is portrayed in Figure 6. The test waveforms are a downscaled terminal voltages of a six-pulse LCC converter and polarity reversal scenarios generated in an environment of interlinked MATLAB and LabVIEW and fed into a high voltage (HV) amplifier (Trek model 30/20A) via a data acquisition card (National Instruments). Transient switching overvoltages were reproduced using programmable function generator (RIGOL DG4000) and fed into the HV amplifier. The stable gain of the HV amplifier is 3kV/V with the maximum attainable output of ±30 kV. An HFCT sensor was clamped around the ground wire of the test sample to detect PD pulses. This sensor is HVPD model 100/50AL and has a trans-impedance of 4.3 mV/mA ±5%. The bandwidth of the sensor’s frequency response covers 200 kHz to 19 MHz which allows detection of individual PD pulses. A digital oscilloscope (LeCroy 7300) with a bandwidth of 3 GHz has been used for the measurement of the detected PD pulses.

5 EXPERIMENTAL RESULTS

5.1 PD BEHAVIOUR UNDER RIPPLED VOLTAGES

The ripple contents can be varied through varying the firing and commutation angles. However, in this investigation the
commutation angle was kept fixed to zero degree for the sake of simplicity. Figures 7a-7d depict the applied test voltages along with the detected PD pulses for firing angles of 0°, 15°, 30°, and 60°. According to the measurement, the PD pulses occur near the peak of the applied voltages. As the delay of firing angle increases—abrupt changes in the output voltage—PD tends to occur following these fast transitions also the probability of PD occurrence increases. Figure 8 summarises the relationship between number of PD (N), firing delay angle (α) and the inter-time between PD occurrences (ΔT). It is observable that as the ripple increases—with increasing firing angle—the number of PD pulses increases and the time interval between consecutive PD pulses reduces.

![Figure 7](image_url)

**Figure 7.** Time trending of PD pulses under HVDC with firing angle of (a) 0 degrees, (b) 15 degrees, (c) 30 degrees and (d) 60 degrees.

![Figure 8](image_url)

**Figure 8.** Number of PD pulses vs. time difference between consecutive PD pulses vs. firing angle (N - ΔT - α).

### 5.2 PD Behaviour under Polarity Reversal

In order to investigate the effect of electric field due to polarity reversal that commonly happens in HVDC LCC converters on PD activity, the applied test waveforms reproduced such scenarios with a bidirectional trapezoidal waveform of ±7.43 kV in positive and negative polarities, and the transition between these two states was reproduced with a ramp of 14.86 kV/s during one second. Figure. 9a and 9b depict the PD pulses that were measured under such transposal conditions from negative to positive and vice versa. According to the measured data, under both scenarios, mostly PD pulses appear as the applied voltages crosses zero level and it continues until the voltage reaches its steady state condition. This behaviour could be explained as an interaction between the accumulated space charge and the polarity changes of the voltage which underpin the net electric field across the defect site within the sample leading to PD occurrence.

Figure 10 illustrates the trend of PD pulse repetition rate under both polarity transitions. There is no well-defined trend of PD pulse...
recurrence, but generally, the number of PD pulses that occurred during these two transitions drops in the course of time. This reduction in PD occurrences under the polarity change from negative to positive is higher than that of the positive to negative transition.

### 5.3 Effects of Transient Overvoltages on PD Behaviour

In order to study the effects of transient overvoltages on partial discharge behaviour within the defected test sample, DC voltages comprising transient overvoltages were generated and applied to the sample. The superimposed switching impulses were generated according to IEC 60060-1, where the waveform characteristics (front time/tail time) of 250/2500 µs have been considered [52].

The experiments were conducted under two scenarios: in the first scenario DC voltage was superimposed with the same polarity switching impulse, and in the second scenario, the DC voltage was superimposed with a switching impulse of opposite polarity. Therefore, in the latter, the test sample experienced transient polarity reversal. Figures 11 a - 11b depict the applied positive and negative test voltages in association with the incident PD pulses under the electric effects of the first group, where the transient overvoltages overly the DC voltages with the same polarity.

It is noteworthy, that the steady state voltage level, in both cases, were kept below the PD inception voltage of the test sample with the aim of investigating the effects of the overvoltages. It is evident from the results, that under both cases, PD pulses appear at the rising front of the applied switching overvoltages. These incidents are due to overstressing effects of the switching impulses that exceed the PD threshold level of the defect and lead to PD occurrence.

Figures 11 c - 11d demonstrate the experimental results under the second scenario. Similar to the first scenario, PD pulses occurred in the rising front of the transient overvoltages, however it is visually evident that the time delay for the occurrence of PD pulses under the second scenario is rather shorter than that of the first scenario. Therefore, the time delays of both scenarios have been statistically compared. For this purpose, the time delay between PD pulse incidents and the pertinent switching overvoltage were extracted and statistically analysed.

Figure 12 illustrates the comparison of time lags under both scenarios: negative DC superimposed with positive switching impulse (NdCPs), negative DC superimposed with negative switching impulse (NdCNs), positive DC superimposed with negative switching impulse (PdCNs), and positive DC superimposed with positive switching impulse (PdCPs). This situation might be explained by the influence of accumulated space charge. Since the PD pulses appear with shorter delay under the case of DC superimposed with opposite polarity it indicates the build-up of hetero-charges within the sample, where the Poisson field from the accumulated space charges underpin the Laplacian field from the applied external test voltages (as the polarity changing occurs) and exceeds the PD threshold resulting to PD occurrence in a shorter time with respect to the case of DC superimposition with similar polarity of transient overvoltages.
DISCUSSION

Insulating materials behave differently when exposed to different types of electric fields due to interactions between the driving voltages and the electrical properties of the dielectrics. Thus, the embedded non-homogeneities (defects) within the insulation react accordingly. Under the influence of alternating features of an AC voltage, dielectrics behave capacitively and, furthermore, under such bipolar fields space charges rarely build up. Therefore, at AC fields the emanating PDs within an insulation system take on a repetitive activity creating specific patterns depending on their origins. However, such a behaviour is absent under the steady state DC electric field. Nevertheless, under the influence of rippled voltages PD activity within the sample shows an observable increase in repetition, which can be explained as the effect of transient voltage that redistributes the net electric field within the sample.

The experimental results of PD measurements under operational polarity reversal – positive to negative transition and vice versa – show that PD pulses appear at the zero crossing of the applied voltage and their activity lasts until the voltage settles in its new steady state. Analogously, similar behaviour can be observed under transient polarity reversal. Mainly, the PD pulses occurred at the rising front of the waveforms. Such behaviour of PDs in the test sample could be explained by the interaction between the accumulated space charge and the fast changing voltages which results in a locally enhanced electric field leading to PD occurrence despite the fact that the steady state level of the underlying DC voltage was kept below the PD threshold of the sample.

CONCLUSION

In this paper, the aforementioned operational and anomalous scenarios were reproduced in down scaled levels under laboratory conditions: terminal voltage of LCC converter, polarity reversal and switching transient were generated and applied to a well-defined polymeric test sample and the PD behaviour under such conditions were measured and analysed. Under the rippled electric fields an observable relation was found between the PD pulses and the rippled waveforms, particularly the PD incidents correlated to a lesser or greater degree with superimposed peak voltage: as the firing angle increases PD pulse repetition augments given in the relevant $n - \Delta T - \alpha$ pattern. During polarity reversal, the
phenomenon of space charge accumulation reflects notably in PD behaviour. As the transition between the two polarities occurs, PD is present despite the steady state DC value being lower than the PD inception level. PD measurement under the effect of superimposed switching transients shows a correlation between PD occurrence and the transient incidents indicating the influence of fast rising front of the overvoltages on PD occurrence. The outcomes of this study will assist in the understanding of PD behaviour under operating conditions and anomalies that could be present in HVDC systems affecting interconnecting cable systems. Considering the effects of such phenomena on PD behaviour could assist network operators in insulation diagnostics and hence asset management.

REFERENCES


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