Influence of HVDC Converter Operation on Partial Discharge Characteristics

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***Abstract*—this paper presents an investigation into the influence of different operating conditions of HVDC converters on partial discharge behavior occurring within solid dielectrics. Cables at the DC side undergo different stresses due to transients and harmonics that may result in an intensified level of partial discharge (PD) activity and could affect their insulation integrity. Most DC converter schemes, nowadays, are bidirectional with the valve firing angles at the heart of power conversion and power flow control. Depending on the mode of converter operation and the properties of the interconnected AC systems, varying levels of harmonics, either characteristic or non-characteristic, appear on the DC side. By reproducing down-scaled equivalent DC outputs of conventional converters under controlled laboratory conditions, PD pulses occurring under characteristic HVDC voltages have be measured. PD was produced using a range of insulation samples containing known defects and measured using an HFCT sensor. Characteristics of the acquired PD pulses have been analyzed with the aim of finding a promising condition monitoring tool to identify the influence of the superimposed harmonics on PD activity. The results will aid HVDC network operators in identifying incipient cable faults by contributing to diagnostic knowledge rules for interpretation of PD parameters under known operating conditions.**

Keywords — Firing angle; Power conversion harmonics; HVDC transmission; Insulation; Partial Discharge; Ripples

I. INTRODUCTION

The expanding pan-European ‘supergrid’ is envisioned to connect offshore renewable energy resources and transmission systems through a network of HVDC interlinks [1] of which submarine HVDC cables are the backbone. However, the switching operation of HVDC converters, imperfections in cable manufacturing and the complex behavior of polymeric cables under DC fields [2, 3] raises some new challenges. Due to the switching of the power electronic valves the output voltage of the converters are not purely DC but contain ripples (harmonics) that increase the dielectric losses in proportion to their crest voltages, potentially leading to hastened degradation and premature failure. Studies under AC fields have shown that distorted voltages could affect insulation integrity and insulation diagnostics, increasing partial discharge repetition rate, intensity and discharge magnitude [4]. Distortions shorten the process of treeing initiation and growth time in polymeric insulation [5], and in general, harmonic voltages decrease the lifetime of polymeric cables [6]. Moreover, distorted voltage waveforms affect the phase location of PD pulses with respect to the power frequency, which affects the analysis of acquired PD data [7]. Therefore, the derived PD statistical parameters and distribution patterns may change, leading to misinterpretation of diagnostic data.

Likewise, many research works have been carried out studying the behavior of partial discharge under DC fields [8-10], however, less work has focused on the effects of rippled HVDC, particularly the effect of firing angle of the power electronic valves on PD behavior. Therefore, in this paper, variable HVDC voltage with firing angle was simulated and applied to the test sample with the aim of investigating the influence of converter output voltage on partial discharge activity within solid polymeric insulation.

II. PARTIAL DISCHARGE MECHANISM AND MESUREMENT

The presence of defects and imperfections within dielectrics causes inhomogeneous electric field distribution across the insulation resulting in localized discharges at the site of inhomogeneities. These discharges are called partial discharges, as they do not completely bridge the insulation between cathode and anode. PD activity results in electrical losses, degradation, and could lead to premature failure of the insulation system. PDs are generally categorized as internal and external, according to their source. PD occurs when the voltage across the defect site increases beyond the PD inception voltage, provided an avalanche-initiating electron is available [11]. These requirements depend on the geometry and location of the defect within the insulation, the type of gas encompassed within the cavity, the material of the insulation and the mechanism of electron emission [12]. Although dielectrics behave differently under steady-state AC and DC voltages, the mechanism of partial discharge is the same under both types of fields. Partial discharge occurs when the requirements of a discharge are fulfilled at the site of the defect [13]. Various methods are employed for the detection of PD activity: electromagnetic techniques [14], electrical pulse detection [15], acoustic detection [16] and chemical test techniques [17], to name a few. In this investigation, electrical PD measurement was applied using an HFCT sensor to measure individual PD pulses.

III. HARMONICS IN HVDC SYSTEMS

Harmonics are an undesirable phenomenon in the realm of power systems and originate from the nonlinearity of the apparatus. They contribute to distortions at AC and ripples at DC voltages. The resultant currents cause power losses, overloading the transmission line and degrading the insulation system. Power converters and the interlinked AC systems are the main sources of harmonics in HVDC stations, the former playing a major role. Due to the switching operation of the power electronic valves both current and voltage on the DC side of HVDC converters are rippled rather than being pure DC. Although the current harmonics contribute to resistive losses in the conductor, their overall effect on insulation is less pronounced with respect to that of voltage harmonics due to the very inductive DC side configuration of line commuted converters (LCC) [18, 19]. Here, we consider the effects of characteristic voltage harmonics on PD behavior in the prepared test sample.

In an HVDC system shown in Fig. 1, a three-phase Bridge rectifier is the building block of LCC converters where the switching valves are of thyristor technology being turned on by gate firing circuitry and commutated by the line voltage. Common 12-pulse converters schemes (two series connected six pulse converters) are fed by a Y-connected and Δ-connected transformers that may operate with symmetrical or asymmetrical firing of the two constituent six-pulse converters [20, 21]. The firing angle is the main parameter that controls the direction and amount of power to be exchanged between two converter stations. Hence, the firing angle determines the amount of harmonics, or ripples, introduced into the current and voltage at the DC side. Generally there is a minimum α limit of about 5° for the firing angle of the switching valves in LCC converters to ensure successful commutation, and the firing angles for normal operation is within the range of 15° to 20° [22]. The commutation angle μ is determined by the reactance of the feeding transformers [23]. Fig. 2 shows the terminal voltage of a typical converter and Fig. 3 illustrates the variation of relative magnitude of the sixth harmonic (the dominant harmonic voltage) appearing in the DC side of a converter as a function of the firing and commutation angles [18, 24].

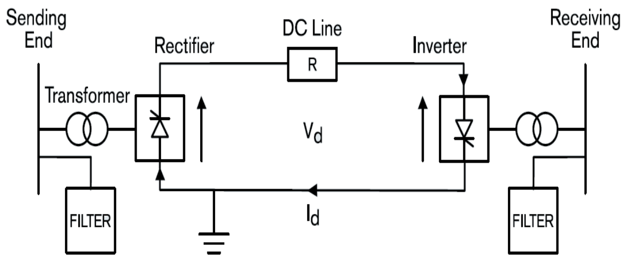

Fig. 1. A generic HVDC transmission system [24].

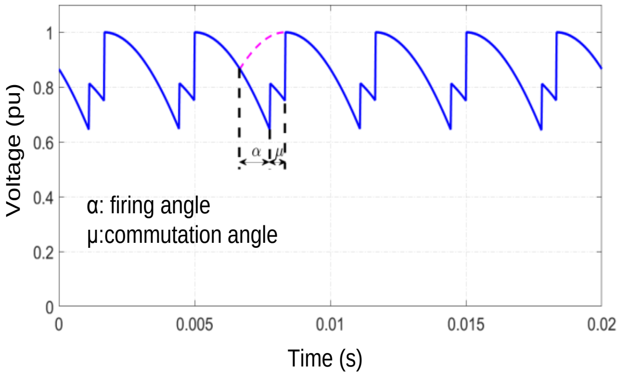

Fig. 2. A typical output of a six-pulse LCC converter considering the firing angle α and the commutation angle μ.

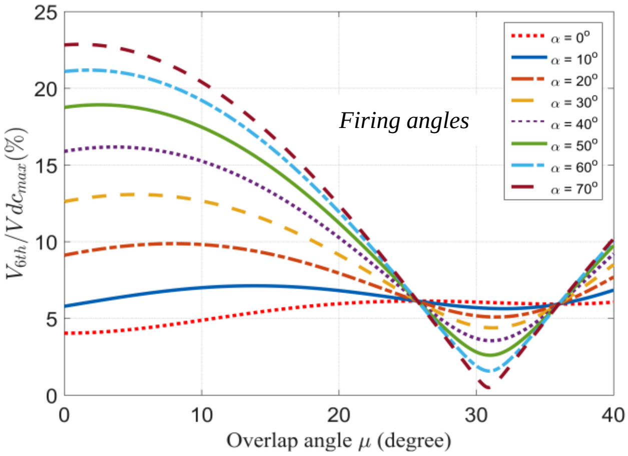

Fig. 3. Relative harmonic magnitude (6th order) as a function of firing angle vs commutation angle.

IV. METHODOLOGY

Fig. 4 shows the experimental test setup for partial discharge measurement. The test voltages (terminal voltage of a six-pulse LCC converter) were simulated using interactive code developed in MATLAB and LabVIEW, where the magnitude, firing and commutation angles of the waveforms can be varied. The generated test voltages were then fed into a high voltage amplifier (HV Amp) via a DAQ card. The maximum amplitude of the voltage that can be achieved with the HV Amp is ±30 kV. The output of the HV Amp was connected to the high voltage terminal of the test sample. The test sample is a slab of epoxy resin with 3 mm thickness enclosing a spherical air filled defect of 1 mm diameter. An HFCT sensor clamped around the ground wire of the test sample was used to detect PD pulses. This sensor has a trans-impedance sensitivity of approximately 4.3 mV/mA with a bandwidth that covers the frequency range 200 kHz to 19 MHz allowing detection of individual PD pulses. In order to measure the detected PD pulses, the output of the HFCT sensor was fed into a digital oscilloscope via a matched coaxial cable. The oscilloscope (LeCroy 7300) has a bandwidth of 3 GHz and a maximum sampling rate of 20 GS/s.

V. RESULTS

In order to investigate the influence of harmonic ripple superimposed on the output voltage of an LCC converter, the ripple content was varied by changing the firing angles from zero to sixty degrees. To study the effect of the firing angle only, the commutation angle was kept fixed to zero degrees. Figs. 5-8 illustrate the applied test voltages in association with the resultant PD pulses for respective firing angles of 0°, 15°, 30° and 60° as representative illustrations of PD activity under such rippled waveforms.

According to the measured PD data, generally, PD pulses occur in the peak region of the applied voltages but as the delay of firing angle increases – generating abrupt changes in the output voltage – PD tends to occur following these fast transitions.

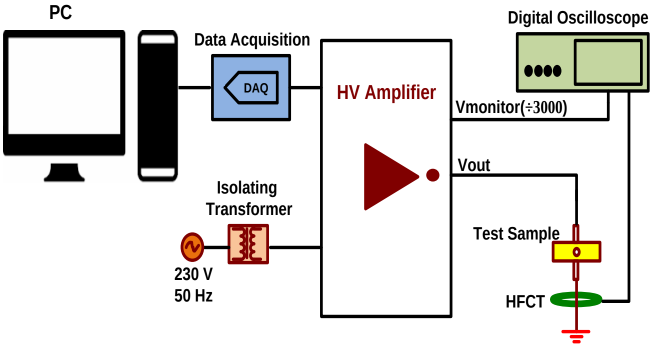

Fig. 4. PD measurement test setup.

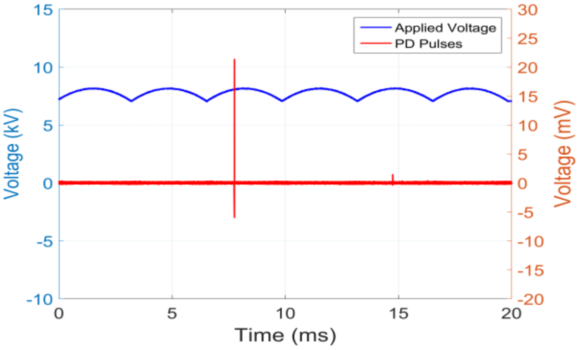

Fig. 5. Time trending of PD pulses under HVDC with firing angle of zero degrees.

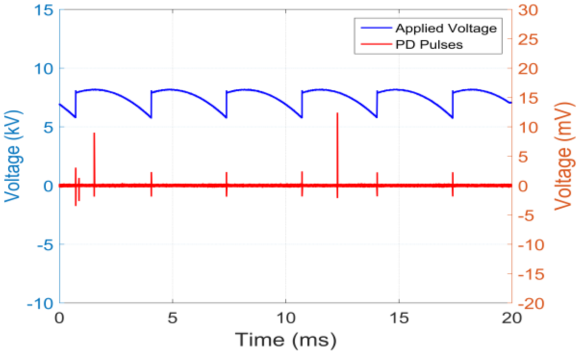

Fig. 6. Time trending of PD pulses under HVDC with firing angle of fifteen degrees.

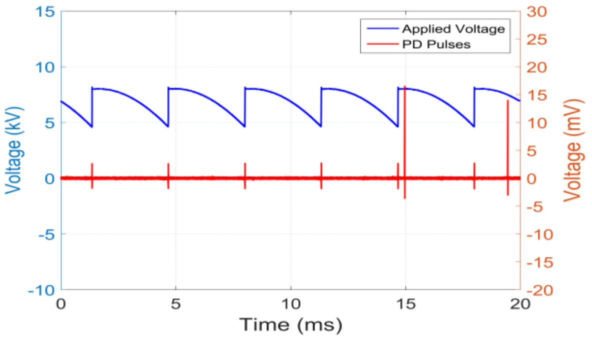

Fig. 7. Time trending of PD pulses under HVDC with firing angle of thirty degrees.

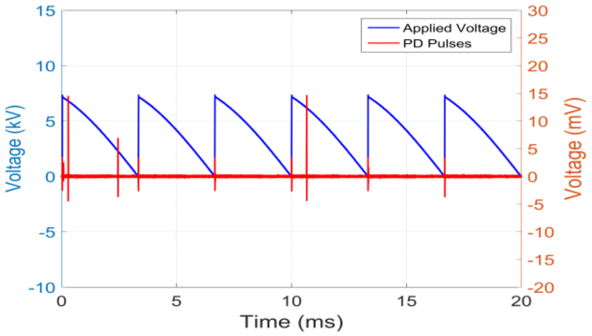

Fig. 8. Time trending of PD pulses under HVDC with firing angle of sixty degrees.

Under the influence of DC fields, dielectrics behave differently than under AC fields, with space charge built-up occurring noticeably [8]. Space charges are accumulated due to unipolarity of DC voltages in crystalline - amorphous interfaces or in charge trap sites [25] and affect the electric field distribution within the insulation. Under different material combinations and voltage values homocharges accumulate in mass impregnated (MI) cables. While there is not such reproducibility in XLPE cables, there is a possibility of accumulation of homocharges and hetrocharges [27, 28]. In the case of lower firing angles, the output voltage of LCC converters (Fig. 3) contains low level ripples, hence less abrupt changes, where the counteracting effect of the Poisson field on the accumulated space charges is noticeable as the majority of PD pulses occur around the peak region of the applied test voltage. This could indicate that the accumulated space charges are of hetrocharge type. However, as the firing angle increases, the harmonic contents augment and abrupt changes in voltage affect the net electric field within the insulation by redistributing the already built-up space charges. This phenomenon increases the possibility of PD occurrence at the defect site.

Fig. 9 characterizes observed PD behavior in terms of number of pulses vs. time difference between consecutive pulses (ΔT) vs. firing angle. As the firing angle increases, the number of PD pulses increases while the reduction of time difference between consecutive pulses is noticeable. In the data considered, there appears to be a direct correlation between the total number of PDs occurring and the firing angle.

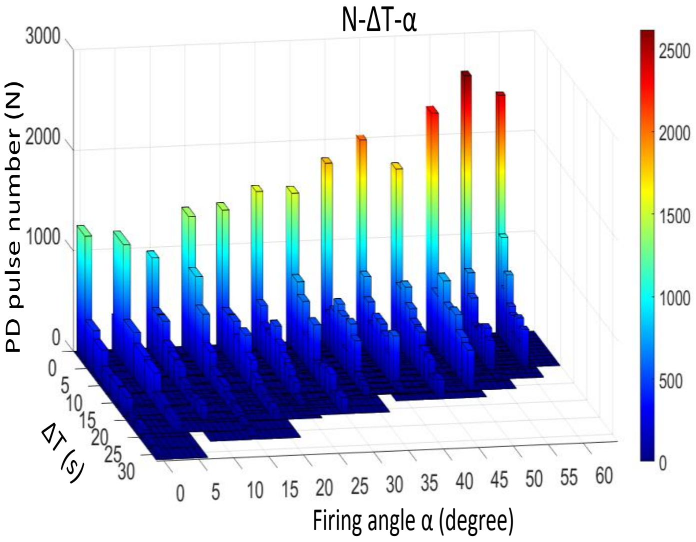

Fig. 9. Number of PD pulses and time difference between consecutive PD pulses vs. firing angle.

VI. CONCLUSION

Cable insulation can undergo overstresses imposed by various operational conditions of HVDC converters that might not be predictable at the design stage, and which may affect the insulation integrity and lifetime of the insulation system.

PD activity within a polymeric test sample was investigated under the influence of simulated LCC HVDC converter voltages varying with firing angle. HVDC ripples superimposed on the converter output voltage have an observable effect on the dielectric. Discharge pulses were observed to concentrate around the voltage peaks for lower firing angles but were less correlated to the peaks as the firing angle increased, as evidenced by the n-ΔT-α characteristic for the insulation sample under test. In general, as the firing angle increases, PD repetition rates rise while the time difference between consecutive PDs decreases, indicating an increased severity of PD pulses. The operating conditions of HVDC converters have a clear influence on the insulation system, affecting PD characteristics. Characteristic features of PD data from HVDC systems should inform future strategies in insulation diagnostic monitoring and failure prevention.

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