

Experimental Investigation of the Corona Discharge in Electrical Transmission due to AC/DC Electric Fields

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Abstract. Nowadays, using of High Voltage Direct Current (HVDC) transmission to maximize the transmission efficiency, bulk power transmission, connection of renewable power source from wind farm to the grid is of prime concern for the utility. However, due to the high electric field stress from Direct Current (DC) line, the corona discharge can easily be occurred at the conductor surface leading to transmission loss. Therefore, the polarity effect of DC lines on corona inception and breakdown voltage should be investigated. In this work, the effect of DC polarity and Alternating Current (AC) field stress on corona inception voltage and corona discharge is investigated on various test objects, such as High Voltage (HV) needle, needle at ground plane, internal defect, surface discharge, underground cable without cable termination, cable termination with simulated defect and bare overhead conductor. The corona discharge is measured by partial discharge measurement device with high-frequency current transformer. Finally, the relationship between supply voltage and discharge intensity on each DC polarity and AC field stress can be successfully determined.

1 Introduction

High Voltage Direct Current has been used in electrical transmission for several decades for bulk electric power transmission, interconnection of systems with different frequencies, undersea cable transmission and connection of off-shore wind farm to electrical grid. Using of HVDC creates high electric field stress on the conductor surface and its surroundings. For this reason, it is easier than alternating current voltage in electrical transmission system for corona inception and corona discharge as well as interference to communication system nearby [1]. The most effective DC transmission is bipolar with one positive and one negative conductor on the same tower. Thus, the effect of polarity on corona inception and corona discharge must be investigated and compared with that of AC electric field stress [2]. The onset of corona and subsequent growing discharge can be detected by using partial discharge measurement system with an appropriate sensor for effective detection. The experimental test setup consists of HVDC generation by half-wave rectifier with smoothing capacitor [3], partial discharge measurement system using high-frequency current transformer (HFCT) as a non-conventional detection method [4], [5] and various test objects. The first group of test object is HV needle, needle at ground, surface and internal discharge inside solid insulation as basic test object for theoretical comparison. The second group of test object is underground cable, which is examined without cable termination for surface discharge

generation and underground cable with simulated defect. The third group of test object is bare overhead conductor in the small scale model to observe the effect of AC/DC electric field stress. The experiments are performed with every test object by supplying DC voltage of both polarities as well as AC voltage to find the corona inception voltage and the relationship between corona discharge amplitude and the magnitude of the supply voltage.

2 Experimental Setup

2.1 Corona discharge and its detection

Corona discharge is theoretically a localized partial discharge, which can not bridge the gap between electrodes. The corona discharge can occur in transmission system because the high electric field stress at the sharp edge ionizes the air molecules surrounding it. This creates loss in transmission system, which should be prevented in the fair weather condition. Corona discharge can be detected by using non-conventional partial discharge sensor such as Ultra High Frequency (UHF) antenna, acoustic sensor or HFCT. Among various sensor types, HFCT provides an accurate result because it measures the electrical discharge pulse flowing to ground through ground conductor. During testing, the supplied AC and DC voltages are gradually increased until corona or partial discharge is detected by HFCT sensor.

2.2 Test Circuit

The test circuit is shown in Figure 1.

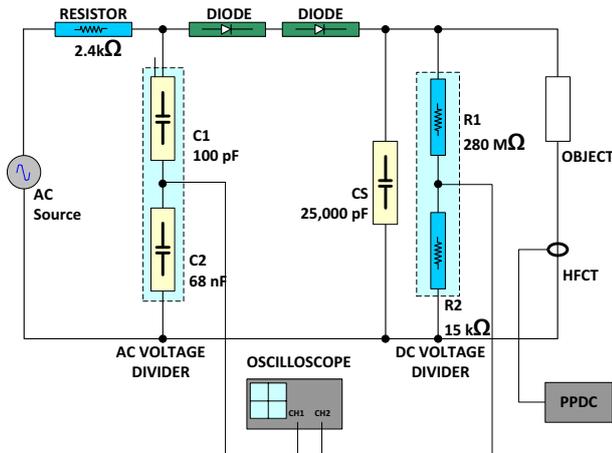


Figure 1. Test circuit for DC voltage generation and partial discharge measurements

The test circuit consists of:

1. High voltage DC generation by using half-wave rectifier: 100 kV insulated tank type test transformer, 2 diodes and 25,000 pF smoothing capacitor (C_S).
2. The generated high voltage DC is measured by resistive voltage divider: $R_1 = 280 \text{ M}\Omega$ and $R_2 = 15 \text{ k}\Omega$ resistors.
3. The corona inception voltage, corona discharge as well as partial discharge in another form are measured by using portable PD check device from TECHIMP with a high-frequency current transformer as a non-conventional sensor to detect PD pulse to ground at ground conductor.

The tests are performed in a partly shielded high voltage laboratory with background noise less than 5 pC or 2 mV by HFCT.

2.2 Test Objects

The test objects are divided into 3 groups as follows:

1. Basic test object for theoretical comparison e.g. HV needle, needle at ground, surface and internal discharge inside solid insulation. The needle at HV and internal discharge test objects are presented in Figure 2. To avoid the surface discharge during internal discharge test, the test object is immersed in the transformer insulating oil as shown in Figure 2 (b).
2. Underground cable, which is used without cable termination for surface discharge generation and underground cable with simulated defect by particle and impurity. Figure 3 shows the underground cable without termination and defected termination under test.
3. Bare overhead conductor in the small scale model. The bare copper wire is installed on the solid supporting insulator.

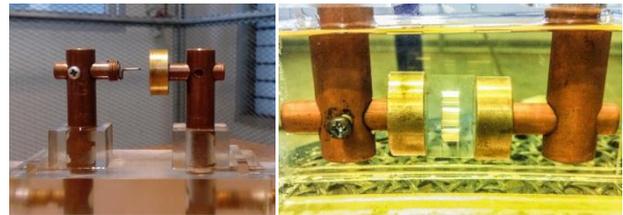


Figure 2. Basic test objects as needle at HV (a) and internal discharge (b)

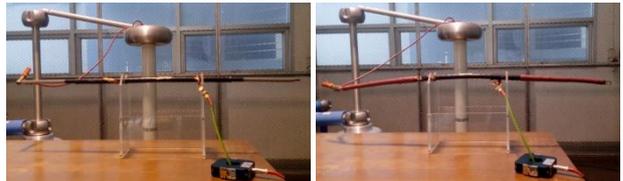


Figure 3. Underground cable under test, without termination (a) and defected termination (b)

The tests are performed by gradually increasing the supplied voltage to the test object until the corona discharges are initiated. This minimum voltage causing the corona discharges is recorded as corona inception voltage. Then, the supplied voltage is gradually increased further and the corona discharge amplitude is recorded until the breakdown is occurred. After that, the same test is performed again on the object with reversed polarity of DC voltage and AC voltage subsequently.

3 Experimental Results

The corona inception voltage and the relationship between supplied voltage and corona/partial discharge amplitude for each test object are presented in this section.

3.1. Basic Test Object

The corona inception voltage in case of positive and negative polarity is listed in Table 1 and the relationship between corona/partial discharge amplitude and supplied voltage is presented in Figure 4.

The first object is needle at high voltage terminal. The measured inception voltage for negative polarity is lower than that of positive polarity. However, the corona discharge amplitude at the instant of inception for negative polarity is 13 mV, which is lower than that of positive polarity 47 mV. This result agrees well with the theory as the corona inception voltage of negative DC is lower than positive due to positive space charge close to the rod tip creating higher electric field stress at negative rod. The discharge amplitude of positive DC is greater than negative due to space charge accumulation.

The second object is needle at ground plane and plate at high voltage terminal. The measured inception voltage value of both the polarities is equal. However, the corona discharge amplitude at the instant of inception for negative polarity is 68 mV, which is greater than that of positive polarity 12 mV. The result of corona discharge amplitude is now reversed because when the high voltage

at plate is positive and the needle is grounded, it is similar to negative voltage at needle. Similarly, when the high voltage at plate is negative and the needle is grounded, it is similar to positive voltage at needle.

The third object is internal defect with air void inside solid insulation. The measured inception voltage of negative polarity is lower than that of positive polarity. However, the corona discharge amplitude at the instant of inception for negative polarity is 14 mV, which is lower than that of positive polarity 34 mV. It can also be clearly seen that the corona discharge amplitude of positive polarity after inception increases significantly, whereas that of negative polarity remains at lower amplitude.

The fourth object is surface discharge along solid insulation. The measured inception voltage in case of negative polarity is lower than that of positive polarity. However, the corona discharge amplitude at the instant of inception for negative polarity is 21 mV, which is lower than that of positive polarity 703 mV. The corona discharge amplitude of positive polarity after inception increases significantly, whereas that of negative polarity remains at lower amplitude.

Table 1. Corona inception voltage of basic test object due to polarity effect

Test Object	Corona Inception Voltage (Positive)	Corona Inception Voltage (Negative)
Needle at HV	5 kV	4 kV
Needle at Ground	6 kV	6 kV
Internal Defect	35 kV	22 kV
Surface Discharge	14 kV	11 kV

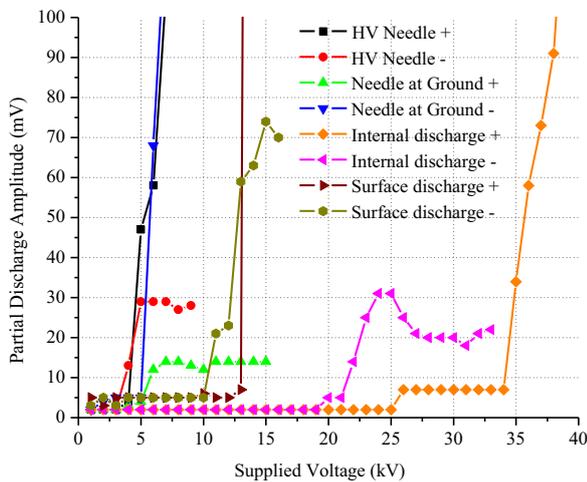


Figure 4. Relationship between corona discharge amplitude and supplied voltage of basic test object

From the partial discharge measurement results of needle at high voltage during corona inception shown in Figure 5, the corona discharge of positive polarity has greater amplitude with large dispersion of amplitude than that of negative polarity due to space charge effect. However, the frequency of occurrence from discharge waveform in time domain is less than negative polarity. The corona discharge of negative polarity has smaller amplitude but occurs more frequently. Figure 6 shows the

corona discharge waveform of internal discharge inside solid insulation. The discharge amplitude of positive polarity is relatively greater than negative polarity, but the discharge waveforms in time domain of both polarities are nearly similar.

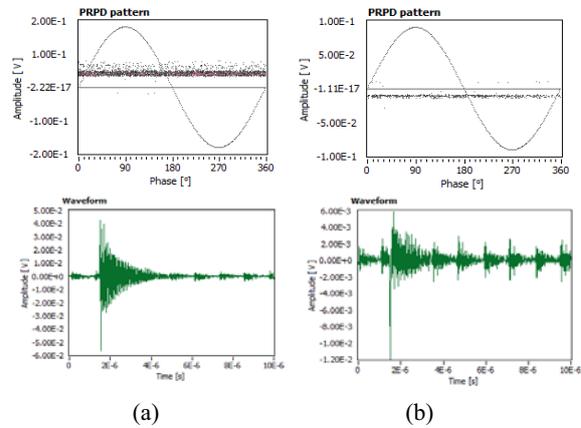


Figure 5. Partial discharge pattern of needle at high voltage for positive (a) and negative (b) polarity

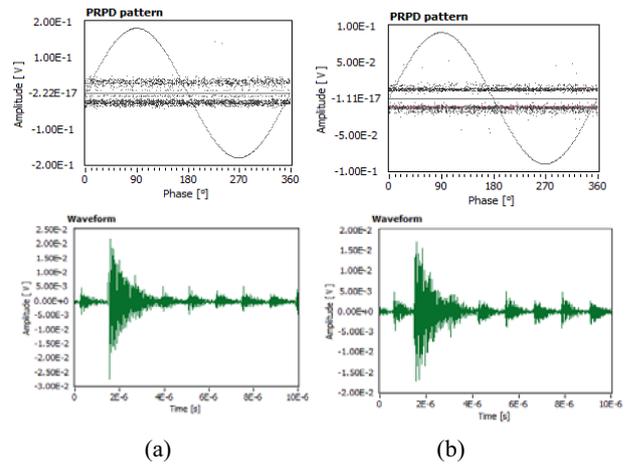


Figure 6. Partial discharge pattern of internal discharge inside solid insulation for positive (a) and negative (b) polarity

3.2 Underground Cable

The underground cable rated voltage 3.6/6 (7.2) kV with XLPE insulation are used in this test. The corona inception voltage and the relationship between corona/partial discharge amplitude and supplied voltage are listed in Table 2 and presented in Figure 7, respectively.

The first object is underground cable without cable termination for surface discharge generation along the XLPE insulation surface due to high electric field stress at the outer semiconductor shield. The measured inception voltage for both polarities is equal, but it is greater than that of AC voltage. However, the surface discharge amplitude at the instant of inception is different, which is 100 mV, 15 mV and 38 mV for positive polarity, negative polarity and AC voltage respectively. Then, this cable without termination can withstand surface discharge from DC less than that of AC voltage due to continuous electric field stress.

The second object is underground cable with defected cable termination. The surface between XLPE insulation and termination was contaminated by particle and impurity. The measured inception voltage of positive polarity is slightly greater than that of negative polarity. However, the corona inception voltage in case of AC voltage is slightly greater than DC voltage. The partial discharge amplitude at the instant of inception is significantly different, which is 441 mV, 27 mV and 13 mV for positive polarity, negative polarity and AC voltage respectively.

Table 2. Corona inception voltage of underground cable and defected cable termination due to polarity effect

Test Object	Corona Inception Voltage (Positive)	Corona Inception Voltage (Negative)	Corona Inception Voltage (AC)
Cable without termination	12 kV	12 kV	6 kV
Termination with impurity	16 kV	15 kV	17 kV

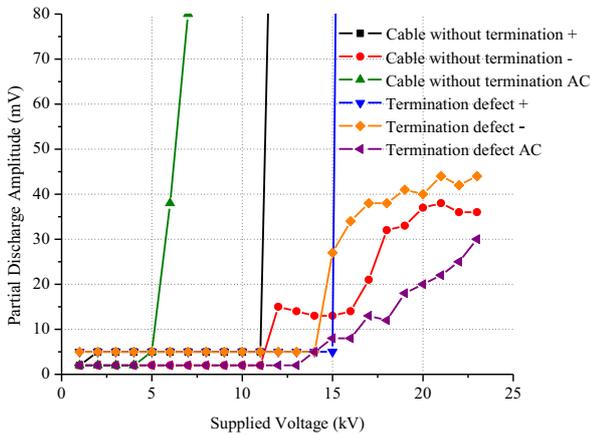


Figure 7. Relationship between supplied voltage and corona discharge amplitude for cable without termination and with defected cable termination

It can be clearly seen that the partial discharge pattern of DC electric field stress is constant with small dispersion of discharge amplitude due to space charge effect. This discharge pattern is different from AC field because of the constant electric field from DC supply. The partial discharge pattern of underground cable without termination for AC voltage in Figure 8 shows the surface discharge pattern [2] due to high electric field stress at the outer semiconducting shield.

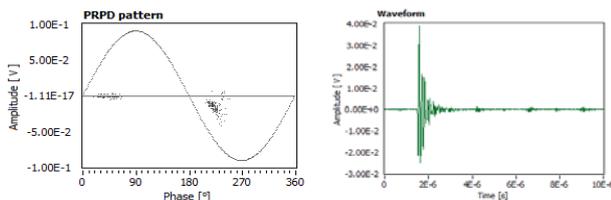


Figure 8. Partial discharge pattern of underground cable without termination for AC voltage

The effect of DC voltage polarity on discharge amplitude and waveform can be seen in Figure 9. The

discharge waveform of positive polarity has greater amplitude with single discharge pulse, whereas that of negative polarity has less amplitude with higher frequency of occurrence or higher repetition rate.

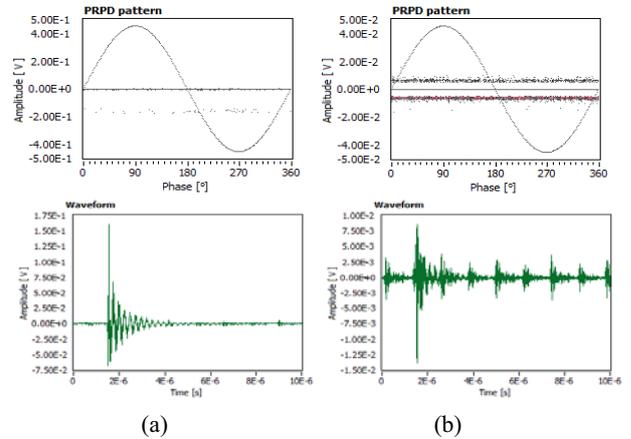


Figure 9. Partial discharge pattern of underground cable without termination for positive (a) and negative (b) polarity

3.3 Bare Conductor

The corona inception voltage and the relationship between corona/partial discharge amplitude and supplied voltage is listed in Table 3 and presented in Figure 10.

The measured inception voltage of positive polarity is greater than that of negative polarity and AC voltage. Moreover, the corona discharge amplitude at the instant of inception for positive polarity (137 mV) is significantly greater than that of negative polarity (11 mV) and AC voltage (11 mV). The corona discharge amplitude of positive polarity after inception increases significantly, whereas that of negative polarity and AC voltage remains at lower amplitude.

Table 3. Corona inception voltage of bare conductor due to polarity effect

Test Object	Corona Inception Voltage (Positive)	Corona Inception Voltage (Negative)	Corona Inception Voltage (AC)
Bare Conductor	15 kV	12 kV	12 kV

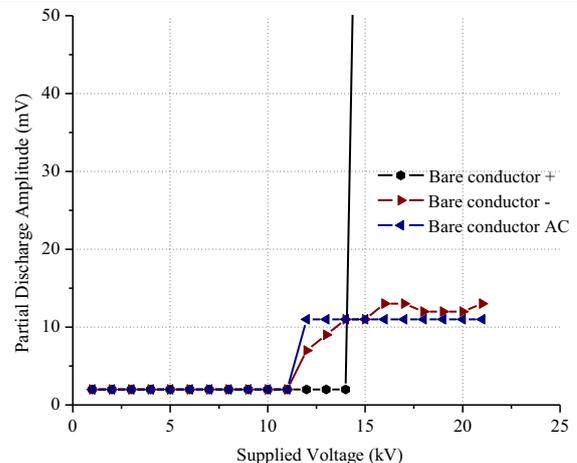


Figure 10. Relationship between supplied voltage and corona discharge amplitude of bare conductor

The partial discharge pattern of bare conductor for AC voltage shown in Figure 11 is the corona discharge at the negative cycle of sinusoidal waveform because the energized bare conductor is at high voltage potential. The effect of DC voltage polarity on discharge amplitude and waveform can be seen in Figure 12. The discharge waveform of positive polarity has greater amplitude with single discharge pulse, whereas that of negative polarity has smaller amplitude with higher frequency of occurrence. This result agrees well with the corona discharge observed from HV needle in basic test object.

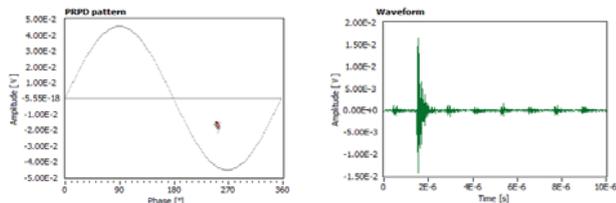
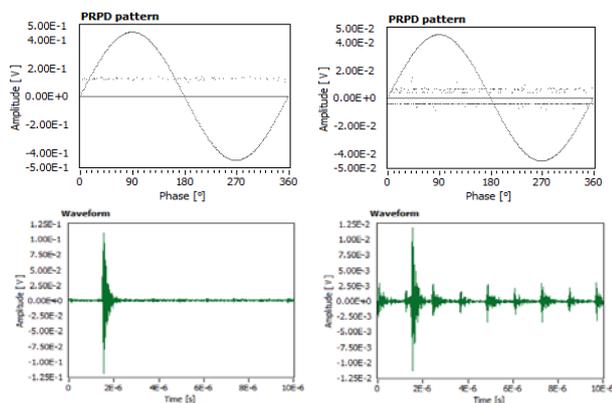


Figure 11. Partial discharge pattern of bare conductor for AC voltage



(a)

(b)

Figure 12. Partial discharge pattern of bare conductor for positive (a) and negative (b) polarity

4 Conclusions

The effect of DC polarity and AC field stress on corona inception voltage as well as partial discharge amplitude and pattern has been investigated on various test objects, such as HV needle, needle at ground plane, internal defect, surface discharge, underground cable without cable termination, cable termination with simulated defect and bare overhead conductor. The corona discharge and partial discharge from test objects are measured by using HFCT to detect the discharge pulse flowing to ground. The measured discharge waveform of positive polarity has greater amplitude with single discharge pulse, whereas that of negative polarity has less amplitude with higher frequency of occurrence or higher repetition rate. Then, the inception voltage of positive DC is usually greater than those of negative polarity and AC voltage. Because of the lower corona and partial discharge inception voltage of negative DC, the corona and partial discharge of negative DC occur more frequent than positive DC as higher repetition rate, however with

less severity. The result can be further used to design the proper insulation and size of conductor for HVDC applications.

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