Partial Discharge Detection on 320 kV VSC-HVDC XLPE Cable with Artificial Defects under DC Voltage

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ABSTRACT

VSC-HVDC power transmission systems based on extruded cables are being commissioned with higher rated voltages and longer distances in recent years. In China, the rated voltage of commissioned VSC-HVDC cable projects has been increased from 160 to 200 kV, and then to 320 kV in the past 5 years. To investigate the feasibility of discovering insulation defects of an XLPE HVDC cable system using partial discharge detection under DC voltage, a test cable loop was built using the same batch of 320 kV HVDC XLPE cable used to construct the Xiamen ± 320 kV VSC-HVDC project. Artificial defects of insulation wound and semi-conductive layer tips were designed and constructed at the joint. The two types of defects were effectively detected by the HVDC partial discharge test, and the measured results show distinguished discharge characteristics. Suggestions for determining trigger level and partial discharge inception voltage under DC voltage for partial discharge detection of extruded HVDC cables are given.

Index Terms —**Partial discharges, HVDC, XLPE cable.**

1 INTRODUCTION

THE VSC-HVDC transmission technology based on HVDC cables has been rapidly developing in recent years in underground transmission, connecting unsynchronized grids, and long distance subsea power transmission, because of high efficiency and stability. The extruded XLPE cables have become the preferred choice due to many benefits, such as easier production, transportation, and installation [1]. The highest rated voltage of the operational VSC-HVDC project is 320 kV, and the XLPE HVDC cable system with a highest rated voltage of 640 kV has been reported to be qualified in Apr. 2017 [2]. On Dec. 17th, 2015 the Xiamen ± 320 kV VSC-HVDC project was put into operation with the rated capacity of 1 GW. As an important international technical publication for testing HVDC extruded cable systems, the CIGRE Technical Brochure (TB) 496 [3] has been adopted by manufacturers. While partial discharge (PD) testing, as one of the quality assurance procedures for AC cables, has not been thoroughly discussed in this technical reference for HVDC cables and accessories.

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PD testing has been adopted as an essential criterion during factory tests for AC cables [4, 5], and has also been employed as one of the few practicable on-site testing methods for a cable system [6]. According to the IEC standards for AC cables, PD testing shall be carried out in accordance with IEC 60885-3 [7] as a part of routine tests by the manufacturer. For HVDC cables, PD testing is recommended by CIGRE TB 496 as a part of factory tests for cable accessories when possible. An AC voltage test combined with PD measurement as a part of routine tests is also recommended in the newly released IEC 62895: 2017 standard [8]. However, the test procedures such as the type of power supply and voltage level have not been specified, leaving the discretion to the manufacturers. For long-distance HVDC power cable systems with large capacitance, the conventional PD measurement under Frequency-tuned Resonant AC (ACRF) [9] is challenged in capacity of power supply. In most cases the rated voltage of commercially available Damped AC (DAC) testing equipment is no higher than 400 kVpeak (283 kVrms) [10] and the rated voltage of the Very Low Frequency (VLF) is no higher than 200 kVpeak (140 kVrms) [11]. PD detections for HVDC cables under DAC and VLF voltages are limited by voltage

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level of power supply. Another problem is that, the type of the power supply, the testing voltage level, and the test duration of the AC test are difficult for the manufacturer and customer to agree on. It also raises concerns about the issue of accumulated space charge if the AC test is conducted after high voltage DC tests.

A fundamental basis has been laid for PD detection and analysis under DC voltage by researchers of TU Delft. The time interval Δt between adjacent discharges was proposed as the substitute for the phase information under AC, along with charge magnitude q to describe PD activities under DC. Typical PD patterns were obtained with model defects, and classification showed promising results. The criteria of cumulative PD product concerning charge quantity and repetition rate were given for type tests and routine tests for mass impregnated HVDC cables [12]. PD characteristics of XLPE under DC voltage have become an interested topic recently since the rising trend of application of extruded HVDC cables. Studies have been carried out using coaxial-structural cable samples. PD testing for HVDC XLPE cables using VLF was proposed, because of the accordance between partial discharge inception voltage (PDIV) and PD magnitude measured under VLF and DC voltage on defective cable models [13]. Another challenge is that, DC PDIV was reported to has a larger dispersion than that under AC for defective cable models [14]. Discharges of the opposite polarity were found after the voltage removal from the defective MV AC cables [15]. However, a basic consensus of how to conduct DC PD measurement for cable systems is still absent, such as the minimum testing duration and the practical criterion of PDIV. PD detection conducted on actual HVDC extruded cable loops has not been reported yet.

In this paper, artificial defects of insulation wound and semi-conductive layer tips were designed and constructed in a 320 kV HVDC cable test loop in the laboratory, to investigate the feasibility of discovering the defects by PD testing under DC. Both defects were detected by DC PD measurement, and the PD characteristics are statistically compared.

2 PD TESTS ON THE 320 KV CABLE LOOP

The rated ampacity of the XLPE HVDC cables used in the Xiamen ± 320 kV VSC-HVDC system is 1600 A. The insulation thickness of the HVDC cable is 26.0 mm and the conductor cross-sectional area is 1800 mm^2. The schematic diagram of the cable cross-section is illustrated in Figure 1.

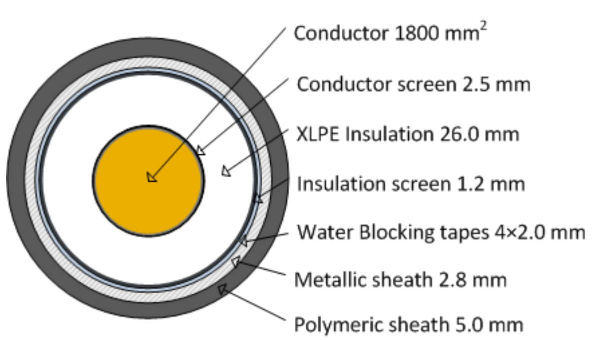

Figure 1. Schematic diagram of the cross-section of the 320 kV HVDC cable.

All the ± 320 kV HVDC cables passed the additional AC PD factory test agreed between the customer and manufacturer under 50 Hz 192 kVrms. Moreover, a test cable loop was constructed using the same batch of 320 kV HVDC cable in the Xiamen project, containing one joint and two terminations. Artificial detects of insulation wound and semi-conductive layer tips were made at the joint for the PD tests.

2.1 EXPERIMENT SETUP

The schematic diagram and picture of the test loop are shown in Figure 2. The HVDC voltage source is a 3-stage Cockcroft-Walton DC generator, and the rated output voltage is ± 1000 kV. The protective resistance R is 50 kΩ. The dividing ratio of R_1: R_2 is 5000: 1. The lengths of the cables between the joint and the two terminations were 6 meters and 20 meters, respectively.

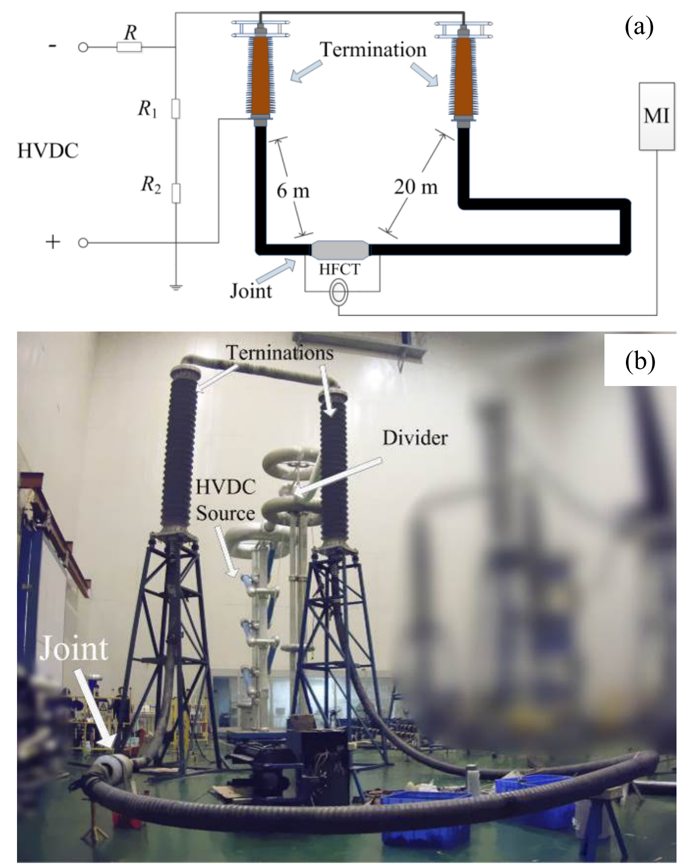

Figure 2. Experimental circuit of the DC PD test; (a) schematic diagram of the cable loop under test, (b) photograph of the cable loop under test.

The cables used for the experiment are the same as those used to construct the Xiamen ± 320 kV VSC-HVDC system. The conductors of the two terminations were connected together to the high voltage source to reduce terminal reflection. The connections between each component were well screened to prevent corona discharge. A pre-molded cable joint was used in the experiment, and the interrupted metallic sheath at the joint was restored via copper wires. The sensor used to detect the PD signal was clamped around the copper wires. In this experiment, MI was an Omicron MPD 600 partial discharge analyzer. This instrument in series with a high frequency current transformer (HFCT) was used to continuously record the PD signals. The bandwidth of the HFCT is 80 kHz-5 MHz. The entire test circuit was PD free.

2.2 CONFIGURATION OF THE ARTIFICIAL DEFECTS

Two types of defects at the cable joint were designed for the HVDC PD test, insulation wound and the semi-conductive layer tips. The semi-conductive layer tips will be referred to as semi-con tips for convenience. They were made as follows:

1) **Insulation wound**: Before the joint was assembled, a knife-cut was created in the insulation layer in the cable 53 mm away from the end of the outer semi-conductive layer. The depth of the cut was 4.5 mm and the width was 6 mm. The surface of the insulation was polished smoothly afterwards.

2) **Semi-con tips**: During the peeling of the outer semi-conductive layer, three tips were created to ensure successful excitation of PD. One tip was 43 mm long, and the other two were 40 mm long. The end of the semi-conductive layer and the edges of the tips were polished smoothly afterwards. The pictures and schematic diagrams of the insulation wound and semi-con tips are shown in Figure 3.

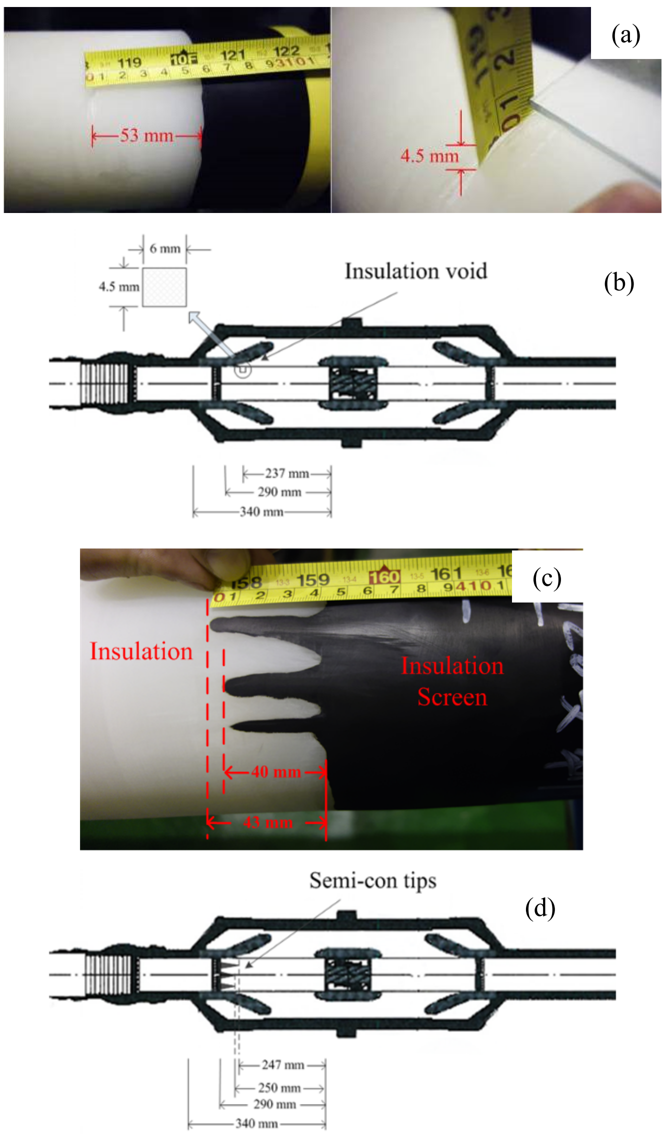

Figure 3. Artificial defect of insulation wound and semi-con tips: a) picture of the insulation wound; b) schematic diagram of the insulation wound; c) picture of the semi-con tips defect; d) schematic diagram of the semi-con tips defect.

2.3 TEST PROCEDURES

The entire cable loop was carefully assembled following the installation requirements of the accessories despite the defects. The output voltage of the HVDC generator was tuned to negative polarity in accordance with the recommendation of CIGRE TB 496.

The laboratory used to carry out the experiments was well shielded, and the background noise level of the test circuit was below 4 pC. The background noise discussed here is the repetitively measured signals. Apart from the repetitive signals, random impulsive signals were detected every a few seconds. If the same condition was fulfilled for PD detection under AC voltage, a trigger level set as 8 pC would be acceptable for a signal to noise ratio (SNR) better than 2:1. And the random impulsive disturbances shall not cause much influence to the AC PD detection results because of the low repetition rate.

However, for the PD detection under DC voltage, the trigger level cannot be simply set as 8 pC because of the existence of the random impulsive disturbances. As the whole experiment would continue for tens of minutes even 2-3 hours for PD detection under DC voltage, and the PD repetition rate can be much lower than that under AC, the impulsive signals which appeared once in several seconds would inevitably be mistaken as PD pulses if the trigger level was set as 8 pC. For now, there is no specification on the minimum detection period to determine the background noise level for detecting PD under DC voltage. The PD repetition rate was essential in determining DC PDIV, and the random impulses could compromise the accuracy of detection. Thus a 5-minute continuous monitoring of disturbances was undertaken to determine the trigger level in this experiment. For each detection, after switching on the HVDC power source, the background noise as well as the impulsive signals would be continuously recorded for 5 minutes. The highest value recorded during the 5 minutes would be found, and the trigger level would be set higher than that value. Only the pulses exceeding the trigger level were to be considered as PD pulses. Although some smaller discharges were missed, this practice would help to ensure the accuracy of the detection.

Another difficulty is to determine the PDIV under DC which is mainly involved with how the test voltage is raised and the inception criterion. The increasing rate of the voltage and the observation duration will greatly affect the determination of PDIV. As defined in IEC 60270 [16], the repetitive PDs shall be observed to determine the PDIV. Under AC voltage when PD repetition rate is much higher, it is not hard to fulfill the requirement of observing 'repetitive' PDs. However, under DC voltage when PD repetition rate can be as low as a few times per minute, it becomes very difficult to interpret 'repetitive'. At present stage, the definition of PDIV under DC voltage is only regulated in the ASTM D1868-13 [17], in which PDIV is defined as the lowest voltage at which continuous PDs occur. Under DC voltage continuous PDs is defined as at least one pulse per minute. When determining the PDIV of DC corona, R. J. Van Brunt chose to raise the applied voltage in discrete steps and count the PD pulses for 20 seconds at each voltage stage, the PDIV corresponded to the voltage at which the repetition rate was 0.1 count per second [18]. During the detection of internal PD of a sandwich model under DC, the applied voltage was reported to be raised at the step of 1 kV each 5 minutes and the PDIV would be decided when at least one PD per minute was observed [19]. In the experiments reported by A. Pirker, the applied voltage was raised step by step and when three PD pulses were detected per 30 seconds, this voltage would be determined as PDIV [20]. When detecting DC PD on defective cable models, the voltage was raised 1 kV / 2 minutes and the PDIV was determined when at least 3 pulses were measured [14]. The continuous rising process of the DC voltage can be considered as a quarter of one AC voltage cycle during which PD may be initiated [21]. It is generally accepted that the test voltage is raised stepwisely, but a well-accepted PD observation duration remains to be an outstanding issue. The confirmation of the low-repetition-rate DC PD requires a much longer observation period than what is needed under AC. However, it will cost more time to perform the whole test with longer observation periods. In this experiment, because the operation of the voltage supply would produce massive interferences, the observation of PD pulses had to be carried out when the voltage was held steady. The test voltage was decided to be raised step by step and the PD observation duration was decided as 2 minutes by the agreements with the manufacturer.

The voltage divider read approximately -30 kV immediately after switching on the power supply. The 5-minute continuous monitoring of disturbances was conducted before raising the voltage for each test to determine the trigger level. After that, the voltage was slowly raised for 10 kV at each step. After the reading from the voltage divider reached the desired voltage, the voltage level would be held for 2 minutes. If the 'at least once per minute' criterion was reached, this voltage would be determined as the DC PDIV, according to ASTM D1868-13. If not, the voltage would be raised to the next level. The voltage rising process of the two tests are shown in Figure 4. The detailed test procedures are described as follows:

1) Test procedures of the artificial defect of the insulation wound.

During the PD measurement under DC voltage, the detection bandwidth of the measuring instrument was chosen as 300 kHz and the center frequency was tuned at 2.445 MHz for better SNR. The test voltage was stepwise raised as described in the above section until -320 kV, when PDIV was determined. Then, the voltage was held for 30 minutes while the triggered signals were continuously recorded.

2) Test procedures of the artificial defect of semi-con tips.

After the semi-con tips were created and the cable loop was assembled, the detection center frequency was chosen as 2.048 MHz with the bandwidth of 300 kHz for better SNR. The voltage was raised to - 290 kV step by step when the PDIV was firstly reached. Because the PD tended to be extinguished in the later period of the 30-minute detection, the voltage was stepwise raised to - 310 kV until the PD was repetitively triggered again. This voltage level was held for 60 minutes while the pulses were simultaneously recorded.

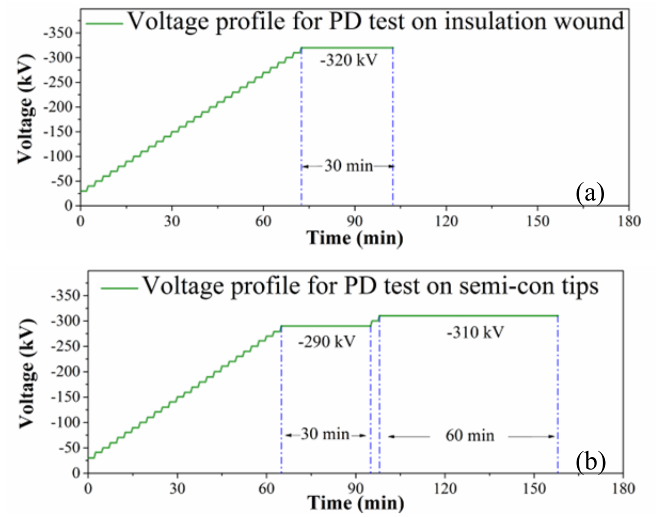

Figure 4. Voltage rising process of the PD tests: (a) voltage profile for the PD test on insulation wound. (b) voltage profile for the PD test on semi-con tips.

2.4 INTERPRETATION OF THE EXPERIMENTAL RESULTS

Because the applied voltage was a negative DC voltage, the direction to install the sensor was chosen to detect the PD pulses as negative pulses as well. Therefore, the charge quantity of the recorded PD signals was presented as a "-" charge to identify the pulse polarity.

1) Partial discharges of the insulation wound.

The discharge quantity is plotted against measuring time in Figure 5a with the trigger level set as 30 pC. The PD activity is relatively stable over time, and the measured pulses range mostly between 30-40 pC.

During the 30-minute detection period, 2,315 pulses were triggered and recorded. The PD repetition rate is calculated as PD number per minute, and it is illustrated in Figure 5b. The PD repetition rate rose in the first 3 minutes from 37 min^{-1} to 119 min^{-1}, and dropped in the following 2 minutes to 63 min^{-1}. Then, the PD repetition rate fluctuated at a rather stable level. An average repetition rate of 77.2 min^{-1} was achieved for the 30 minutes.

In Figure 5c, PD numbers are calculated versus charge magnitude for the detected signal of the insulation wound. The discharge magnitudes are summed with the bin width of 1 pC. It can be seen from Figure 5c that during the 30-minute measurement, the largest discharge was below 41 pC while the trigger level was set as 30 pC. Most of the discharges were distributed between 30-39 pC, and the PD numbers decreased monotonically with the increase of the charge magnitude. In the measuring period 839 discharges occurred in the section of 30-31 pC, and only 2 discharges occurred between 40 and 41 pC.

2) Partial discharges of semi-con tips.

During the first 30-minute PD measuring of semi-tips under -290 kV, the discharge activities varied significantly in both pulse height and pulse repetition. The measured charge quantity is plotted versus measuring time in Figure 6a with the trigger level set as 18 pC. Charge quantity distributed between

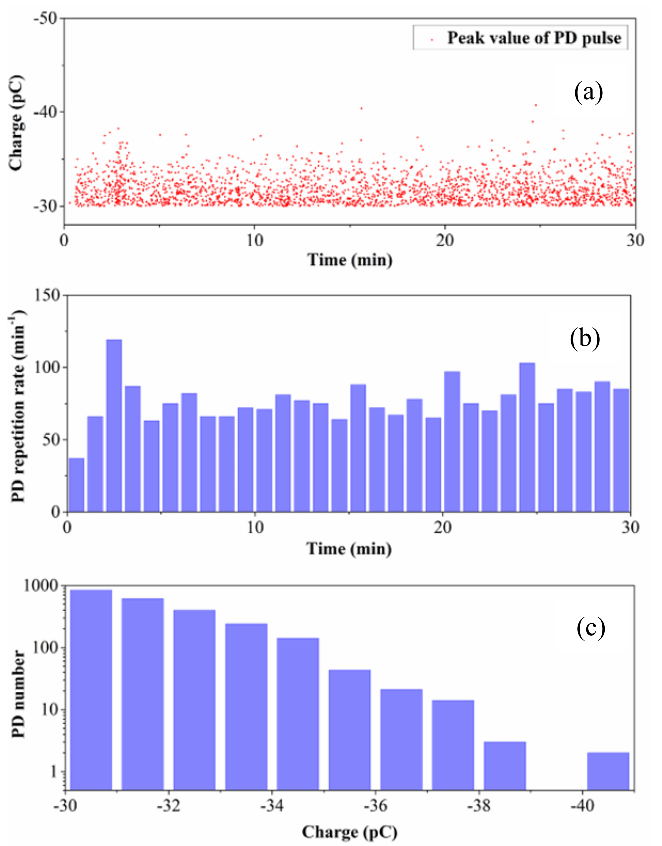

Figure 5. Characteristic PD plots of the insulation wound under -320 kV for 30 min: (a) Q-T plot; (b) PD repetition rate versus measuring time; (c) PD number versus charge magnitude (bin width = 1 pC).

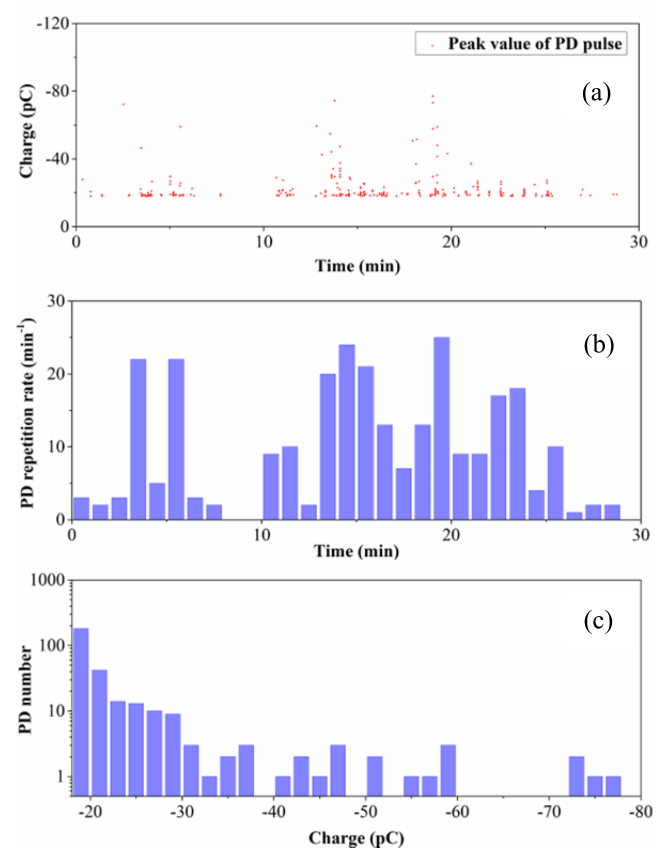

Figure 6. Characteristic PD plots of the semi-con tips under -290 kV for 30 min: (a) Q-T plot; (b) PD repetition rate versus measuring time; (c) PD number versus charge magnitude (bin width = 2 pC).

18 pC to 80 pC. Several intervals can be observed in the time axis. At the end of the detection period, PD activities tended to be extinguished that few pulses were recorded just above the trigger level.

The PD repetition rate per minute is calculated and shown in Figure 6b. For the major part of the measuring time, the repetition rate remained under 10 min^{-1}. The repetition rate went over 20 min^{-1} for only 6 times. The highest repetition rate of 25 min^{-1} was achieved in the 19th minute. The average repetition rate is 9.9 min^{-1}, and it is much lower than that of the defect of the insulation wound.

The cumulative PD numbers are summed with the bin width of 2 pC versus the distribution of charge quantity in Figure 6c. Most of the PD pulses occurred between 18-24 pC. No more than 3 PDs were detected for each section higher than 30 pC.

After the voltage was raised to - 310 kV, PD pulses were constantly triggered at a much higher repetition rate. Then, the voltage level was held for the next 60 minutes. The measured PD signals ranged from 18 pC to over 100 pC as plotted in Figure 7a. An interval between 32nd and 42nd minutes can be clearly observed. In this interval, few PD pulses were detected, and the time gap between one pulse and its successive pulse can be over 3 minutes. From the 43rd minute, the continuous PD activity re-initiated till the end of the recording.

The PD repetition rate per minute, which also varied remarkably during the recorded 60 minutes, is depicted in Figure 7b. In the first 6 minutes the repetition rate went up to 81 min^{-1} and down to 0 min^{-1}, and then reached the relatively stable 25-minute-long period since the 7th minute. The PD repetition rate averaged 51.8 min^{-1} in this period. Afterwards, the time interval appeared, within which 6 pulses were triggered in 11 minutes. In the last 17 minutes, two peaks of 378 min^{-1} and 228 min^{-1} were achieved. Except for the two unexpected high PD repetition rate peaks, the overall repetition rate was 32.1 min^{-1}. This was lower than before the interval. In total, 2,641 discharge pulses were recorded within 60 minutes, and the average PD repetition rate was 44.0 min^{-1}.

In Figure 7c the PD numbers are calculated versus charge magnitude. The PD number roughly decreases with the increase of charge magnitude. More than 70% of the discharges in number occurred in the section of 18-20 pC, which is 1,879 discharge pulses. For the discharges over 32 pC, the PD numbers remained no more than 10 for each charge section.

When comparing the measured PD data of the two types of artificial defects, distinguishing characteristics can be found in the PD repetition rate and charge magnitude. In general at PDIV, the discharges generated from the insulation wound occurred more frequently than those from the semi-con tips. That cannot be the consequence caused by different trigger levels, because the trigger level selected for the detection of the insulation wound was 30 pC, which is higher than 18 pC for the detection of semi-con tips. The overall average PD repetition rate of the defect of the insulation wound is much higher than those of the semi-con tips under – 290 kV and – 310 kV, and the PD repetition rate of the semi-con tips became higher with the rise of the voltage.

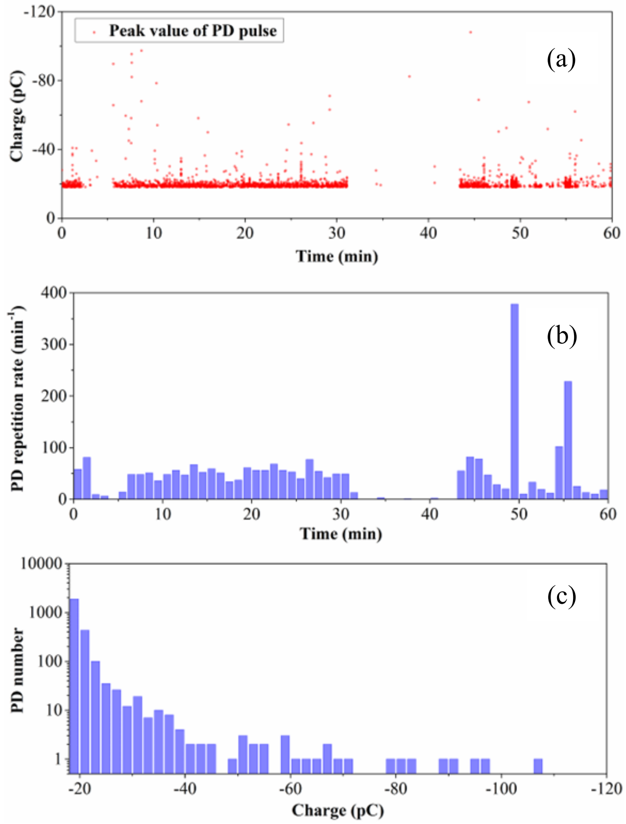

Figure 7. Characteristic PD plots of the semi-con tips under -310 kV for 60 min: (a) Q-T plot; (b) PD repetition rate versus measuring time; (c) PD number versus charge magnitude (bin width = 2 pC).

Noticeable diversity can also be seen from the PD charge magnitudes of the two defects. From Figure 5c it can be concluded that the discharge magnitude of the insulation wound at the PDIV mainly distributed under 40 pC, and PD numbers gradually decreased with the increase of charge magnitude. From Figure 6c and Figure 7c, the PD charge magnitude of semi-con tips distributed in a larger interval than that of the insulation wound. Charge magnitude of semi-con tips can be higher than 40 pC and as high as nearly 80 pC at PDIV. With the voltage raised up to – 310 kV, the charge magnitude could be higher.

For the defect of insulation wound, it can be considered as a large insulation cavity. The electric field inside the cavity was less likely influenced by the space charge that could accumulate in the insulation. Therefore, the PD activity remained relatively stable without abrupt change in either PD repetition rate or PD magnitude. On the other hand, for the defect of semi-con tips, the field strength was quite concentrated at the ends of the tips. As a matter of fact, the tips were located at the interface of the cable and the joint. With the presence of the grease used during the assembly at the interface, and the mechanical stress from the joint, the accumulation of space charge could prevail over its extraction. The electric field at the semi-con tips was more severely affected by the space charge, and this could be part of the explanation for the significant change in the PD characteristics.

3) Differentiated charge magnitude against time.

Under DC voltage one discharge may have an influence on its successive discharge, and the correlations between the discharges are assumed to be distinct for different types of PD [21]. To demonstrate the PD characteristics better than the simple *Q-T* plot, the modified differentiated *Q-t* pattern 'NoDi* Pattern' proposed in [32] is adopted to analyze the measured PD data. Assuming one PD occurred at time t_i, and the charge magnitude is Q_i. The successive discharge occurred at t_{i+1} and the discharge magnitude is Q_{i+1}. Thus, the variation between the adjacent discharges in time and charge magnitude can be calculated as:

$$\Delta t_i = t_{i+1} - t_i$$

$$\Delta Q_i = Q_{i+1} - Q_i$$

As the time increases monotonically, the Δt values will always be positive figures. However, the discharge magnitude of the successive discharge can be either higher or lower than the previous one that the values of the differentiated charge ΔQ can be positive and negative. The derived ΔQ-Δt pattern can be used to demonstrate the possible "memory effect" of the previous discharge on its successive discharge. The characteristic patterns of the defects of insulation and semi-con tips are shown in Figure 8.

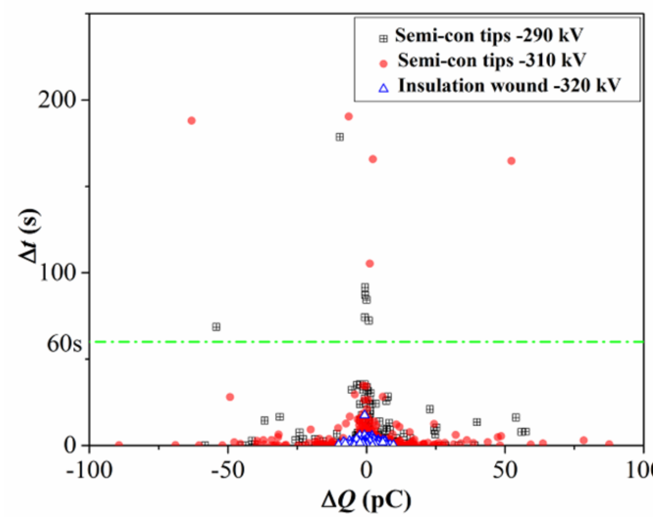

Figure 8. Characteristic ΔQ-Δt patterns of insulation wound and semi-con tips.

The majority of the points are overlapped around the origin of coordinates, and all 3 patterns are roughly symmetric. This means for the two types of defects under test, most discharges occurred at a relatively constant level of charge quantity. During the detection period, there was no uptrend or downtrend in the change of charge quantity with time. Judging from the green reference line marking the Δt of 60 s that after one PD occurred, the successive discharge was most likely to initiate within the following 1 minute. The PD pattern of the insulation wound has a more focused distribution than those of the semi-con tips. For the pattern of the insulation wound, the differentiated time Δt mainly concentrates below 6 seconds. The distribution of the differentiated charge magnitude ΔQ is limited between ± 10 pC. For the PD patterns of semi-con tips, the ΔQ-Δt plots have larger dispersions in both time and charge magnitude compared with the pattern of the insulation wound, suggesting a type of more drastic PD activity. The time intervals between adjacent discharges could be larger than 1 minute, and sometimes it would take about 3 minutes for the next PD to occur. The difference in the charge magnitude can be larger than 80 pC. Although the PD characteristics discussed in the above section under – 290 kV was quite different from those under – 310 kV, the characteristic ΔQ-Δt patterns are similar.

3 DISCUSSION

Considering that PD measurement is an essential quality assurance procedure during the manufacturing of AC cables, a PD test under AC voltage was chosen to be a part of factory tests for the 320 kV HVDC cable. The AC test voltage for PD measurement at power frequency was agreed as 192 kVrms by the manufacturer and customer, and all the cables passed the test. However, the peak value of the AC test voltage is 271.5 kV and it is lower than the rated operating voltage of the HVDC cable. This test can only serve as a part of quality control procedure, but it may not be a sufficient guarantee for defect-free cables. Although the AC PDIV of a defective cable model was reported to be much lower than PDIV under DC voltage [13], further research indicated that DC PDIV has a large dispersion and sometimes it can be lower than AC PDIV [14]. In addition, under steady state the field distribution is determined by conductivity under DC rather than by permittivity under AC, the field distributions at the defect are totally different even when the peak value of applied AC voltage equals the value of DC voltage. Another important issue is that under DC voltage, the accumulation of space charge will remarkably enhance the field distortion at defects and may be involved in discharge activities [22]. That is the significant influence which cannot be inspected under AC voltage.

During the detection of semi-con tips, the PD pulses were triggered at a more varying rate compared with that of the insulation wound. For detection period of semi-con tips under – 290 kV, the repetition rate was generally quite low in the first 10 minutes and the last 4 minutes. In addition, under – 310 kV the 11-minute time interval could be observed with only 6 pulses detected. Similar result of a period with lower PD repetition rate was observed in Wang's research about PD in XLPE cavity under AC voltage [23]. However, because the applied DC voltage in this experiment was just around the PDIV, with the PD repetition rate lower than that under AC by orders of magnitude, the drastic change of the PD activity during the 1.5-hour measuring period cannot be solely determined by the same mechanism that caused the decrease of PD repetition under AC voltage, such as the by-products generated by PD induced degradation. Apart from this, these intervals with very low PD repetition rate may also be caused by the accumulation of space charge, and future work will be dedicated to the relationship and interaction between space charge and partial discharge. The detection period of 30-60 min was previously recommended because of the low PD repetition rate under DC [21]. It should be noted that the PD activity would exhibit unstable characteristics, such as those obtained from the detection of the semi-con tips. Another reason is that the time interval observed under – 310 kV appeared after 30 minutes in the experiment. This kind of phenomenon would be missed if the detection time was too short.

The applied voltage was selected as negative polarity for the experiments, and the HFCT sensor was installed to detect the calibration pulse as a negative pulse. The PD pulses were expected to be negative pulses; therefore, the recorded pulses with the opposite polarity were regarded as interferences and not taken into the analysis. However, a few positive pulses were detected in the experiments. Considering the accumulated space charge and residual charge deposited by previous discharges, it may be able to initiate PDs with polarity opposite to the applied voltage. Whether pulses with the opposite polarity can be neglected in practice still needs to be further researched.

4 CONCLUSIONS AND FUTURE WORK

Artificial defects of insulation wound and semi-con tips were designed and constructed in the 320 kV HVDC XLPE cable test loop in the laboratory. The defects were effectively detected under DC voltage by partial discharge detection for 30-60 minutes. The PDIVs of the two defects were – 320 kV and – 290 kV, respectively. The trigger level was determined from a 5-minute monitoring. The test voltage was raised step by step for 10 kV and then held steadily for 2 minutes. During the 2-minute detection period, the PDIV would be determined if at least one pulse per minute was detected. The modified differentiated Q-t pattern is adopted to analyze the measured PD data along with conventional statistical graphs. The basic Q-T patterns show the change of charge quantity with time, and the n-T patterns which demonstrate the importance of PD repetition rate are essential in describing PD activities under DC voltage. By plotting the PD data as the differentiated Q-t pattern, the two types of defects can be easily distinguished.

A time interval was observed for the defect of semi-con tips under -310 kV in Figure 7a. During this interval the PD repetition rate decreased to once in a few minutes, only 6 pulses were triggered in 11 minutes. The mechanism behind this may be attributed the space charge phenomenon and the accumulation of by-products generated by PD induced degradation, and it will be investigated by space charge measurement and analysis of PD induced aging under DC voltage in future work.

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