Study on Partial Discharge Performance Testing of High Voltage Cables for EMUs

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Abstract. EMU high voltage cable partial discharge detection is an important means that is to ensure the reliable operation of EMU. This thesis summarizes the causes of partial discharge of EMU high voltage cable, and the mechanism of its formation is analyzed, then the corresponding cable partial discharge model and its interference model are designed. The main components of the test system are introduced. The partial discharge test system for high voltage cable of EMU is tested on site, and corresponding test data is obtained and then analyzed. At the same time, measures of anti-interference on site are put forward. Partial discharge testing detects the potential risks through state detection, and handles this problem by taking some effective measures to reduce the operational risks of the power supply system and ensure the safety and stability of the vehicle operation.

1. Introduction
The roof high voltage cable of EMU is the most important power transmission line connecting various high voltage electrical equipment in the whole train power supply system. Its performance is directly related to the normal operation of EMU. There may be some bubbles or other impurities inside the insulation layer of the roof high voltage cable of the EMU. As a result, the electric field is not uniform in all regions of the insulator of the cable insulation material. During the use of the cable, partial discharge phenomenon occurs in the insulator under strong electric field, which damages the cable insulation. Partial discharge is an important indicator of insulation defects, and it is also one of the main reasons for deterioration of the insulation. Cable partial discharge measurement can promptly detect the early failure [1-2]. Experts and scholars both at home and abroad, as well as IEEE, CIGRE and other international authoritative organizations have consistently recommended that partial discharge testing is the best method for evaluating the insulation status of cables [3]. There have been a great deal of papers on studying the status monitoring, diagnosis, and positioning of the medium and high voltage cables insulation through partial discharge testing [4-7]. High-voltage cables need to be tested for partial discharge before its delivery, after installation and during overhaul, thus ensuring the safe and reliable operation of EMU [8]. In this paper, EMU high voltage cable partial discharge experiment testing research is conducted.

2. Partial discharge causes analysis
The causes of EMU high voltage cable partial discharge can be grouped into the following three categories [9].
(1) Cable core with burrs
In the production and processing or assembly process of EMU high voltage cables, it will form burrs on the surface of the cable core due to production condition constraints. If it is not detected before delivery, the cable may generate partial discharge after being loaded and running for a period of time.

(2) Insulation moisture
The exterior of the EMU high voltage cables is protected by an insulation made of an ERP compound and a sheath made of a red halogen-free crosslinked EVA material. However, at the interface between the high-voltage cable and the cable terminal, trains are often eroded by rain, snow, wind, sand and sunlight during the running, and the insulation is easily moist.

(3) Insulation partially damaged
In the process of transport, loading and unloading, installation, and use of EMU high voltage cables, the outer insulation of the cable may be damaged. In addition, some high-voltage cables are exposed after loaded. During high-speed operation, they are impacted by fierce and sharp objects, causing damage to the cable insulation. All the above factors may cause partial discharges of the cables.

3. Partial discharge mechanism analysis

3.1. Partial discharge indicator parameters
Partial discharge of high voltage cable is a complicated physical process, and its physical state needs to be represented by a variety of relevant indicator parameters. The mechanism of partial discharge on cable insulation damage is also relatively complicated and the degree of damage to the cable insulation needs to be evaluated by various parameters.

In general, many parameters are used to indicate the partial discharge. Apparent discharge charge \( q_a \), discharge repetition rate \( N \), discharge energy \( W \), average discharge current \( I \), and discharge power \( P \) are widely used. The indicator parameter used in this paper is apparent discharge charge \( q_a \).

Inject a certain amount of charge at both ends of the high voltage cable sample, if the change of terminal voltage caused by the charge is the same as that of partial discharge, then the charge is the apparent discharge charge. The unit of apparent discharge capacity is pC. In the partial discharge test, when the parameter settings are different, and there are external factors and error interferences, the measured apparent discharge charge may vary. Generally, in the case of no changes in various factors, the measured maximum apparent discharge charge is the cable partial discharge capacity.

When partial discharge occurs in the internal air gap of the cable insulation, the exchange and accumulation of the charge in the air gap are difficult to measure at present. However, partial discharge will cause the change of charge at both ends of the cable insulator, and such change can be analyzed and verified by the equivalent circuit.

Use bubbles to replace broken parts in the insulator, such as burrs, tips, etc., as shown in Fig. 1. The equivalent circuit shown in Fig.2 consists of the equivalent resistance \( R_c \) and capacitance \( C_c \) of the bubble, the equivalent resistance \( R_b \) and capacitance \( C_b \) of the medium of bubble and insulator, and the equivalent resistance \( R_a \) and capacitance \( C_a \) of other parts.

Since the discharge time of bubbles in the cable insulation is relatively short, only \( 10^{-8} \sim 10^{-7} \) s, the frequency of the discharge pulse is very high. Therefore, when analyzing the response of the partial
discharge signal in the equivalent circuit, the resistance is negligible, i.e. the effective circuit is only composed by the equivalent capacitance.

The difference between the apparent discharge charge \( q_a \) and the actual discharge charge \( q_c \) can be derived from the equivalent circuit diagram of the cable insulation internal air gap. When the bubble in the cable insulator discharges, suppose the voltage change on the bubble is \( \Delta u_c \), then the actual discharge charge at both ends of the bubble is:

\[
q_c = \Delta u_c \left( C_c + \frac{C_a C_b}{C_a + C_b} \right)
\]

In general, \( C_a \gg C_b \), \( q_c \) can be simplified as:

\[
q_c = \Delta u_c \left( C_c + C_b \right)
\]

A discharge process lasts only \( 10^{-8} \sim 10^{-7} \) s, much less than the time constant of the power circuit, and it is too late for the power to replenish charge, so the charge on the capacitance \( C_a \) and \( C_b \) transfers. The voltage change of \( C_a \) is \( \Delta u_a \) and that of \( C_b \) is \( \Delta u_b \), then the voltage change \( \Delta u_c \) on the bubble can be expressed as:

\[
\Delta u_c = \Delta u_a + \Delta u_b = \Delta u_a \frac{C_a + C_b}{C_b} \approx \Delta u_a \frac{C_a}{C_b}
\]

The transient charge at both ends of the high voltage cable samples, i.e. the apparent discharge charge \( q_a \) can be expressed as:

\[
q_a = \Delta u_c \left( C_a + \frac{C_a C_b}{C_a + C_b} \right) \approx \Delta u_a C_a \approx \Delta u_c C_b
\]

Through the above analysis, we can draw the relationship between \( q_a \) and \( q_c \):

\[
q_a = \frac{C_b}{C_c + C_b} q_c
\]

Generally the air gap is thin, i.e. \( C_c \gg C_b \), so \( q_a \) is often much less than \( q_c \), and the apparent discharge charge is often much less than the actual discharge one.

3.2. Partial discharge diagram analysis

Partial discharge detection system graphical display part is to map the graph in accordance with the relationship between the various parameters of partial discharge, such as discharge capacity \( Q \) and the number of discharges \( N \), and the phase \( \Phi \) and time \( T \), which can directly reflect the discharge phenomenon.

Partial discharge diagram analysis are mainly the following categories: the two-dimensional diagrams, such as discharge capacity and phase diagram \( (Q - \Phi) \), base circle diagram, the number of discharges and phase diagram \( (N - \Phi) \), and the discharge capacity and time diagram \( (\Phi - T) \), and the three-dimensional diagram of discharge capacity, phase and time \( (Q - \Phi - T) \).

Divide a power frequency cycle of test voltage into a number of intervals, and calculate the average of discharge capacity of the same phase in different periods, and draw the histogram among partial discharge capacity, phase and time, then the partial discharge diagram can be obtained. The partial discharge diagram \( Q - \Phi \) is shown in Fig.3, and the base circle diagram is shown in Fig.4.
It can be seen from the $Q - \Phi$ diagram and the base circle diagram that the cable partial discharge is a process of charge accumulation, and then releasing. Under the sinusoidal AC voltage, the partial discharge of the cable mainly occurs in the first and the third quadrants of one sinusoidal period, i.e. the stage of voltage rising from the minimum to the maximum value. At the same time, it can be concluded that the discharge capacity, the number of discharges and the discharge energy of the cable samples are normally distributed. It can be seen from the $Q - \Phi$ diagram and the base circle diagram that the pulse amplitude and its location of partial discharge are not fixed.

3.3. Interference signal diagram analysis

There are a lot of interferences in actual test environment. The partial discharge signal tested by EMU high voltage cable test is generally mixed with other interference pulse signal. Through the graphical comparative analysis and processing of the collected signal, we can weaken or reduce the influence of the interference signal on the partial discharge pulse signal, and extract the signal which is really needed, and analyze the result so as to achieve the optimal test result [10-13].

There are many external factors that affect the partial discharge detection results. According to their characteristics, they can be summarized into two types: one is continuous wave interference signals, such as space radio interference, high harmonics in power supply, electromagnetic radiation, etc. The second is pulse interference signals, such as generators, SCR trigger pulse, exciter brush sparks, relays and other high voltage switch on and off. For continuous waveform interference, based on its continuous waveform characteristics, it can be separated from the partial discharge pulse signal or adopt the corresponding filtering means to eliminate. High-frequency characteristics of impulsive interference signals have a high coincidence with partial discharge pulse characteristics. In addition to professional and technical personnel, it is difficult for common operators to identify the difference, which is extremely detrimental to the discovery the insulation hazard of high voltage cables. The partial discharge diagram analysis can show the amplitude, phase, time and other features of pulse signals on the graph. Based on these characteristics, the operators can distinguish the actual high voltage cable partial discharge pulse signal from the pulses mixed with various forms of interference signals, so as to understand the actual insulation of the cable.

From a large number of tests we can summarize the following types of interference signal:

(1) The fixed phase impulse interference, as shown in Fig.5.
It can be seen from the waveform diagram that such interference signals occur within a power frequency sinusoidal period, at approximately the same position, and have approximately the same amplitude. Due to its fixed nature, interference of this nature presents a single peak in the diagram of $Q - \Phi$ spectrum analysis and exhibits a neat arrangement in the $Q - T$ diagram, so the fixed phase interference waveform can be easily filtered out from the partial discharge signal.

(2) Interference pulses associated to the sinusoidal voltage phase and time, as shown in Fig.6.

Such pulse interfere signal is associated with the phase and time with a certain law. Therefore, this pulse will appear in some fixed phase range, and these features will form some regular graphics, such as oval, S-shaped, oblique type, etc. if they are presented in the three-dimensional diagram $Q - \Phi - T$. This feature facilitates the use of separation techniques to filter out such interference from the partial discharge signal.

4. Test experiment

4.1. Normative references for testing
GB/T 3048.12-2007  Partial discharge test
TB/T 1484.3-2010  30 kV EPR insulated single phase power cable
JB/T 10435-2004  Cable partial discharge test system verification method

4.2. Test circuit composition
The test circuit includes a non- partial discharge source $W$, a single-channel digital partial discharge instrument $D$, a coupling capacitor $C_k$, a calibration capacitor $C_{cal}$, a filter $Z$, an input unit $ZA$, a high voltage voltmeter $V$ and tested cables $CX$, test circuit diagram is shown in Fig.7.
4.3. Test equipment

The test power supply should be an AC power supply with a frequency of (49-61) Hz. The voltage waveform of the power supply is approximately a sine wave with two same half-waves, as well as a ratio of peak to RMS of $\sqrt{2} \pm 0.07$. As the utility cannot meet the test requirements, so we add the isolation transformer to the test device power supply system. Test system mainly consists of the isolation transformer, voltage regulator, high voltage test transformer with no partial discharge, partial discharge tester, coupling capacitors, calibration capacitors and other components. Test system wiring diagrams are shown in Fig.8 and Fig.9.

1) Isolation transformer technical parameters:
Model: GD50  
Input voltage: 380 V  
Input Current: 132 A  
Output voltage: 380 V  
Output Current: 132 A  
Interference attenuation index: 15 kHz~1 MHz, over 10 dB

2) Voltage regulator technical parameters:
Model: TDG-50 kVA  
Input voltage: 380 V  
Input Current: 132 A  
Output voltage: 0~420 V

3) No partial discharge high voltage test transformer technical parameters:
Model: YDTW-50 kVA/80 kV  
Output voltage: 0~80 kV  
Partial discharge capacity: Less than 2 pC at 80 kV.

4) Partial discharge tester technical parameters:
Model: JF-1205  
Voltage: 80 kV

5) Coupling capacitor technical parameters:
Model: DIV-80kV/1000 pF  
Voltage: 80 kV  
Capacitance: 1000 pF

6) Calibration capacitor technical parameters:
Model: CIC-80kV/100 pF  
Voltage: 80 kV  
Capacitance: 100 pF
4.4. Test Data
Five cables tested on site are respectively as:
(1) the UHV throughout cable of car No. 3 roof of 250 km Unified EMU CRH2239.
(2) the UHV bridge connecting cable between cars No.3 and 4 of CRH2088A (Five-level repair).
(3) the UHV bridge connecting cable between cars No.3 and 4 of CRH2173 (Four-level repair).
(4) the UHV bridge connecting cable between cars No.13 and 14 of CRH2124 (Five-level repair).
(5) the UHV connecting cable used by Guangzhou-Shenzhen-Hong Kong EMU high voltage test.

Test data of the UHV throughout cable of car No.3 of E28 250 km unified EMU CRH2239 is shown in Table 1. Partial discharge of Voltage "0" in Table 1 is the background interference signal.

| Five-level repair cable | Voltage (kV) | Partial discharge capacity (pC) |
|------------------------|-------------|--------------------------------|
|                         | 0           | 7.5                            |
|                         |             | 11.2                           |
|                         |             | 14.9                           |
|                         |             | 20.1                           |
| Four-level repair cable 1|            | 11.8                           |
|                         |             | 73.2                           |
|                         |             | 138                            |
|                         |             | 139                            |
|                         |             | 140                            |
| Four-level repair cable 2|            | 12.3                           |
|                         |             | 72.3                           |
|                         |             | 137                            |
|                         |             | 137                            |
|                         |             | 139                            |
|                         |            | 10.2                           |
|                         |             | 15.1                           |
|                         |             | 19.9                           |
|                         | 0           | 7.4                            |
|                         |             | 10.6                           |
|                         |             | 14.9                           |
|                         |             | 20.2                           |
|                         | 10.8        | 74.9                           |
|                         |             | 134                            |
|                         |             | 134                            |
|                         |             | 138                            |

4.5. Test data analysis
It can be seen from Table 1 that the cable partial discharge capacity is much larger than the standard one. The main reason is that the background interference signal is large, and the partial discharge capacity is already 11.8 pC when the voltage is "0". Factors that cause the big background interference are:
(1) The test point is too far from the ground pole, and the ground leading wire is nearly 200 meters long;
(2) The test time is at 4 o'clock, and there was a lot of work in the near plant, as well as a 100 meters long working train parallel to the grounding wire.
4.5.1. Background interference in the process of the cable test

Background interference is the standard amount of power injected into a test cable by a tester using a standard electrical signal, called "calibration" in the industry. When the calibration is completed, and the calibration switch is turned off, the reading and clutter are displayed on the discharge meter and the graphic instrument. Fig.10 and Fig.11 show the experiment background interference. In Fig.10, the discharge meter shows 103.0 calibrated power, the two vertical lines on the ellipse of the graphic instrument is 103.0 calibrated power, and the clutter is the background interference. In Fig.11, the tester closes calibration, the ellipse on the graphical display shows the interference diagram, and the background interference power is 15.7 pC. This interference is mainly from the grounding wire, which is relatively long (about 200 meters). What’s more, there is space radio interference because of no space shielding. This interference can be improved by standard grounding pole(<5pC).

Fig.10 Background interference situation 1

Fig.11 Background interference situation 2

4.5.2. Reasons for partial discharge capacity less than the background interference

Among some of the test data, the partial discharge capacity is less than the amount of background interference, the reason is that the specimen has a small burr, and it will discharge under very low voltage. However, the burr will burn up when the voltage increases, and the partial discharge will reduce. Moreover, the background interference is not stable.

5. Conclusions

(1) Partial discharge test can be more easily than the power frequency withstand voltage test to find the insulation defects of the high voltage cable assembly. Compared with the power frequency withstand voltage test, partial discharge test has a high test accuracy. For the EMUs upcoming on-line operation or has been put into operation, by the partial discharge detection of high voltage cables, and collecting and analyzing the test data, we can quickly understand the weaknesses in insulating materials, and master the state of partial discharge and the degree of insulation aging, so as to accurately judge the insulation defects of the cables, and to find out the cause of the faults and take corresponding measures to ensure the quality of the cables, ensuring the safety, reliability and stability of the running of the EMUs.

(2) Through the analysis of the mechanism of partial discharge and on-site testing, the environmental requirements, the composition of the test equipment and the test methods of high voltage cable partial discharge test for EMUs are grasped. It provides the technical reserves for the deep study on the EMUs high voltage cable partial discharge test. It reduces the operation risk of the EMUs power supply system and improves the operation efficiency of the power supply equipment. What's more, it provides the technical guarantees for the safety, reliability and stability of the running of the EMUs.

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