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ABSTRACT

This paper focuses on the discharge of cross-linked polyethylene (XLPE) insulated DC cables, which has become a concern of power utilities when carrying out a voltage withstand test or an outage maintenance. Based on the electrical tree initiation test of XLPE block samples under grounded DC voltages, the main cause and key factors for damages of DC insulation resulted by grounding discharge were investigated, and the allowable voltage level to start the accelerated discharge operation was estimated. By the laboratory tests of two XLPE cable samples discharged under different conditions, the basic discharge rules were observed, the equivalent circuit was set up, and the equipment parameters were determined. In addition, a method to estimate the discharge time for cable lines with different lengths was proposed. Finally, the on-site measured data of decay voltage and leakage current were presented for a 200 kV DC XLPE cable line which had been discharged steppedly through a resistance grounding device after the DC voltage withstand test, and the experimental results were found to be in good agreement with the theoretical data.

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I. INTRODUCTION

Recently, cross-linked polyethylene (XLPE) cables have been increasingly used in DC transmission and distribution power systems, with an ever higher rated voltage level. In addition, in the prequalification test, type test, or after-laying test, the voltage can be as high as 1.45 or 1.85 times of the rated operating voltage.[1,2] After the high voltage test or line power off, the cables need to be effectively discharged so as to avoid unexpected injuries to the cable insulations or field workers. However, no standards or regulations have been issued on the specific requirements or procedures for the discharge process.

In China, there is an electric power industry standard issued in 2013, which gives recommendations for the parameters and procedures of the DC withstand test for submarine oil-filled cables up to 500 kV but provides no theoretical or experimental data.[3] Due to the big difference in insulation material, this standard is not considered fully applicable to XLPE DC cables.

Dev Paul presented his study on the cable inherent capacitance, its stored energy, maximum transient voltage, and the time to discharge such voltage and energy to a safe level with and without a grounding device. In his research, the objects were 11 and 6.6 kV three-core AC cables used in the power supply system of big ships, and except for the theoretical analysis based on the R–C (resistance-capacitance) equivalent circuit, no measured data were provided.[4]

Lafaia carried out some experimental and theoretical analysis of the cable discharge process based on the tests, calculations, and simulations of 275 kV pressurized-oil-filled (POF) cables. Her contributions included the field and laboratory measurements of voltages and currents during the cable discharge, an estimation method for the leakage resistance and discharge time by a simple R–C parallel circuit, and typical values of the leakage resistance, leakage current, and discharge time for 275 kV AC POF cable systems.[5]

Besides above research, obviously, more work is still needed in order to formulate reasonable procedures of cable discharge and develop appropriate discharge devices for HV DC XLPE cables. In this paper, the electrical treeing test of XLPE insulation samples under grounded DC voltages was carried out first to investigate the failure mechanism of DC insulation and estimate the safe voltage level of the XLPE cable to start the accelerated discharge by a

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resistance grounding device. Next, the discharge test of two short cable samples after DC prestress was performed to research the basic discharge rules. By theoretical analyses, the key equipment parameters were determined, and the calculation method for the discharge time of cable lines with different lengths was proposed. Finally, the measured voltage and current data of a long-length 200 kV DC XLPE cable during its discharge process after a field DC withstand test were presented, which verified the research conclusions.

II. ELECTRICAL TREEING TEST OF XLPE INSULATION SAMPLES

The breakdown of a XLPE cable is believed to occur on a weak point of the insulation, which can be one of the protrusions or impurities contained in it. Because the breakdown test of the cable sample is costly, time-consuming, and laborious, the treeing test has been widely taken as an alternative means of it by using polymer blocks into which a metallic or semi-conducting needle electrode is inserted. In the treeing test, a needle is introduced to artificially produce a weak point, and the characteristic of the electrical tree growth is used to reflect the overall breakdown performance of the solid insulation.

In this paper, before the discharge test was carried out on power cables, the electrical tree initiation experiment was performed on XLPE insulation samples first under different grounding conditions after being DC prestressed. Due to the advantages of controllability and observability, the treeing test was expected to open a view window for the research on the failure mechanism and key factors of the XLPE cable discharge process.

A. Sample preparation and experimental setup

The samples for the electrical treeing test were disk like pieces of 5 mm thickness cut from the XLPE insulation of a high voltage direct current (HVDC) cable. Within each sample, there was a typical pin-plane electrode system consisted of a steel needle and the semi-conducting layer. The needle with a trunk of 1 mm and a tip curvature radius of (5 ± 1) μm was inserted into the sample to serve as a high voltage electrode, and it was fixed approximately (2 ± 0.2) mm away from the low voltage plane electrode on the opposite side. Figure 1 is a diagram of the sample preparation and the electrode system.

The prepared samples were mounted in a test container. The DC voltage was applied on the needle electrode before it was switched from the DC power supply to the grounding line by a charging/discharging change-over device. The experiments were carried out at room temperature. Ten samples were tested in each group. After being DC prestressed and grounded under specified conditions, these samples were observed under a microscope and the tree initiation rate could be determined, which was the percentage of the number of samples with trees to the total number of samples in the group.

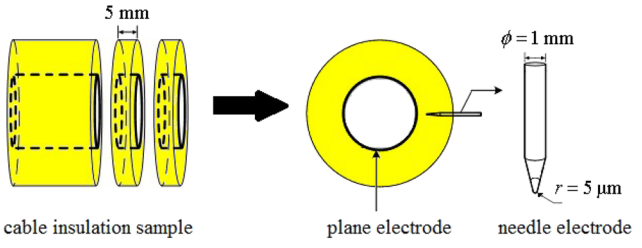


FIG. 1. Schematic diagram of the cable insulation sample and electrode system used for the electrical treeing test.

The schematic diagram of the charging/discharging change-over device is shown in Fig. 2. The action of switch SB2 is controlled by an armature, and its position determines the state of the sample, with "a" standing for DC stressing and "b" for grounding. R_d is a grounding resistor whose resistance can be changed as needed.

B. Experiments and results

By grounding the samples after they had been DC prestressed for 10 min, the influence of the DC voltage and the grounding resistance on the tree initiation rate of samples had been investigated. In this experiment, the voltage precision was 0.1 kV, and the XLPE samples were observed at 400 times magnification under a microscope to find out if any electrical trees existed. The results are listed in Table I.

The experiments were carried out in two steps. First, the resistance of grounding resistor was fixed as zero, and the magnitude of DC voltage was changed. Under the DC voltage of −10 kV, no electrical tree has been triggered. Along with the increase in the DC voltage magnitude, the tree initiation rate goes up as well. When the voltage reaches −35 kV, electrical trees appear in all ten samples under test, which makes a tree initiation rate of 100%. Second, the DC voltage was fixed at −35 kV, and the resistance of the grounding

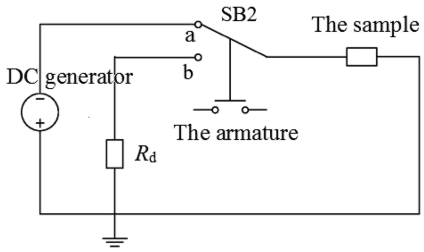


FIG. 2. Schematic diagram of the charging/discharging change-over device.

TABLE I. Tree initiation rates of the samples in the grounded DC test.

DC voltage (kV)	Resistance (kΩ)	Tree initiation rate (%)
−10	0	0
−15	0	20
−20	0	60
−25	0	70
−30	0	90
−35	0	100
−35	0.25	100
−35	1	80
−35	10	50
−35	100	0

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resistor was changed. Along with the increase in resistance from 250 Ω to 100 kΩ, the tree initiation rate decreases from 100% to 0.

C. Analysis of insulation failure mechanism

It was found that the continuous application of a DC voltage of −60 kV for 20 days did not trigger an electrical tree in the DC XLPE samples, even at an elevated temperature of 90 °C.[6] On the contrary, by grounding the needle electrode of the sample after being DC prestressed for 10 min, as shown in Table I, −15 kV is high enough to trigger some trees and −35 kV can trigger electrical trees even when a resistor of 10 kΩ is connected in the grounding line. In fact, not only grounding after DC prestress but also applying impulses superimposed on the DC voltage or impulses after DC prestress were also reported to cause tree initiation in XLPE samples.[7,8]

Similar phenomena have been found in DC withstand tests of cable samples. Two DC XLPE cable lines were connected in parallel to be type tested. One line broke down and shortly so did the other one. It was speculated that the failure of the second cable was the result of the voltage fluctuation caused by the breakdown of the first cable. Frank recommended taking abrupt grounding as a quality control method for polymeric insulated HVDC cables after his experiments on a 200 m long XLPE cable, and he found that the voltage variation rate was more critical than its amplitude.[9]

Based on the above discussion, it can be concluded that although the XLPE insulation has a good endurance to stable DC voltages, it is prone to damages caused by stress changes. For example, an improper discharge procedure of the XLPE cable after the DC withstand test may be one of such cases. In order to investigate the insulation failure mechanism, some theoretical analyses are performed as follows.

The R–C model in series is adopted here, where C_0 and R_0 are the equivalent capacitance and resistance of the XLPE dielectric between the needle and plane electrode. As shown in Fig. 3(a), during the charging process, a DC source which outputs a voltage of U_s is connected to the sample. After 10 min, the DC source is disconnected and a grounding resistor R_d is introduced to discharge the sample, as shown in Fig. 3(b). At the end of the charging process, a voltage of U_0 is built up across the capacitance C_0.

U_0 is equal to or smaller than U_s, depending on the charging duration. Because the charging duration and time constant are the same for all samples, the ratio between U_0 and U_s will be the same. Thus, for the convenience of analysis, introduce a coefficient k and take U_0 as kU_s. Two sets of test data are adopted to calculate the equivalent resistance R_0 of the sample, which are those listed in the first and last row of Table I. Under the two cases, no trees have been initiated, and the peak discharge current I_L flowing through R_0 is regarded as the critical value not to trigger a tree. Therefore, an equation can be obtained as

$$I_L = \frac{10k}{R_0} = \frac{35k}{R_0 + 100}. \quad (1)$$

By (1), the equivalent resistance R_0 is determined as 40 kΩ and the critical current I_L is $0.25k$ A.

Now make a simple verification. As shown in the next-to-last row of Table I, the DC prestress of −35 kV and a grounding resistor of 10 kΩ give a tree initiation rate of 80%, and the peak discharge current is calculated as

$$I_H = 35k/(40 + 10) = 0.7k \text{ A}.$$

If the resistor is removed from the grounding line, the voltage needed to produce the same current should be

$$U_H = 0.7k \times 40/k = 28 \text{ kV}.$$

This voltage amplitude is between 25 and 30 kV, under which the tree initiation rate is 70% and 90%, respectively, as shown in the fourth and fifth row of Table I. It can be seen that the same current results in similar tree initiation rate, namely, similar degree of insulation damage under different conditions, and the equivalent circuits in Fig. 3 agrees well with the experimental data in Table I.

If the relationship of voltage vs time or current vs time of the test sample can be recorded during the charging or discharging process, the equivalent capacitance C_0 can also be determined. Although the analysis based on Fig. 3 is a simplified one, two definite conclusions can be drawn.

① The R–C composite model can be applied for the discharge process analysis of the XLPE sample, which is grounded after DC prestressed.
② The damage degree of samples caused by the grounding of the needle electrode depends on the release rate of charges injected by DC prestress, which can be characterized by the initial discharge power or the maximum discharge current.

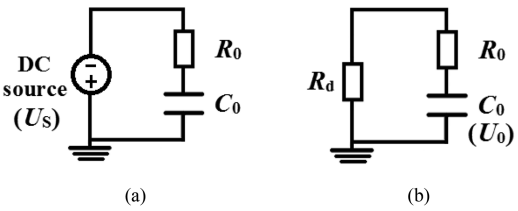


FIG. 3. The equivalent circuits used for the analysis of tree initiation in XLPE samples: (a) the charging process by the application of a DC source and (b) the discharging process through a grounding resistor.

D. Estimation of the safe discharge voltage for XLPE cables

Just as the grounding discharge after DC prestress will lead to the initiation of electrical trees in the XLPE block, the improper discharge process will also cause unexpected damages to XLPE insulated cables operated or tested under DC voltages. Therefore, it seems necessary to estimate the allowable voltage level for the start of the accelerated discharge of XLPE cables.

As shown in Table I, under the DC prestress of −10 kV, no electrical trees are triggered in the XLPE insulation by the grounding of the needle electrode. Thus, this voltage value can be regarded as an upper limit for the allowable discharge voltage of the XLPE sample under test.

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The static electrical field E_{tree} at the needle tip for the voltage U of −10 kV is calculated to be 299 kV/mm by the following equation:

$$E_{tree} = \frac{2U}{r \ln\left(1 + \frac{4d}{r}\right)}, \quad (2)$$

where r is the curvature radius of the needle tip and d is the distance between the needle and the plane electrode, 2 mm. In this calculation, the effective radius 10 μm of the needle tip is taken instead of the geometric radius 5 μm. It was reported that the accumulation of space charges would make the apparent radius of the needle tip larger than its geometric radius, and the value of the effective radius would stabilize at 10 μm.[10,11]

This electrical field is the threshold not to trigger an electrical tree at the needle tip of the XLPE sample, which needs to be converted into the global electrical field of the cable insulation. This can be done by the field enhancement factor k_f at a microscopic defect in the cable insulation.

The field enhancement factor k_f is calculated based on the most dangerous defect, in this case, a metal defect with the maximum size allowed by the Chinese national standard, 125 μm, and a tip radius of 10 μm.[12,13] Now, k_f can be determined as follows:[14]

$$\lambda = \frac{1}{\sqrt{1 - 10/125}} \approx 1.04,$$

$$\alpha = \frac{1}{2} \ln \frac{\lambda + 1}{\lambda - 1} - \frac{1}{\lambda} \approx 1.00,$$

$$k_f = 1 - \frac{1}{\alpha}\left(\frac{1}{2} \ln \frac{\lambda + 1}{\lambda - 1} - \frac{\lambda}{\lambda^2 - 1}\right) \approx 11.8.$$

The enhancement factor k_f describes the distortion degree of local field at the defect tip compared to the global field of cable insulation. As the breakdown of a XLPE cable is believed to occur on a weak point of the insulation, it is most likely that the electrical tree will start from the most dangerous defect and develop to trigger the breakdown of insulation bulk. Therefore, the global field of the cable insulation E_{bd} can be obtained from E_{tree} by

$$E_{bd} = \frac{E_{tree}}{k_f} = \frac{299}{11.8} \approx 25 \text{ kV/mm}.$$

This field strength value is close to the working field stress of modern UHV DC polymer cables, such as those with a rated voltage of 525, 600, and 640 kV, a little bit higher than the mean field stresses between 12 and 20 kV/mm, which are reported for the HV DC cables already put into commercial operation.[15–18]

From the calculation result, it can be concluded that the accelerated discharge can be started safely if the voltage of the cable is no higher than its rated voltage for XLPE cable of 500 kV and below. In the Chinese Electric Power Industry Standard,[3] it is recommended that for 500 kV oil-filled submarine cables, the discharge device cannot be connected until the residual voltage of the cable has declined to one-half of the DC test voltage, which is 1.5 times the rated voltage. For the XLPE cable, a lower voltage level is recommended here because it is more heavily affected by space charges and more prone to be damaged by an improper grounding discharge after the DC withstand test.

The tree initiation voltage of XLPE samples under grounded DC was measured by one-time grounding for new cable insulation. For cables that have been operated for some time, considering the performance degradation of the XLPE insulation due to the aging effect, the accelerated discharge can be started on a voltage level lower than the rated operating voltage.[19,20]

After the electrical treeing test on XLPE bulk samples and the failure mechanism analysis and discharge voltage estimation based on it, the discharge tests of actual cable samples were carried out.

III. DISCHARGE TESTS OF XLPE CABLE SAMPLES

A. The two cables under test

Two sample sections of the XLPE cable were tested in the DC charging and discharging experiment, one DC cable with a length of 150 m and a type of HYJQ41-F-200 kV 1 × 500 mm^2 and one AC cable with a length of 35 m and a type of HJQF41-64/110 kV 1 × 500 mm^2. Their detailed structural and dimensional parameters are listed in Table II. As both are submarine cables, they have very

TABLE II. The structures and dimensional parameters of the two cables under test.

The 200 kV DC cable		The 110 kV AC cable	
Constituents	Diameter (mm)	Constituents	Diameter (mm)
Copper conductor	26.6	Copper conductor	26.6
Conductor screen	30.2	Conductor screen	30.6
XLPE insulation	64.2	XLPE insulation	64.6
Insulation screen	67.0	Insulation screen	67.4
Swelling tape	70.0	Swelling tape	69.9
Lead sheath	76.4	Lead sheath	75.3
PE jacket	81.2	PE jacket	85.3
Optical cable layer	93.2	Under layer	88.9
Bedding layer	97.2	Optical cable layer	100.9
Steel armor	109.2	Bedding layer	101.8
Outer serving	117.2	Steel armor	113.8
...	...	Outer serving	124.0

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similar structures. In addition, the insulation thickness is 17 mm for both but made of different XLPE raw materials.

B. The experimental system

The discharge experiments of the two cables were carried out in two laboratories, where different DC voltage generators integrated with different voltage dividers were used. The equipment connection mode, test procedure, and discharge device were all the same. Due to space limitations, only the site picture of the DC cable test is given in Figs. 4(a)–4(b) is the schematic diagram of the DC voltage generator. For the DC cable test, the voltage-multiplying rectifier is a three-stage series circuit, the resistance of the high voltage arm resistor R1 is 1000 MΩ, and that of the low voltage arm resistor R2 is 10 kΩ.

For the AC cable test, the fundamental structure of the DC voltage generator is the same, only that the voltage-multiplying rectifier is a two-stage series circuit and that the resistance of the high voltage arm resistor R1 is 600 MΩ. The same resistance discharge device with a type of ZGS-DR360 kV/160 MΩ was used in both experiments. As shown in Fig. 4(c), it consists of four resistors connected in series, which are 20, 20, 40, and 80 MΩ from 1 to 4. By connecting the grounding terminal of the base to the grounding hook at different positions, the resistance of the grounding device can be changed accordingly.

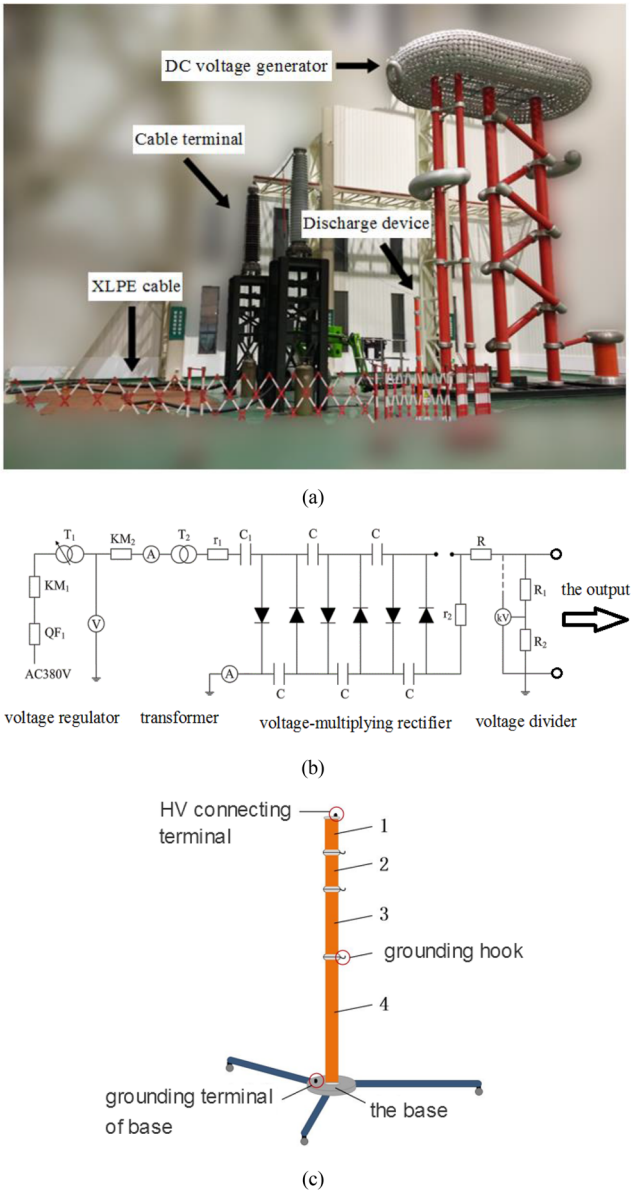


FIG. 4. The diagram of the cable DC charging and grounding discharge test: (a) the experimental connection diagram, (b) the schematic diagram of the DC voltage generator, and (c) the resistance discharge device.

C. The experimental procedure

First, turn on the DC voltage generator and increase its output voltage to 30 kV. After 60 min, reduce the voltage to zero and turn off the generator. The residual voltage decay of the cable is recorded by an oscilloscope, with a voltage precision of about 1%.

The charging condition remains the same. The discharge tests of cables are carried out under three conditions with different discharge resistances.

Condition 1: The resistance of the voltage divider.
Condition 2: The total resistance of the discharge device (which is paralleled with the voltage divider).
Condition 3: Resistors 1 and 2 of the discharge device (which is paralleled with the voltage divider).

D. Voltage decays of cables during the discharge process

The residual voltage on the cable decays with time, as shown in Fig. 5. When different resistances are used for the discharge of the cables, the curves of voltage vs time are different as well.

When the DC voltage is applied on the XLPE cable, a large number of charges will be accumulated in the insulation. Then, if the DC voltage generator is powered off, these charges will be released into the earth through the grounding resistor. In theory, this process can be mathematically described by the zero-input response of the first-order R–C circuit, as shown in the following equation:

$$u = U_0 e^{-t/\tau}. \tag{3}$$

The voltage u of the cable decays exponentially from its initial value U_0 at a rate dependent on the time constant τ. The discharge voltage curves of the two cables are shown in Fig. 5, which are fitted well by (3) with different values of time constant. Each experiment is carried out twice, and the data of the time constant are listed in Table III.

E. The analysis of the discharge process

Based on the dimensional parameters of the two cables listed in Table II, the resistance R_c and capacitance C_c of the XLPE insulation can be determined by the following equations:

$$R_c = \frac{\rho}{2\pi} \times \ln\frac{D_2}{D_1} \times \frac{1}{L}, \tag{4}$$

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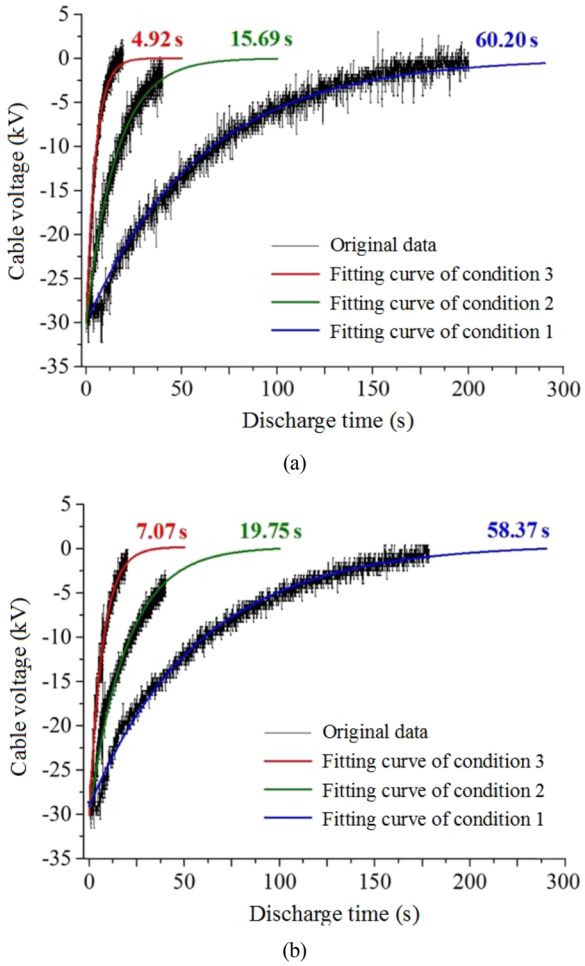


FIG. 5. The curves of voltage vs time for the two cable samples discharged through different resistances: (a) the DC cable and (b) the AC cable.

$$C_c = \frac{\varepsilon}{18 \times \ln \frac{D_2}{D_1}} \times L \times 10^{-9}, \tag{5}$$

where ρ is the resistivity of the insulation material, ε is the relative permittivity, D_2 is the outer diameter of the insulation layer, D_1 is the inner diameter, and L is the cable length. It is reported that the relative permittivity is nearly the same for both the AC and DC XLPE insulation, which is 2.3, while the resistivity is different, which is usually in the range from 10^{14} to 10^{16} Ω m,[21,22] For convenience, a same resistivity value is taken here, 1×10^{15} Ω m. As will be shown in the following discussion, this has no big impact on the analysis result.

During the discharge progress of the cables, the DC voltage generator is still connected with the cable terminal although the output is turned off. Hence, the equivalent circuit of the whole system should be as in Fig. 6, where R_s and C_s are the equivalent resistance and capacitance of the DC voltage generator system, which are unknown; R_1 and R_2 are the resistances of the voltage divider; R_c and C_c are the resistance and capacitance of the cable insulation, which can be calculated by (4) and (5); and R_d is the resistance of the discharge device. Switch K_1 is used to connect or disconnect the discharge device.

For clarity, the parameters of the elements in Fig. 6 are listed in Table IV. According to Fig. 6, the time constant of the cable discharge system can be determined by

$$\tau = R_{eq} \times C_{eq} = (R_s \, R_1 \, R_c \, R_d) \times (C_s + C_c), \tag{6}$$

where ‖ represents the parallel relationship between the resistances and R_2 is neglected because it is small enough compared to R_1 in series.

The values of the time constant have been obtained by the cable decay voltage curves recorded during the discharge process, as listed in Table III. Thus, by substituting the parameters, three equations can be established for each cable according to the three experimental conditions, and then, R_s and C_s can be solved. The calculation process is not given here, and only the results are presented. The values of R_s and C_s are those listed in Table IV at the last two rows.

As can be seen from Fig. 5 and Table III that after the application of the DC voltage, a grounding resistor can be used to release the charges in the XLPE cable insulation. The smaller the resistance, the shorter the discharge time. Once the equivalent resistance and capacitance of the voltage generator are known, the resistance of the grounding device can be determined by Fig. 6 or (6) to fulfill the requirement of the discharge time. In some circumstances, the voltage generator will be disconnected from the cable after the DC withstand test. In such a case, the discharge process will become faster because the removal of R_s and C_s from Fig. 6 or (6) makes the discharge time constant smaller.

TABLE III. The fitted values of time constant for the cable discharge test.

	The time constant (s)			
	The 200 kV DC cable		The 110 kV AC cable	
Experimental grouping	Original	Average	Original	Average
Condition 1	60.20 57.42	58.81	58.37 55.09	56.73
Condition 2	15.69 15.75	15.72	19.75 17.85	18.80
Condition 3	4.92 4.69	4.81	7.07 6.42	6.75

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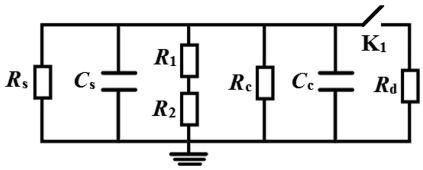


FIG. 6. The equivalent circuit of the cable discharge system.

In addition to the time requirements, the safety of the cable needs to be considered as well when selecting a resistance discharge device. For the modern high-voltage long-length cable lines, discharging through only one fixed resistor may be unable to meet both the time and safety requirements. In such cases, the usage of several resistors for stepped discharge will be a reasonable solution.

F. Relationship between the discharge time and the cable length

The two cable samples tested are short, with a length of 150 and 35 m, respectively. In practical engineering, the length of cable lines is usually much longer, especially for DC cable systems. Along with the increase in the cable length, the discharge time constant will become larger. Taking the 200 kV DC cable discussed in this chapter as an example, the relationship between the time constant and the cable length can be established by the following equation:

$$\tau = \left(R_s R_1 \frac{1.2 \times 10^{14}}{L} R_d\right) \times \left(C_s + 1.7 \times 10^{-10} L\right). \quad (7)$$

Once the cable length is determined, the discharge time can be estimated by 5τ. For example, under the three discharge conditions, the relationships between the discharge time and the cable length are established, as shown in Fig. 7.

It can be seen from Fig. 7 that when a small discharge resistance is used, as in condition 3, the relationship between the discharge time and the cable length is nearly linear. This is easy to be understood. As you can see from (7) that because R_d is much smaller than the other three resistances and C_c is larger than C_s, the time constant can be approximated by the following equation:

$$\tau \approx R_d \times 1.7 \times 10^{-10} \times L. \quad (8)$$

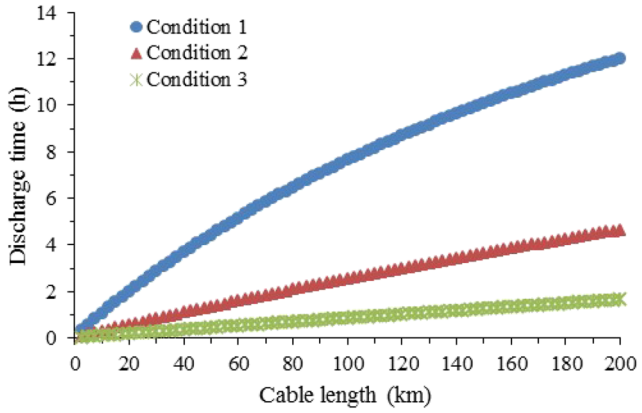


FIG. 7. The discharge times for the 200 kV DC cable with different lengths under the three discharge conditions.

Therefore, for the XLPE cable lines with a length of tens of kilometers as usually used in the practical projects, the discharge time can be estimated by (8). For example, for a cable line of 50 km and a discharge resistor of 40 MΩ, the discharge time calculated by (7) is 0.43 h, very close to the value of 0.47 h given by (8).

IV. THE DISCHARGE OF A LONG DC CABLE LINE AFTER THE FIELD WITHSTAND TEST

The test object was a 200 kV optical fiber-integrated submarine cable line with a type of YJQ41 1×300+2×12 and a length of 16.36 km, to be adopted in a multi-terminal voltage source converter (VSC)-HVDC transmission project. According to CIGRE TB 496,[2] a negative DC voltage of 1.45 times rated voltage should be applied on the XLPE insulation for 1 hour in the after-laying acceptance test of the cable system. Thus, by introducing an allowable fluctuation of 5% in the rated DC voltage of 200 kV, the magnitude of the withstand test voltage was finally determined to be −305 kV.

For this cable line, the resistance and capacitance of the insulation bulk are calculated to be 5.6×10^3 MΩ and 3.6 μF by (4) and (5), respectively. The resistance of the voltage divider is 1500 MΩ. The equivalent resistance and capacitance of the DC voltage generator are unknown. In addition, two protective resistors, R_p, of 1 MΩ are

TABLE IV. Parameters of elements in the equivalent circuit of the cable discharge system.

The element		The parameter	
		The DC cable test	The AC cable test
R_1 (MΩ)		1000	600
R_2 (kΩ)		10	10
R_c (MΩ)		8.0×10^5	3.4×10^6
C_c (nF)		25.4	6.0
R_d	Condition 2 (MΩ)	160	160
	Condition 3 (MΩ)	40	40
R_s[a] (MΩ)		781	700
C_s[a] (nF)		106	170

[a]The parameter values of these two elements are determined by the calculation.

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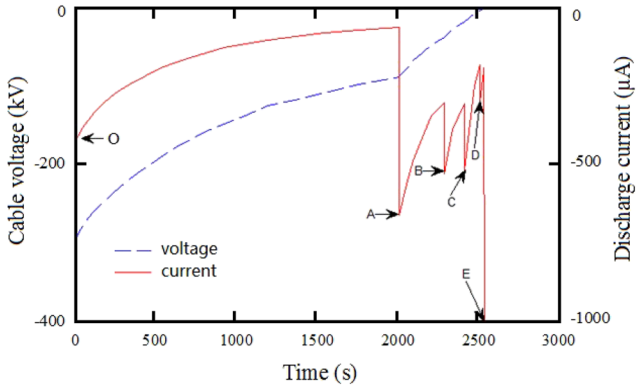


FIG. 8. The voltage and current during the cable discharge process.

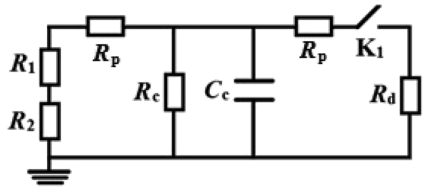


FIG. 9. Equivalent circuit of the discharge system for the 200 kV DC XLPE cable line.

connected to the high voltage terminals. The type of the discharge device is ZGS-DR360 kV/160 MΩ, the same as in Fig. 4(c).

After the 1-h DC withstand test under −305 kV, the discharge of the cable was carried out in the following stages:

O: The output voltage of the DC generator declined to zero, and the cable discharge process started.

O → A: Charges in cable insulation were released through the cable itself, the voltage generator, and the voltage divider. The cable voltage decayed from −305 to −100 kV.

A → B: The discharge resistor of 160 MΩ was connected to the cable to accelerate the discharge process. The cable voltage decayed from −100 to −40 kV.

B → C: The discharge resistor was changed to 80 MΩ. The cable voltage decayed from −40 to −20 kV.

C → D: The discharge resistor was changed to 40 MΩ. The cable voltage decayed from −20 to −6 kV.

D → E: The discharge resistor was changed to 20 MΩ. The cable voltage decayed from −6 to −1 kV.

E: The grounding rod was connected to the cable terminal, which marked the near end of the cable discharge process.

The voltage decay and current variation curves of the 200 kV DC cable are recorded during the discharge process and shown in Fig. 8, with a precision of about 1%. As you can see, at different stages, the voltage of the cable decays exponentially at different rates, which depends on the discharge resistance of the system.

A comparison is made between the equivalent discharge resistance and the theoretical one. The equivalent discharge resistance is determined by the ratio of voltage to current measured during the test. The theoretical discharge resistance is estimated by the equivalent circuit of the system shown in Fig. 9, which is similar with that in Fig. 6. In this case, the equivalent resistance and capacitance of the DC voltage generator are not taken into consideration because they are unknown and their influence on the discharge of long cable lines is small, as already discussed in Sec. III. In addition, two protective resistors, R_p, are added in the circuit.

The data of voltage, current, and resistance are listed in Table V. A good coincidence can be found between the equivalent and theoretical discharge resistance. In addition, the total discharge resistance of the system is close to the resistance of the grounding discharge resistor, especially when the resistance is lower than 100 MΩ, which testifies the applicability of (8) in engineering practice.

For the field withstand test of this 200 kV DC cable, the grounding discharge resistor is connected when the residual voltage reaches −100 kV, one-half of the rated operating voltage of the cable system. Then, the resistance is reduced in several stages to speed up the discharge process under the premise of limiting the discharge current.

It takes nearly 0.7 h for the cable to be safely discharged before the grounding rod is connected, which means a remarkable time saving. It needs to be pointed out that after the cable is connected to the grounding rod, some charges remain in the XLPE insulation.

TABLE V. Voltage, current, and resistance of the cable discharge system in different stages.

The stage	Voltage (kV)	Current (μA)	Resistance of the discharge resistor (MΩ)	Discharge resistance of the system (MΩ) Equivalent	Theoretical
A → B	−90	−666	160	135.1	141.9
	−50	−348		143.7	
B → C	−40	−533	80	75.0	75.9
	−30	−393		76.3	
C → D	−20	−523	40	38.2	39.7
	−10	−254		39.4	
D → E	−6	−307	20	19.5	20.7
	−4	−205		19.5	
E	−1	−1000	0	1.0	1.0

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Hence, the cable should be grounded for some time, 1 h at least in our proposal, to release the residual charges as much as possible.

For the research works performed in this paper, the pre-stress duration of the DC voltage is 1 h, and the cable is at room temperature. Although the measured data for both short cable samples in the laboratory and the long cable line at site are in good agreement with the theoretical analysis, some further work is still in need on the possible effect of the DC voltage application time and the elevated temperature on the breakdown performance and discharge characteristic of the XLPE cable. Since the time duration of the DC voltage will affect the electrical field built up in the cable insulation and the temperature will affect the charge release, they are expected to have some influence on the discharge procedure of the HVDC cables, which needs to be investigated and clarified through the follow-up studies.

V. CONCLUSION

Compared with the long-term operation under a stable HV DC voltage, an uncontrolled sudden grounding will be fatal to a XLPE DC cable. The damage is caused by the fast release of charges in XLPE insulation, and the initial discharge power or current is the key parameter.

The resistance–capacitance composite model can be applied for the discharge characteristic analysis of both XLPE block samples and cable insulation bulks. For the long DC cable lines used in practical projects, the discharge time constant can be estimated by the product of cable capacitance and discharge resistance.

The natural discharge process of a cable system is very slow, and a resistance discharge device can be applied to accelerate the discharge process. For XLPE cables of 500 kV and below, the resistance discharge device should not be introduced until the residual voltage has declined to the rated operating voltage of the cable.

In order to effectively shorten the discharge time, a discharge device of several resistors in series connection can be applied for a stepped discharge of the cable system. For the convenience and safety of engineering application, a device with the remote-control function is preferred.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts of interest to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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