

## METHOD OF DETECTING CABLE JOINT FAULT IN A POWER DISTRIBUTION CABLE

### Technical Field

**[0001]** The present disclosure relates to a method of detecting cable joint fault in a power distribution cable and particularly of detecting water ingress of a cable joint in the power distribution cable.

### Background

**[0002]** Power distribution networks typically use medium-voltage power cables such as 22kV and 6.6kV power cables. An exemplary medium-voltage power cable is a cross-linked polyethylene (XLPE) power cable that uses XLPE as an insulation material around the conductor in the cable. For continuous flow of electricity over long distances, cable joints are used to electrically connect discrete lengths of cable to form a continuous power distribution cable. FIG. 1 shows an exemplary cable joint 10 connecting two lengths of cable 21, 22. Each cable 21, 22 is shown to typically comprises a conductor 15 insulated with a conductor insulating material 13 such as XLPE. The insulating material 13 is typically surrounded by a semiconducting screen 11, 16. In the cable joint 10, the conductors 15 of both cables 21, 22 are electrically connected to a connector 14 provided between both cables 21, 22. The connector 14 and connected ends of both cables 21, 22 are encapsulated with a reinforced insulation 12 that typically comprises silicon rubber (SR). Within the reinforced insulation encapsulation of the cable joint 10, an interface 18 exists between the reinforced insulation 12 and the conductor insulating material 13. This interface 18 is where water ingress from the surrounding environment where the cable joint 10 is laid may occur. When water enters the interface 18 of a cable joint, this can result in cable degradation which causes undesirable failure of the power distribution cable.

**[0003]** Existing methods to detect cable failure include using an oscillating wave test system (OWTS) with accompanying software to pin-point potential cable or joint failures. However, this requires using costly equipment (typically SGD160,000) and each test using the OWTS takes about 45 minutes to perform. Another method to test

for cable failure is VLF (Very Low Frequency) cable testing, where the testing time can range from 15 to 60 minutes. While the small size of the VLF test set is advantageous for field testing, it may be difficult to obtain conclusive results with VLF testing if there is significant water damage to the cable insulation. VLF testing using very high testing voltage may also cause undesirable space charges in some types of cable insulation, e.g. extruded polyethylene rubber (EPR) insulation.

**[0004]** It is therefore desirable to provide a low cost and quick method to test for water ingress of a cable joint in a power distribution cable that does not have the disadvantages found in existing cable testing methods.

### Summary

**[0005]** According to a first aspect, there is provided a method of detecting cable joint fault in a power distribution cable of a power supply network, the power distribution cable comprising at least one conducting core, the method comprising:

- (a) disconnecting the power distribution cable from the power supply network;
- (b) applying a DC voltage for a predetermined duration to one end of the conducting core;
- (c) obtaining polarization current in the power distribution cable during application of the DC voltage; and
- (d) plotting a curve of the polarization current against time;
- (e) wherein increase in the polarization current over time indicates water ingress of a cable joint in the power distribution cable; and
- (f) wherein a non-monotonic variation in the polarization current over time indicates water ingress of a cable joint in the power distribution cable.

**[0006]** The method may further comprise fully discharging the power distribution cable after step (a) before performing step (b).

**[0007]** The power distribution cable may comprise a plurality of conducting cores and the method comprises performing steps (b) to (d) on each of the plurality of conducting cores.

**[0008]** The predetermined duration may range from 50s to 100s.

[0009] The DC voltage may have a value between 2kV to 6kV.

[0010] The power distribution cable may comprise a cross-linked polyethylene (XLPE) insulated medium voltage power cable.

### **Brief Description of the Drawings**

[0011] In order that the invention may be fully understood and readily put into practical effect there shall now be described by way of non-limitative example only exemplary embodiments of the present invention, the description being with reference to the accompanying illustrative drawings.

FIG. 1 is a schematic illustration of a cable joint structure.

FIG. 2(a) is a schematic illustration of a single-layer insulation before application of a voltage.

FIG. 2(b) is a schematic illustration of the single-layer insulation of FIG. 2(a) after application of a voltage in a polarization process.

FIG. 2(c) shows response characteristics in current vs time curves of the polarization process of FIG. 2(b).

FIG. 3 is a physical model of a double-layered insulation.

FIG. 4 is a physical model of a double-layered nonlinear insulation provided in series.

FIG. 5 is a graph of polarization currents as a function of applied voltage for all three phases.

FIG. 6(a) is a polarization current vs time curve showing an abnormal increase of total current with time.

FIG. 6(b) is a polarization current vs time curve showing non-monotonic variation of total current with time.

FIG. 7(a) is an experimental polarization and depolarization current (PDC) test result of a first circuit showing abnormal increase of polarization current with time for one of the three phases.

FIG. 7(b) is an experimental PDC test result of a second circuit showing normal decrease of polarization current with time for all three phases.

FIG. 8 is a functional diagram of a time domain reflectometry (TDR) test performed on a power cable showing injection and reflection waveforms.

FIG. 9 is a schematic illustration of TDR waveforms obtained for power cables under different test conditions.

FIG. 10(a) shows TDR waveform results obtained from a TDR test performed on the first circuit.

FIG. 10(b) shows TDR waveform results obtained from a TDR test performed on the second circuit.

FIG. 11 is a flowchart of an exemplary method of detecting cable joint fault in a power distribution cable.

### **Detailed Description**

[0012] Exemplary embodiments of a method 100 of detecting cable joint fault in a power distribution cable will be described with reference to FIGS. 1 to 11.

[0013] The presently disclosed method 100 comprises performing a polarization and depolarization current (PDC) test on one end of a power cable that has been switched off, de-energised and isolated. The PDC test may be performed using an insulation resistance (IR) tester such as a Megger® S1-1568 DC (direct current) IR tester. As the cable circuit consists of the cable body and cable joint, the PDC test results can reflect both cable body and joint states. The PDC test is able to diagnose cable joint states based on the polarization current results.

#### Polarization Current Characteristics of Single-layer Insulation

[0014] In the PDC test, when a DC test voltage is applied across a single-layer insulation, current with more than one component flows through the insulation. As can be seen in FIG. 2(a), the single-layer insulation 20 normally comprises dipoles 21 that are randomly oriented before a voltage is applied to the electrodes 22 placed one on each side of the single-layer insulation 20. Once the voltage is applied to the insulation 20 as shown in FIG. 2(b), the dipoles 21 align themselves according to the polarity of the voltage, leading to bound charges 24 forming on the electrodes 22. Free charges 23 are also formed on the surface of the electrodes 22, generating a current in the

external circuit, which is initially large but diminishes quickly to zero and can hardly be measured. The generated current is called the capacitive charging current since the bulk insulation 20 behaves as a charging capacitance. FIG. 2(c) shows the corresponding currents generated by the behaviour of the charges formed during polarization. The total current is formed of three component currents: the capacitive charging current, the absorption current, and the conduction current.

**[0015]** As can be seen in FIG. 2(c), the absorption current decays at a decreasing rate to a value close to zero over a period. This current is mainly due to the alignment of polarized molecules under the DC electric field. The conduction or leakage current flows steadily through the insulation 20, and can be measured when the insulation is fully charged and complete absorption has taken place.

**[0016]** From the above, it can be seen that the capacitive current, absorption current, and conduction current are the three principal response characteristics of a single-layer insulation 20 under DC voltage. However, due to the quick dissipation of the capacitive current, the measured total current does not include the capacitive current. Therefore, in PDC tests, only the absorption current and conduction current are used to diagnose the state of cable and joint health.

#### Polarization Current Characteristics of Double-layer Insulation

**[0017]** For a double-layer insulation, according to the Maxwell-Wagner polarization theory described in the publication 'Suo, Changyou, et al. "Dynamic characteristics analysis on interface polarization and depolarization of nonlinear double-layered dielectrics" IEEE Transactions on Dielectrics and Electrical Insulation 24.3 (2017): 1511-1526", if each layer of the double-layer insulation is linear, meaning that the conductivity and permittivity are constants, then the physical model of the double-layered insulation can be simplified as shown in FIG. 3. Notably, the polarization current of a linear double-layered interface polarization also decreases with time, similar to that of the single-layer insulation 20 shown in FIG. 2(b).

**[0018]** However, conductivity of the insulation in a power cable system, which belongs to nonlinear insulation, is a function of temperature and electric field  $E$ . Normally,

hyperbolic sine and power functions are extensively used to describe the relationship between the electric field  $E$  and the conductivity  $\gamma$  of nonlinear insulation. In some cases, within a small range of electric field  $E$ , the relationship can be a linear approximation, where the relationship of conductivity  $\gamma$  with the applied electric field  $E$  can be described approximately with equation (1) below:

$$\gamma = a + b \cdot E \quad (1)$$

where  $\gamma$  is the conductivity of insulation, and  $E$  is the electric field.

[0019] Therefore, based on a nonlinear insulation with  $a+bE$  -type nonlinear conductivity (that is, the conductivity  $\gamma$  of the insulation is a linear function of the applied electric field  $E$ ), the interface polarization model of a double-layered nonlinear insulation may be established and represented with a physical model of double-layered nonlinear insulation provided in series, as shown in FIG. 4.

[0020] In the model of FIG. 4, the double-layered insulation or dielectrics are assumed to be homogeneous, and referred to as dielectrics 1 and 2.  $\epsilon_{r1}$  and  $\epsilon_{r2}$  are the permittivity of dielectrics 1 and 2 in Farad per metre (F/m), which are almost independent of the electric field  $E$ , so they can be regarded as constants.  $d_1$  and  $d_2$  are the thicknesses of dielectrics 1 and 2, respectively, in metres (m).  $\gamma_1(E_1)$  and  $\gamma_2(E_2)$  represent the conductivity of dielectric 1 and 2 in Siemens per metre (S/m). If the temperature is constant, the conductivity is a function of the electric field strength, as described by equation (2) below:

$$\begin{cases} \gamma_1(E_1) = a_1 + b_1 \cdot E_1 \\ \gamma_2(E_2) = a_2 + b_2 \cdot E_2 \end{cases} \quad (2)$$

[0021] Under a DC step voltage  $U(t)$ , equations (3) and (4) below can be obtained according to the principle of continuity of current and loop voltage law.

$$E_1(t)d_1 + E_2(t)d_2 = U(t) \quad (3)$$

$$\gamma_1(E_1)E_1(t) + \epsilon_0 \frac{d[\epsilon_{r1}E_1(t)]}{dt} = \gamma_2(E_2)E_2(t) + \epsilon_0 \frac{d[\epsilon_{r2}E_2(t)]}{dt} \quad (4)$$

[0022] It was found that when there is water ingress in a cable joint, conductivity will be higher than usual and come to almost linearly increase with the applied voltage in a PDC test, as can be seen in FIG. 5 where each data point is the average value of the data taken from the last two minutes of measurements. This results in the polarization current curve of a cable with water ingress showing abnormal trends as can be seen in FIGS. 6(a) and 6(b). The total polarization current of a double-layered insulation with a+bE-type conductivity variation with time shows two possible abnormal trends. One is monotonically increasing and then tending to a steady state, as shown in FIG. 6(a). Another one is a non-monotonic variation of current over time, such as the curve which is monotonically decreasing and then increasing toward steady state as shown in FIG. 6(b).

[0023] From the observed abnormal polarization current curves, a PDC test was developed to diagnose cable joint fault such as water ingress of a cable joint 10. Experimental PDC cable joint tests and the experimental results are described below.

#### Experiments and Results

[0024] In the experiments conducted, two circuits, namely, Circuit 1 and Circuit 2 were tested. Each circuit comprised a 6.6kV XLPE power distribution cable in service in Singapore's power supply network. Each power distribution cable was a three-core cable having three conducting cores in the cable, each conducting core corresponding to one of the three phases of the power distribution cable. Each power distribution cable comprised a number of cable sections that were connected by a number of joints, as detailed in the circuit specifications given in Tables 1 and 2 below respectively.

| Section | Origin | Destination | Accum. Dist. (m) | Laying year |
|---------|--------|-------------|------------------|-------------|
| 1       | Sub A  | Joint 1     | 229              | 1994        |
| 2       |        | Joint 2     | 322              | 1993        |
| 3       |        | Joint 3     | 387              | 1984        |
| 4       |        | Joint 4     | 481              | 2016        |
| 5       |        | Joint 5     | 565              | 2016        |
| 6       | Sub B  |             | 570              | 2016        |

Table 1 – Circuit 1 Specifications

| Section | Origin | Destination | Accum. Dist. (m) | Laying year |
|---------|--------|-------------|------------------|-------------|
|---------|--------|-------------|------------------|-------------|

|   |       |         |     |      |
|---|-------|---------|-----|------|
| 1 | Sub A | Joint 1 | 39  | 2001 |
| 2 |       | Joint 2 | 99  | 1998 |
| 3 |       | Sub B   | 118 | 1998 |

Table 2 – Circuit 2 Specifications

**[0025]** Using a Megger® S1-1568 DC (direct current) IR tester remotely controlled by a laptop, PDC tests were performed on Circuit 1 and Circuit 2 according to the IR tester operation guidelines, using a test DC voltage of 5kV and a test duration of 70s. Performing the PDC test comprised first disconnecting the power distribution cable from the power supply network (101). Next, the DC voltage was applied to one end of a conducting core of the power distribution cable for 70s (102). Polarization current in the power distribution cable during application of the DC voltage was obtained (103) and a curve of the polarization current curve against time was plotted (104) for that conducting core. The PDC test was performed for all three conducting cores of the power distribution cable to obtain polarization curves for all three phases of the power distribution cable, as shown in FIGS. 7(a) and 7(b). The first ten seconds of the polarization currents obtained were omitted from consideration as they were affected by the initial response of the test equipment. Preferably, the disconnected power distribution cables were fully discharged before applying the DC voltage.

**[0026]** From FIG. 7(b), it can be seen that the polarization currents of all three phases of Circuit 2 decreased with time, obeying the polarization current characteristics of single-layer insulation described above with reference to FIGS. 2(a) to 2(c). However, the polarization current increased with time for the yellow phase of Circuit 1. As discussed above with reference to FIG. 6(a), increasing polarization current with time is an abnormal trend that could be indicative of cable joint fault due to water ingress.

**[0027]** While a test voltage of 5kV was used in the experiments conducted, the DC voltage applied in the method 100 can range from 2kV to 6kV. Besides a test duration of 70s as used in the experiments, the test duration may range from 50s to 100s. The power distribution cable may comprise a different number of conducting cores and the PDC test should be conducted for all the conducting cores in the cable.

[0028] To confirm that the abnormal PDC curve obtained is indicative of cable joint fault due to water ingress, time domain reflectometry (TDR) tests were performed. In the TDR test, a power distribution cable is taken off-line and a pulse of a known quantity of low-voltage energy is injected into the off-line cable. The amplitude of the reflected waveform at any impedance discontinuity can be determined and expressed as the reflection coefficient  $\rho$  by equation (5) below:

$$\rho = \frac{Z_d - Z_0}{Z_d + Z_0} \quad (5)$$

where  $Z_0$  is the characteristic impedance of the cable;  $Z_d$  is the impedance of any discontinuity along the cable, such as a defect or cable joint;  $Z_d = 0$  for cable short circuit and  $Z_d = \infty$  for open circuit. From equation (1),  $\rho$  is between -1 to 1. The injection and reflection waveforms of a TDR test set-up are shown in FIG. 8. Typical waveforms obtained from TDR tests under different conditions are shown in FIG. 9. In the TDR test, any impedance discontinuities, such as cable joints and suspected defects, will generate reflections and cause distortions to the original impulse. By capturing the injection and responding signals in the time domain, the locations of the abnormal cable joints and the defects can be identified.

[0029] FIGS. 10(a) and (b) show the TDR waveforms obtained from TDR testing of Circuit 1 and Circuit 2 respectively. According to the TDR waveforms shown in FIG. 9, it can be seen in FIG. 10(a) that abnormal TDR waveforms for all three phases (red, yellow and blue) of Circuit 1 occurred at around 230m which is near Joint 1 as indicated in Table 1. It was noted that only the yellow phase of Circuit 1 showed an abnormal trend in the PDC test results while all three phases of Circuit 1 showed abnormalities in the TDR waveforms. This could be due to the IR value of the yellow phase of Circuit 1 being very low, thereby giving rise to the abnormal polarization current curve as a result of water ingress into joint 1. From FIG. 10(b), it can be seen that the TDR waveforms for all three phases of Circuit 2 were normal, indicating no issue with the cable body or cable joints in Circuit 2.

[0030] From the results of the PDC tests on Circuits 1 and 2 and the TDR verifications of the PDC test results, it can be seen that PDC testing of power distribution cables is

sufficient to provide an indication of cable joint fault in a power distribution cable, which may be a result of water ingress into a cable joint in the power distribution cable.

**[0031]** While there has been described in the foregoing description exemplary embodiments of the present invention, it will be understood by those skilled in the technology concerned that many variations in details of design, construction and/or operation may be made without departing from the present invention. It will be appreciated that many further alterations, modifications and permutations of various aspects of the described embodiments are possible that fall within the spirit and scope of the appended claims. The reference in this specification to any prior publication (or information derived from it), or to any matter which is known, is not, and should not be taken as an acknowledgment or admission or any form of suggestion that that prior publication (or information derived from it) or known matter forms part of the common general knowledge in the field of endeavour to which this specification relates.

**Claims**

1. A method of detecting cable joint fault in a power distribution cable of a power supply network, the power distribution cable comprising at least one conducting core, the method comprising:
  - (a) disconnecting the power distribution cable from the power supply network;
  - (b) applying a DC voltage for a predetermined duration to one end of the conducting core;
  - (c) obtaining polarization current in the power distribution cable during application of the DC voltage; and
  - (d) plotting a curve of the polarization current against time;  
wherein increase in the polarization current over time indicates water ingress of a cable joint in the power distribution cable; and  
wherein a non-monotonic variation in the polarization current over time indicates water ingress of a cable joint in the power distribution cable.
2. The method according to claim 1, further comprising fully discharging the power distribution cable after step (a) before performing step (b).
3. The method according to claim 1 or claim 2, wherein the power distribution cable comprises a plurality of conducting cores and the method comprises performing steps (b) to (d) on each of the plurality of conducting cores.
4. The method according to any one of the preceding claims, wherein the predetermined duration ranges from 50s to 100s.
5. The method according to any one of the preceding claims, wherein the DC voltage has a value between 2kV to 6kV.
6. The method according to any one of the preceding claims, wherein the power distribution cable comprises a cross-linked polyethylene (XLPE) insulated medium voltage power cable.