Experimental and Theoretical Analysis of Cable Discharge

Isabel Lafaia, *Member, IEEE*, Foroozan Ghassemi, Akihiro Ametani, *Life Fellow, IEEE*, Jean Mahseredjian, *Fellow, IEEE*, Simon Dennis, A. M. Haddad, *Member, IEEE*, and Stephen Robson

***Abstract*—This paper focuses on the phenomenon of discharge of HVAC cables, which is a concern for utilities when performing AC/DC tests, during maintenance works, and more recently when switching cables for grid voltage control. The study is based on field and laboratory tests of 275 kV pressurized-oil-filled (POF) cables, analytical calculations, and simulations. The contributions of this paper are: field and laboratory measurements of voltages and leakage currents during cable discharge, including a field test carried out in 2015 by the National Grid (UK) on a 275 kV POF cable of 21 km; a method for estimating the leakage resistance and the time required to discharge a cable system using simple parallel *RC* circuit theory; and typical values of leakage resistance, leakage current, and discharge time for 275 kV cable systems. The influence of temperature, electric field, and humidity on cable discharge is also discussed and a correction factor to account for the impact of humidity is proposed.**

***Index Terms*—Cable discharge, cable leakage current, cable field tests.**

I. Introduction

THE cable charging and discharging phenomenon has been a concern to cable engineers when performing AC/DC tests and during maintenance work [1]–[5]. Recently, the charging/discharging phenomenon has received new consideration from utilities when using high-voltage (HV) cables for voltage control during periods of light load which require nightly switching of cables [6] and it is the main concern of an informal forum formed by several European system operators.

Very few test results of cable charging and discharging can be found in the literature [7]–[9]. For this reason, National Grid (UK) performed a series of cable discharge tests on a 275 kV pressurized-oil-filled (POF) cable of 21 km length.

In this paper, cable discharging is investigated based on three laboratory and field test results carried out in Japan and in the UK. The tests present important aspects, such as typical values of leakage current, and impact of temperature, applied voltage and humidity on the leakage current of the system.

It will be shown in this paper that the response of a cable system during discharge can be explained based on simple equations of parallel *RC* circuits.

A simple method is derived for calculating the leakage resistance and discharge time of the system based only on the voltage level, cable insulation type, number and type of insulators connected to the cable. A correction factor which accounts for changes in the ambient temperature is also proposed. Typical values of leakage resistance and discharge time for 275 kV cable systems are provided. The method and proposed values are validated by simulating the field test results.

This paper is focused on cables without compensation, which present the longest discharge times. When a long cable is compensated by shunt reactors, the discharge time is only a few tens of seconds [3], [4] and is not a concern. Compensated cables are out of the scope of this paper.

II. Test Results

A. Field Test of a 275 kV PT-POF Cable in Japan

A field test for commissioning of an underground 275 kV pipe-type pressurized-oil-filled (PT-POF) cable with 20 km length was performed in Japan in 1971. At that time, the 275 kV PT-POF cable installation was a first-time experience. The field test was thus intended to give a basis for the creation of standards for PT-POF cables in Japan. The field test involved a series of measurements: characteristics of oil behavior, DC voltage withstand, surge propagation, thermal/mechanical behavior of steel pipes, etc. [7]. Cable charging and discharging characteristics were also measured.

1) Test Setup and Cable Data: Other than the measured results, a significant contribution of [7] is that the leakage currents of components used in the test are given, which are necessary for estimating the corresponding leakage resistances. These parameters allow theoretical calculations and simulation of the charging and discharging processes. Although the cable capacitance is easily calculated from the cross-section geometry and the insulation permittivity, the leakage currents of insulator poles, bushing and cable insulation are not available in general and are very difficult to measure or to estimate theoretically.

The description of the tested cable is given in Table I. According to the test description and theoretical analysis in [7],

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I. Lafaia, A. Ametani, and J. Mahseredjian are with the Power Systems Department, Polytechnique Montreal, C.P.6079, Montréal, QC H3C 3A7, Canada (e-mail: isabel.lafaia@polymtl.ca; aametani@mail.doshisha.ac.jp; jean.mahseredjian@polymtl.ca).

F. Ghassemi and S. Dennis are with National Grid, Warwick, CV34 6DA, U.K. (e-mail: forooz.ghassemi@nationalgrid.com; simon.dennis@nationalgrid.com).

A. M. Haddad and S. Robson are with Cardiff University, Cardiff, CF24 3AA, U.K. (e-mail: haddad@cardiff.ac.uk; robsonS1@cardiff.ac.uk).

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TABLE I
DATA OF 275 kV PT-POF CABLE IN JAPAN [7]

Core conductor inner radius	0 mm	Core conductor resistivity	$1.728\cdot10^{-8}$ Ω-m
Core conductor outer radius	23.65 mm	Screen resistivity	$73\cdot10^{-8}$ Ω-m
Screen inner radius	43.65 mm	Pipe resistivity	$10\cdot10^{-8}$ Ω-m
Screen outer radius	44.65 mm	Pipe permeability	300 μ_0
Cable outer radius	46.65 mm	Core/screen/pipe insulation permittivity	3.7 ε_0
Pipe inner radius	127.3 mm	Semiconducting layers thickness	3 mm
Pipe outer radius	133.7 mm	Burial depth	2.5 m

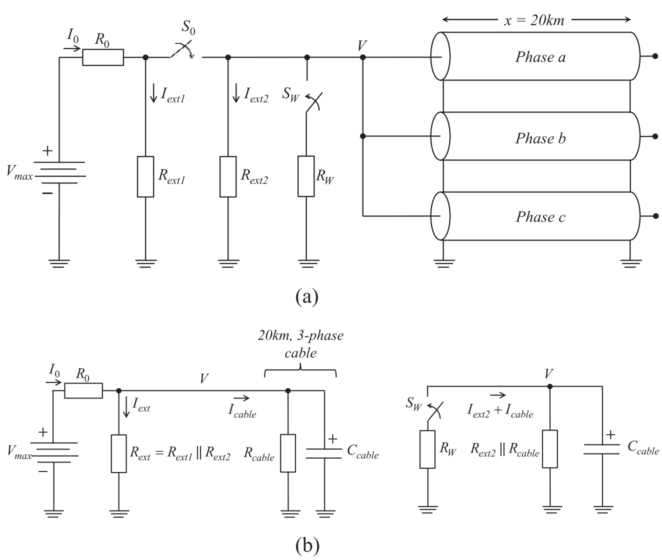

Fig. 1. Circuits for field testing on a 275 kV PT-POF cable in Japan. a) Field test circuit. b) Approximate equivalent circuits for charging (left) and discharging (right).

the cable is charged through a resistance R_0 for 1 hour up to a certain voltage using a DC voltage generator. The cable is then switched off and slowly discharges due to leakage current in its insulation and in the components connected to it. After 88 minutes, a forced discharge leads the cable voltage to zero. The three cores are bonded together and the sheaths are grounded at both terminals. The following values are given in [7]

1) $I_0 = 3\,\text{mA}$, generator rated current,
2) $V_{\max} = 414\,\text{kV}$, maximum cable voltage,
3) $I_{\text{ext}} = 0.6\,\text{mA}$, leakage of external components at $V_{\max}$,
4) $R'_{\text{cable}} = 22\,\text{G}\Omega\text{-km}$, cable leakage resistance (inverse of per-unit-length shunt conductance G'_{cable} in S/km),
5) $R_W = 30\,\text{M}\Omega$, resistor used to force full discharge of the cable,
6) $V_{\min} = 250\,\text{kV}$, voltage just before the forced discharge.

The above data together with the description and theoretical analysis in [7] lead to the circuit in Fig. 1(a). The remaining unknown values in the circuit can be easily calculated as follows. The charging resistance is $R_0 = V_{\max}/I_0 = 138\,\text{M}\Omega$. $R_{\text{ext}} = V_{\max}/I_{\text{ext}} = 690\,\text{M}\Omega$ is the leakage resistance of the external circuit, assumed in this study as equally distributed on both sides of the switch ($R_{\text{ext1}} = R_{\text{ext2}} = 2R_{\text{ext}} = 1380\,\text{M}\Omega$). The total

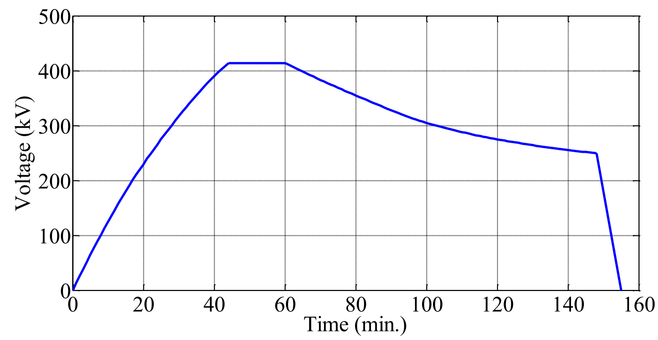

Fig. 2. Field test of 275 kV PT-POF cable in Japan (reproduction of measured result in [7]).

cable leakage resistance is calculated from

$$R_{\text{cable}} = R'_{\text{cable}}/\left(n\, l\right) \quad (1)$$

where $R'_{\text{cable}} = 22\,\text{G}\Omega\text{-km}$, $l = 20\,\text{km}$ and $n = 3$ phases in parallel, resulting into $R_{\text{cable}} = 367$ MΩ. The total cable capacitance is found using

$$C_{\text{cable}} = n\, l\, C'_{\text{cable}} \quad (2)$$

$$C'_{\text{cable}} = \frac{2\pi\varepsilon_0\varepsilon_r}{\log_e\left(r_{\text{out}}/r_{\text{in}}\right)} \quad (3)$$

where $\varepsilon_r = 3.7$ is the relative permittivity of core insulation, $r_{\text{out}} = 40.65\,\text{mm}$ and $r_{\text{in}} = 26.65\,\text{mm}$ are respectively the external and internal radii of insulation in Table I, resulting into $C_{\text{cable}} = 29.3\,\mu F$.

The switch S_0 is closed at $t = 0$ to charge the cable and opens at $t = 60$ min, letting the cable discharge. The switch S_W is closed (S_0 is now open) at $t = 148$ min forcing the complete discharge of the cable.

2) Measured Discharge Voltage: The measured voltage characteristic of the cable during charging and discharging is shown in Fig. 2.

As a first approximation, the result in Fig. 2 can be explained using the equations of an *RC* circuit. This approximation is explained further in Section IV. Based on the circuit in Fig. 1(b), the cable response during discharge is

$$v\left(t\right) = V_{\max}\, e^{-t/\tau} \quad (4)$$

for $60 < t < 148$ min, with $t_1 = 60$ min and $t_2 = 148$ min. The time constant is calculated using the total leakage resistance $R_{\text{total}} = R_{\text{ext2}}||R_{\text{cable}} = 290\,\text{M}\Omega$ and the cable capacitance $C_{\text{cable}} = 29.25\,\mu F$

$$\tau = R_{\text{total}}\, C_{\text{cable}} \quad (5)$$

resulting into $\tau = 8483$ s $= 141.38$ min.

The time required to discharge the cable from $v(t_1) =$ 414 kV to $v(t_2) = 250$ kV is calculated from

$$t_2 - t_1 = \tau \log_e\left(\frac{v\left(t_1\right)}{v\left(t_2\right)}\right) \quad (6)$$

resulting into $t_2 - t_1 = 71.3$ min. This value is too low compared to the 88 minutes of the voltage in Fig. 2 (measured in the

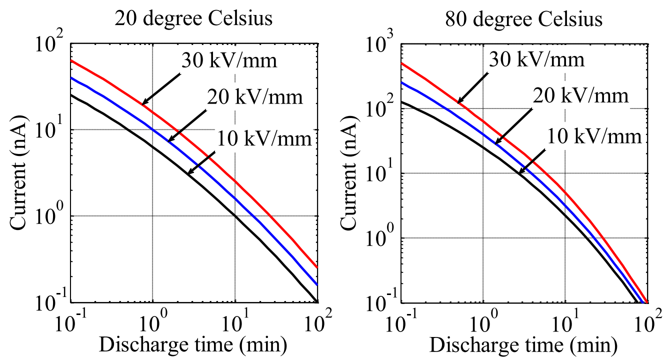

Fig. 3. Measured leakage currents: left: 20 °C, right: 80 °C (reproduction of the measurements in [8]).

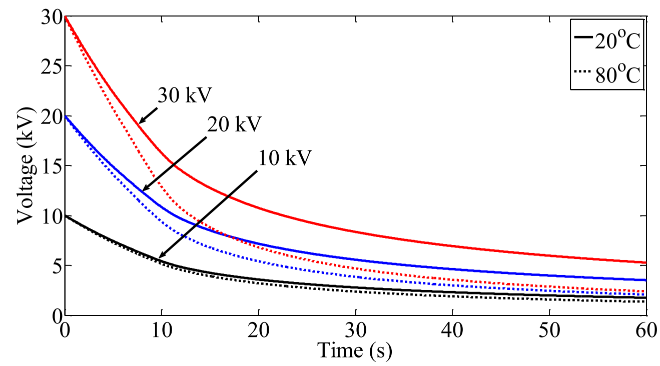

Fig. 4. Voltage of model cable of 1 mm thick insulation during discharge test for different values of initial applied voltage and temperature.

field test) and it shows that the leakage estimate was incorrect in [7].

B. Laboratory Tests of Leakage Currents, Cable in Japan

In 1970, the same cable manufacturer performing the field test in Section II-A [7] carried out a laboratory test using 1 m length model cables [8], [9]. The goal of the test was to observe the variation of leakage current with applied voltage and insulation temperature.

1) Test Setup and Cable Sample: The laboratory test was carried out on specially designed model cables. A copper electrode of 35 mm radius and 1 m length used as core conductor is lapped over by an insulation of oil immersed paper with 125 μm thickness and relative permittivity of 3.6. Four model cables were produced with 0.5, 1, 3 and 5 mm thick insulations. The paper insulation is itself lapped over by a lead tape sheath. The model cables are inserted each into a chamber filled with oil at a pressure of 1 kg/cm^2. The oil temperature is controlled by forced circulation.

The model cables were charged for 20 hours, and then discharged to measure the leakage current of the thin insulation film.

2) Measured Leakage Currents: Fig. 3 shows measured curves of leakage currents as a function of time for insulation temperatures of 20 °C and 80 °C. The three curves in each figure correspond to the initial applied voltages per millimeter of insulation thickness, of 10 kV/mm, 20 kV/mm and 30 kV/mm.

Due to normalization of applied voltage used in [8], [9], the curves in Fig. 3 are applicable to all four model cables with different insulation thickness. Given the small thickness of the insulation (d varies between 0.5 and 5 mm) in relation to the insulation inner radius ($r_{\text{in}} = 35$ mm), the electric field strength E (kV/mm) is nearly uniform inside the insulation and can be calculated from the applied voltage V using the relation $V = E\,d$.

Fig. 3 clearly shows the influence of insulation temperature. The leakage currents for 80 °C are about 10 times higher than those for 20 °C.

It is also observed in Fig. 3 that the leakage current decreases with electric field strength E, but the three curves are nearly parallel in Fig. 3 (left), which indicates that the leakage resistance calculated as $R_{\text{total}} = E\,d/I$ is not much dependent on the variation of electric field strength in this case. On the other hand the curves of leakage current for 80 °C are not parallel. This indicates that the influence of electric field on the value of leakage resistance may be more important at higher temperatures [10].

The test results in Fig. 3 can be used to estimate the voltage of the model cables during discharge as

$$v\,(t) = \frac{E_0\,d}{I_0}\,i\,(t) \tag{7}$$

where E_0 is the initial electric field applied to the model cable, $i(t)$ is the leakage current in Fig. 3 and I_0 its initial value, and d is the insulation thickness of the model cable. The voltages for the case of 1 mm thick insulation are shown in Fig. 4, where the impact of temperature on the rate of decay is clearly observed.

The leakage currents in Fig. 3 have a characteristic given by

$$i\,(t) = I_0\,e^{-t/\tau} \tag{8}$$

where I_0 is the current at $t = 0$. The capacitance for the model cable with 1 mm insulation thickness is calculated from (2) and (3) with $\varepsilon_r = 3.6$, $r_{\text{in}} = 35$ mm, $r_{\text{out}} = 36$ mm, $l = 1$ m and $n = 1$, resulting into $C_{\text{cable}} = 7.11$ nF. References [8], [9] do not give details on the leakage resistance, but it can be estimated from the cable capacitance and the time constant of the current in Fig. 3(a) calculated with (6)

$$\tau = \frac{60\,(100\ -\ 1)}{\log_e\,(10/0.1585)} = 1433.2\,\text{s}$$

Using $C_{\text{cable}} = 7.11$ nF and $\tau = 1433.2\,\text{s}$ in (5), $R_{\text{total}} = 201.6\ \text{G}\Omega$ is found. This value includes the leakage of the model cable and the external circuit. Such a high leakage resistance may be explained by very low losses in paper insulated cables and by the fact that a laboratory test has better conditions (low humidity, low levels of contamination) than a field test.

C. Field Test of National Grid 275 kV POF Cable

In 2015 National Grid (UK) in collaboration with Cardiff University, carried out field test measurements of discharge of a POF cable. The cable voltage, temperature, pressure and the relative humidity of air were measured simultaneously allowing to see the impact of these factors on discharge time.

TABLE II
DATA OF 275 kV POF CABLE IN UK [6]

Core conductor inner radius	6.8 mm	Core conductor resistivity	$1.724 \cdot 10^{-8}$ Ω-m
Core conductor outer radius	26.75 mm	Screen resistivity	$21.3 \cdot 10^{-8}$ Ω-m
Screen inner radius	43.00 mm	Core insulation permittivity	$3.8\ \varepsilon_0$
Screen outer radius	47.20 mm		
Semiconducting layers thickness	3 mm	Screen insulation permittivity	$8\ \varepsilon_0$
Cable outer radius	51.56 mm	Depth	1 m

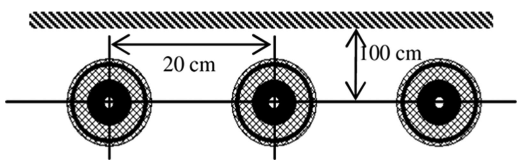

Fig. 5. Layout of 275 kV POF cable in the UK [6].

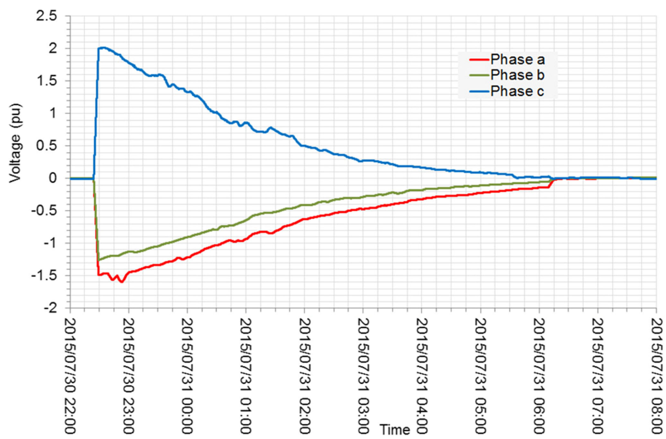

Fig. 6. Test results of discharge characteristic, 275 kV POF cable, courtesy of National Grid, UK.

1) Test Setup and Cable Data: Table II and Fig. 5 show the details of the 275 kV POF cable with a length of 21 km. The cable is used in a trench with a depth of 1 m. The cable sealing end at ground level is connected to a piece of overhead horizontal busbar with a length of about 13.5 m. The busbar is supported by two vertical insulator poles, each with an axial length (not creepage) of 2.4 m. The capacitance of each cable phase is calculated using the data in Table II, i.e. $\varepsilon_r = 3.8$, $r_{\text{in}} = 29.75\,\text{mm}$, $r_{\text{out}} = 40\,\text{mm}$, $l = 21 \times 10^3$ m and $n = 1$ into (2) and (3), resulting $C_{\text{cable}} = 15.0\ \mu F$.

The three cable phases are fed by a balanced (positive sequence) AC voltage source. When the source is switched off, the cable has 2 pu $(2 \times 275\sqrt{2/3} \approx 450\,\text{kV})$ on phase-c, -1.3 pu in phase-b and -1.6 pu in phase-a. The source is switched off and the voltage on the cable is measured for 10 hours.

2) Measured Discharge Voltage: Fig. 6 shows the measured cable voltage during discharge. It took about 8 hours to fully discharge the cable.

The voltage measured in each phase in Fig. 6 follows a characteristic given by (4).

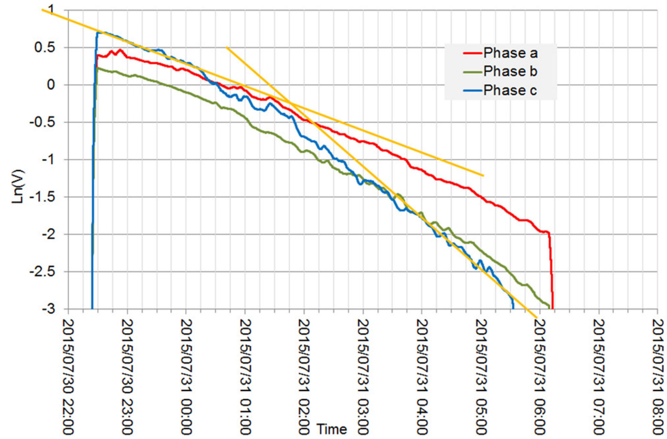

Fig. 7. Test results of Fig. 6, logarithmic scale, courtesy of National Grid, UK.

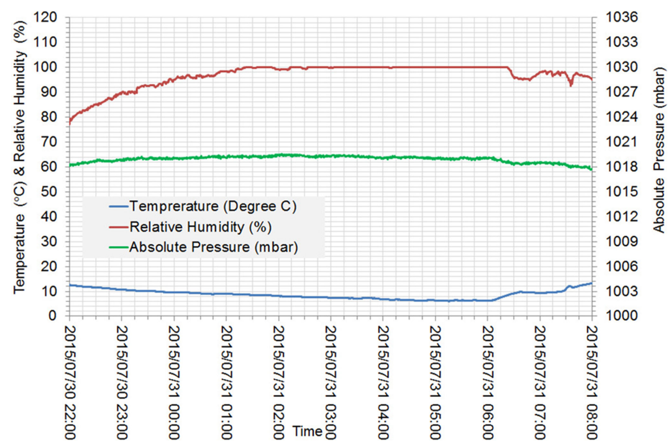

Fig. 8. Temperature, humidity and absolute pressure measured during the field tests by National Grid, UK (courtesy of National Grid).

The time constant for discharging each phase can be obtained using any two points t_1 and t_2 of a curve in Fig. 6 and equation (6), resulting $\tau_a = 3.04$ h, $\tau_b = 3.20$ h and $\tau_c = 3.50$ h. The leakage resistances can be estimated using the time constants and the capacitance $C_{\text{cable}} = 15.0\ \mu F$ in (5) giving $R_{\text{total - a}} = 729.8\,\text{M}\Omega$, $R_{\text{total - b}} = 768.2\,\text{M}\Omega$, and $R_{\text{total - c}} = 840.2\,\text{M}\Omega$. These values include the leakage in the cable and in the external circuit.

In reality, the above leakage resistances are average values based on the initial voltage characteristics in Fig. 6. Another approach is to estimate the time constant from (6), rewritten as

$$\log_e\left(\frac{v(t)}{v(0)}\right) = -\frac{t}{\tau} \tag{9}$$

The above equation shows that if the vertical axis in Fig. 6 is transformed to logarithmic scale, the value of τ can be observed simply from the slope of the voltage characteristic. This is illustrated in Fig. 7, and it is easily observed that the time constant changed during the test. This is because the humidity in air increased during the test, which caused an increase of the leakage current and a reduction of the time constant.

Fig. 8 shows temperature, pressure and relative humidity measured during the field test. The humidity increased from 80%

to 100%. The impact of this change is that the time constant is reduced from 3.5 hours (initial) to 1.5 hours and the leakage resistance is reduced from $R_{\text{total - c}} = 840.2$ MΩ to 360.1 MΩ.

The impact of air humidity is caused by the busbar, insulator poles connected to the cable, as well as the cable sealing ends which are exposed to air.

III. Calculation of Leakage Resistance and Time Constants for Cable Discharge

As observed in Section II, the time required to discharge a cable depends not only on the leakage of cable insulation but also on the leakage of components connected to the cable. The term "insulator" is henceforward used for all components providing a path for leakage currents, e.g. cable sealing ends, insulator poles, and bushing.

The discharge of distributed-parameter systems, e.g. cables and lines, is in general different from the discharge of lumped-parameter systems, e.g. reactive power compensation capacitor. However, since the phenomenon of cable discharge is very slow, the wavelength will be much larger than the cable length. At 60 Hz, assuming a typical propagation velocity of 150 m/μs, it is $\lambda = (150 \times 10^6)/60 = 2500$ km, being even larger for lower frequencies. In such case, the cable is considered as "short" and the response of the cable and insulators connected to it follows the equations of a simple parallel *RC* circuit with time constant given by (5).

It must be noted that discharge through a grounding switch, which represents a short circuit across a charged cable, or equipment such as wound voltage transformers would be different to discharge considered in this paper as in those cases the cable series parameters influence the discharge. Those discharge types are out of the scope of this paper.

The value of R_{total} in (5) depends both on the leakage through the cable insulation and through the insulators connected to the cable. The cable insulation is practically not affected by external factors, like weather and pollution. On the other hand, insulators (cable sealing ends, insulator poles and bushing) are generally exposed to air and thus are directly affected by humidity and contamination.

This section presents a method for calculating a model of a cable system during discharge. Typical values of cable and insulator parameters are given and allow estimating the discharge time constants based only on the voltage level, cable insulation material (EPR, XLPE, paper insulation) and insulator type (ceramic or composite).

A. Cable Parameters

Cable response during discharge is influenced by its per-unit shunt parameters, i.e. the shunt capacitance in (3) and shunt conductance, or more commonly used, the shunt resistance of its insulation

$$R'_{\text{cable}} = \frac{1}{G'_{\text{cable}}} = \frac{\rho \log_e (r_{\text{out}}/r_{\text{in}})}{2\pi} \tag{10}$$

where ρ and ε_r are the resistivity and relative permittivity of insulation between core and sheath, r_{in} and r_{out} are the internal and external radii of insulation. The total cable capacitance and shunt resistance are calculated using (3) and (10) into (2) and (1), respectively, with l the length of the cable and n the number of phases bonded together ($n = 1$ if the phases are not bonded).

TABLE III
Properties of Cable Insulation Material [11]–[13].

Insulation	EPR	XLPE	Paper (Kapton, Polyimide)
Resistivity	10 GΩ-km	100 GΩ-km	1000—1500 GΩ-km
Relative permittivity	2.5—2.6	2.3—2.5	3.4—3.8

TABLE IV
Leakage Resistance and Current in 275 kV Cables

	EPR	XLPE	Paper
Leakage Resistance	0.49–1.92 GΩ-km	4.53–18.4 GΩ-km	66.9–280 GΩ-km
Typical values	C = 0.35 μF/km, R = 0.63 GΩ-km	C = 0.25 μF/km, R = 8.1 GΩ-km	C = 0.45 μF/km, R = 74.8 GΩ-km
Leakage Current	0.35 mA/km	0.028 mA/km	0.003 mA/km

Combining (1)–(3) and (10), it is possible to calculate R_{cable} using the cable capacitance and permittivity parameters commonly found in cable datasheets

$$R_{\text{cable}} = \frac{\varepsilon_0 \varepsilon_r \rho}{C_{\text{cable}}} \tag{11}$$

Table III gives the resistivity and relative permittivity for typical cable insulation [11]–[13]. The capacitance for 275 kV cables is generally within 0.12-0.45 μF/km [14], [15].

Based on Table III and typical capacitance values, it is possible to calculate the leakage resistance and leakage current for 275 kV cable systems in Table IV. Paper insulated cables have by far the least leakage current.

B. Insulator Parameters and Leakage Current

The performance of insulators (cable sealing ends, insulator poles and bushing) is generally evaluated through specific tests under wet and contaminated conditions and it is quantified in terms of equivalent salt deposit density (ESDD) which is used to calculate the dielectric strength of the insulator. These tests are good enough for porcelain and glass insulators, but they are insufficient for composite insulators which, in addition to contamination and moisture, are also affected by aging of the housing material. Furthermore, they do not inform on the leakage current or leakage resistance of the insulator.

The IEEE Working Group on Insulator Contamination proposed an alternative method for evaluating the performance of insulators using measures of surface resistance and published results for three types of insulators: porcelain, ethylene propylene diene monomer (EPDM) and silicone rubber [16]. Table V shows values of surface resistance measured by the IEEE working group [16]. The surface resistance is expressed in Ohm per mm of leakage (or creepage) distance.

It is clear from Table V that composite insulators (EPDM and silicone) have substantially better performance (higher surface

TABLE V
SURFACE RESISTANCE PER MM OF LEAKAGE DISTANCE (kΩ/mm) FOR TYPICAL INSULATOR MATERIAL [16].

	EPDM	Silicone	Porcelain
Uncontaminated	80 — 210	>5300	3.1—10
Contaminated	0.27 — 5.3	2.7—8	Not Measured

TABLE VI
TYPICAL RESISTANCE AND LEAKAGE CURRENT AT NOMINAL VOLTAGE OF 275 kV INSULATORS

	EPDM	Silicone	Porcelain
Resistance (MΩ)	400 - 1638	>26500	25 - 100
Leakage current (mA)	0.1 - 0.6	<0.008	2 - 9

resistance) than porcelain. It is also clear from Table V that the presence of contaminants in the walls of the insulator greatly reduces its performance.

The leakage resistance of an insulator can be obtained as

$$R_{\mathrm{insulator}} = R_{\mathrm{surf}}\ d_{\mathrm{leakage}} \tag{12}$$

where R_{surf} is the surface resistance given in Table V and d_{leakage} is the leakage distance of the insulator. Values of leakage distance are easily found in manufacturer catalogs. For 275 kV insulators the usual values are 5000-7800 mm for composite and 8000-10000 mm for ceramic [17]. Using these values and those in Table V, allows calculating typical values of resistance and leakage current at nominal voltage for 275 kV insulators in Table VI.

C. Formula and Typical Values of Discharge Time Constant

The time constant associated with the discharge of cable and surrounding insulators is calculated as

$$\tau = \left(\frac{R_{\mathrm{cable}} R_{\mathrm{ext}}}{R_{\mathrm{cable}} + R_{\mathrm{ext}}}\right) C_{\mathrm{cable}} \tag{13}$$

where R_{cable} and C_{cable} are given in (1)-(2) and R_{ext} is the leakage resistance of external components calculated as

$$R_{\mathrm{ext}} = R_{\mathrm{insulator}}/p \tag{14}$$

where $R_{\mathrm{insulator}}$ is defined in (12) and p is the number of insulator components connected to the cable.

Using the formula for cable discharge voltage in (4) with $V_{\max} = V_n\sqrt{2/3}$ the time required to discharge the cable voltage to a safe level (25 V according to IEC 60479-1) is 10τ for 275 kV cables.

Table VII shows time constants τ and time required to discharge the cable to the safe voltage level for different combinations of cables and insulators. These values are based on the typical values of cable insulation and insulator properties shown in Table IV and Table VI, respectively. It is worth noting that the most severe cases, i.e. the longest discharge times (lowest leakage currents), are found when the insulators and cable insulation are at their best condition. This is observed in Table VII for paper insulated cables with silicone insulators.

TABLE VII
TYPICAL DISCHARGE TIME CONSTANTS FOR 275 kV 20 KM CABLE WITH CABLE SEALING END

A. Discharge Time Constants				
		Insulator		
		EPDM	Silicone	Porcelain
Cable Insulation	EPR	3.4 - 3.6 min	3.7 min	1.6 - 2.8 min
	XLPE	17 - 27 min	33 min	2.0 - 6.7 min
	Paper	54 - 170 min	8 - 9 h	3.7 - 14.6 min
B. Time to discharge the cable to safe voltage level				
		Insulator		
		EPDM	Silicone	Porcelain
Cable Insulation	EPR	34 - 36 min	37 min	16 - 28 min
	XLPE	2.8 - 4.5 h	5.5 h	20 min - 1 h
	Paper	9 - 28 h	3.3 - 3.75 days	0.6 - 2.4 h

TABLE VIII
DATA FOR THE RESISTANCE R(T) IN THE CIRCUIT OF FIG. 11.

Time	0h	0h30	3h15	10h00
Resistance (MΩ)	1359.3	1359.3	430.6	430.6

D. Correction Factor for Humidity

The field tests results provided by National Grid represent a very important contribution of this paper. Not only they show the evolution of voltage during the discharge of a 275 kV POF cable, a result rarely found in the literature, but they also show the evolution of relative humidity, temperature and atmospheric pressure during those measurements, carried out during a total of 10 hours.

These results, presented in Section II-C, allow the definition of a correction factor to apply to the leakage resistance of external insulators to account for a modification in the relative humidity of air. From Fig. 8 it is observed that the relative humidity increased from 80% to 100%. At the same time, the leakage resistance of external insulators, excluding leakage of cable insulation, measured from the test results, was reduced from 1359.3 MΩ to 430.6 MΩ (see Table VIII). Let's define h_1 and $R_{\mathrm{ext-h_1}}$ the initial values of relative humidity and insulator resistance, and h_2 and $R_{\mathrm{ext-h_2}}$ the values after a change in the relative humidity. In the case of the field test by National Grid,, $h_1 = 80\%$, $R_{\mathrm{ext-h_1}} = 1359.3\,\mathrm{M\Omega}$, $h_2 = 100\%$, and $R_{\mathrm{ext-h_2}} = 430.6\,\mathrm{M\Omega}$. The correction factor to apply to insulator resistance to account for a modification in the relative humidity is

$$R_{\mathrm{ext-h_2}} = \frac{h_1}{2.5\,h_2} R_{\mathrm{ext-h_1}} \tag{15}$$

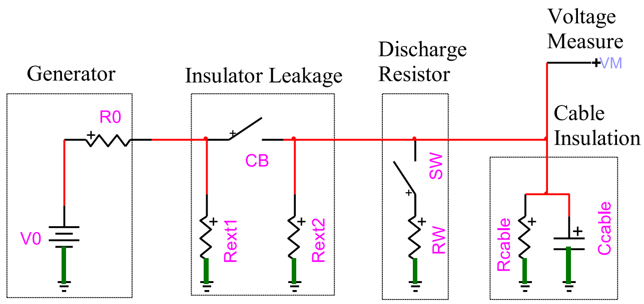

Fig. 9. Circuit for simulation of field test in Fig. 1.

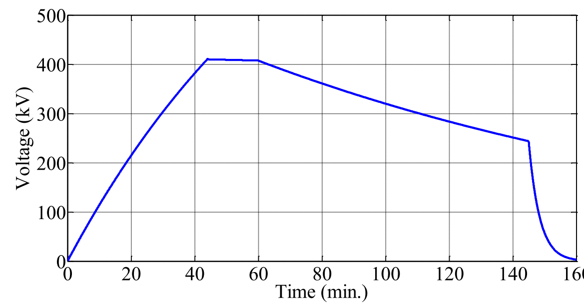

Fig. 10. Simulation of charging/discharging voltage.

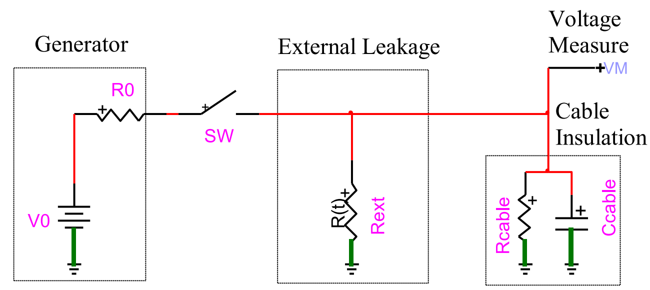

Fig. 11. Circuit for simulation of discharging of a 275 kV POF-cable in the UK.

IV. Validation Based on Test Results

This chapter presents the simulation of field tests given in Section II using simple parallel *RC* circuits whose parameters are calculated according to the methods given in Section III.

A. 275 kV PT-POF Cable in Japan

The paper in which the field test of Fig. 2 was first published [7] gives estimated values of leakage resistance which result in a discharge time nearly half (49 min) of that observed in the field test (88 min). This means that the leakage in the system was not as severe as estimated and the components presented a resistance higher than expected.

Cable leakage resistance is calculated using half of the resistivity for paper insulation in Table III, i.e. $\rho = 500 \times 10^{12}\ \Omega{-}\mathrm{m}$, together with $n = 3$, $l = 20 \times 10^3$ m, $r_{\mathrm{in}} = 26.65$ mm and $r_{\mathrm{out}} = 40.65$ mm in Table I into (10) and (1) resulting $R_{\mathrm{cable}} = 560.0\,\mathrm{M}\Omega$.

The lower value of resistivity is based on typical insulation properties in PT-POF cables of 1970's, which have been improved since then [18].

The leakage resistance of external components is calculated using the surface resistance of EPDM $\rho = 210 \times 10^3\ \Omega/\mathrm{mm}$ in Table V and a leakage distance of $d_{\mathrm{leak}} = 5000$ mm into (12) and (14) resulting $R_{\mathrm{ext}} = R_{\mathrm{insulator}} = 1050\,\mathrm{M}\,\Omega$.

The total leakage resistance is calculated as $R_{\mathrm{total}} = R_{\mathrm{cable}}||R_{\mathrm{ext}} = 365.2\,\mathrm{M}\Omega$. The time constant of the system is obtained using this value and the cable capacitance $C_{\mathrm{cable}} = 29.3\,\mu\mathrm{F}$ into (5) resulting $\tau = 178.3$ min.

The time required to discharge the cable from $v(t_1) = 414\,\mathrm{kV}$ to $v(t_2) = 250\,\mathrm{kV}$ is calculated using $\tau = 178.3\,\mathrm{min}$ into (6) as $t_2 - t_1 = 89.9$ min. This value is only 2% above the one observed in the field tests (88 min).

The values of leakage resistance for cable insulation and external circuit calculated above, were used to simulate the field test in Fig. 2. The circuit used to simulate the cable system is shown in Fig. 9. The 20 km cable is modeled using a parallel *RC* circuit using the parameters of cable insulation for 3 phases in parallel, that is, $C_{\mathrm{cable}} = 29.3\,\mu\mathrm{F}$ and $R_{\mathrm{cable}} = 560.0\,\mathrm{M}\Omega$. The leakage of external circuit is $R_{\mathrm{ext1}} = R_{\mathrm{ext2}} = 1050$ MΩ. Other circuit parameters (defined in Section II-A) are

1) $V_0 = 414\,\mathrm{kV}$, voltage of DC generator,
2) $R_0 = 138\,\mathrm{M}\Omega$, charging resistance,
3) $R_W = 30$ MΩ, resistor used for full discharge.

The switch S_0 is closed from $t = 0$ to $t = 60$ min and S_W closes at $t = 148$ min (S_0 being open).

The simulation result in Fig. 10, agrees with the field test result of Fig. 2, which validates the modeling approach.

B. National Grid 275 kV POF Cable

From the field test result in Fig. 6 and from the value of cable capacitance, the total leakage resistance of the system has been estimated as 840.2 MΩ for low humidity and 360.1 MΩ for increased humidity.

Cable leakage resistance is calculated using (10) and (1) with the resistivity for paper insulation $\rho = 1000 \times 10^{12}\ \Omega/\mathrm{m}$ in Table III, $l = 21 \times 10^3$ m, $r_{\mathrm{in}} = 29.75$ mm and $r_{\mathrm{out}} = 40$ mm in Table II, resulting into $R_{\mathrm{cable}} = 2.2\,\mathrm{G}\Omega$.

The leakage resistance for 3 insulators in parallel (2 insulator poles and cable sealing end) is calculated using $p = 3$, the surface resistance of silicone $\rho = 5300 \times 10^3\ \Omega/\mathrm{mm}$ in Table V and a leakage distance of $d_{\mathrm{leak}} = 5334$ mm (supplied by National Grid) into (12) and (14) resulting into $R_{\mathrm{ext}} = 9.4\,\mathrm{G}\Omega$. With previously found $R_{\mathrm{cable}} = 2.2\,\mathrm{G}\Omega$, the total leakage resistance is calculated as $R_{\mathrm{total}} = R_{\mathrm{cable}}||R_{\mathrm{ext}} = 1811.4\,\mathrm{M}\,\Omega$. This value is about 2 times the value observed in the field tests (840.2 MΩ). However, it must be observed that the calculated insulator resistance considers uncontaminated material. With a total leakage resistance of $R_{\mathrm{total}} = 840.2\,\mathrm{M}\,\Omega$ calculated from the field test in Section II-C, the leakage resistance of external components can be reevaluated from

$$\frac{2200 \times R_{\mathrm{ext}}}{2200 + R_{\mathrm{ext}}} = 840.2\,\mathrm{M}\Omega,\ R_{\mathrm{ext}} = 1359.3\,\mathrm{M}\Omega$$

Using $R_{\mathrm{total}} = 360.1\,\mathrm{M}\Omega$ instead of 840.2 MΩ, results into $R_{\mathrm{ext}} = 430.6\,\mathrm{M}\Omega$ when humidity rises to 100%.

The field test in Fig. 6 was simulated using the circuit in Fig. 11. The cable is modeled with a parallel *RC* circuit using the parameters of its insulation, that is $R_{\mathrm{cable}} = 2.2\,\mathrm{G}\Omega$

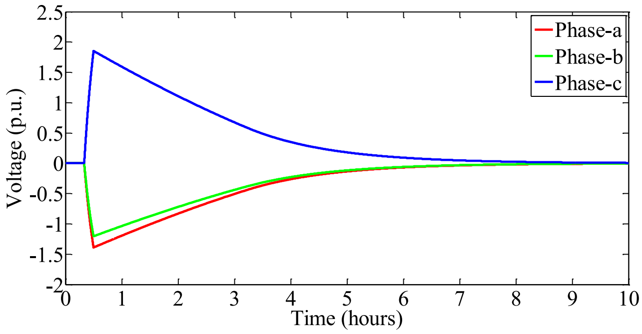

Fig. 12. Simulation of discharge of a POF-cable in the UK.

and $C_{\mathrm{cable}} = 15.0\ \mu F$. The leakage in the external circuit (2 insulator poles and cable bushing) is modeled with a time varying resistance to account for the rise in ambient humidity during the field test. The values for this leakage resistance are given in Table VIII. The charging resistance is $R_0 = 100$ MΩ (calculated from the rise time of voltage in Fig. 6). Fig. 12 shows the simulated discharge voltage of the cable and the agreement with the field test result in Fig. 6 is evident.

V. Conclusion

Recently, cable charging/discharging phenomenon has received new consideration from utilities which are using high-voltage (HV) cables for voltage control during periods of light load. This paper has investigated discharge characteristics of 275 kV POF cables based on laboratory and field tests, theoretical analysis and simulations. The main conclusions are as follows.

The natural discharge of cable systems can be explained using simple equations of parallel *RC* circuits. This was verified from simulation of field test results for two cable systems.

The factors affecting the discharge time are the cable capacitance, which is easily found in manufacturer catalogs, the leakage resistance of cable insulation and external components, such as insulator poles, bushing and cable sealing ends. Leakage in insulators exposed to air is highly affected by temperature, humidity and contamination.

Leakage in the cable insulation and external components can be estimated based only on the voltage level, types of cable insulation (EPR, XLPE, paper) insulator material (composite, ceramic) and the number of parallel insulator poles connected to the cable terminations. Estimation of leakage and knowledge of cable capacitance, directly provide a sufficiently accurate estimate of the discharge time.

The discharge time constants observed in the two field tests on 275 kV POF cables of 20 km, range from 1.5 to 3.5 hours. The time to discharge the cable to a safe voltage level (25 V according to IEC 60479-1), is in theory ten times the discharge time constant.

The leakage resistance of POF cables is about 74.5 GΩ-km (3.7 GΩ for 20 km). For XLPE insulated cables the value is 1/10 of that. The leakage resistance of 275 kV insulators is about 100 (porcelain) to 1600 MΩ (EPDM) per element. For silicone insulators, this value can rise to 26.5 GΩ.

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Isabel Lafaia (M'14) received the M.Sc. degree in electrical and computer engineering from Instituto Superior Técnico (IST), Portugal, in 2012 and is currently pursuing the Ph.D. degree at Polytechnique Montreal, Canada. Her research interests are modeling and simulation of electromagnetic transients in power systems.

Foroozan Ghassemi received the Ph.D. in degree from City University, London, U.K., in 1989. He has since been working in academia, manufacturing and utility sectors, all related to power system engineering. He is currently working for the UK Grid operator, National Grid Electricity Transmission. He is involved in the connection of new grid users and setting design policies and specifications related to security and quality of supply. He is the named inventor of two patents, a Chartered Engineer in U.K., and Fellow of IET.

Akihiro Ametani (M'71–SM'84–F'92–LF'09) received the Ph.D. degree from the University of Manchester (UMIST), Manchester, U.K., in 1973. He was with UMIST from 1971 to 1974, and with Bonneville Power Administration for summers from 1976 to 1981, and developed electromagnetic transients program. He was awarded the D.Sc. degree from University of Manchester in 2010.

Beginning in 1985, he was a Professor at Doshisha University, Kyoto, Japan. In 1988, he was a Visiting Professor at the Catholic University of Leuven, Belgium. From April 1996 to March 1998, he was the Director of the Science and Engineering Institute, and the Dean of the Library and Computer/Information Center, Doshisha University from April 1998 to March 2001. He was the Chairperson of the Doshisha Council until March 2014. He was the Vice-President of IEE Japan in 2003. Since April 2014, he has been an Emeritus Professor at Doshisha University, and is an Invited Professor at Polytechnique Montreal, Montreal, Canada.

Jean Mahseredjian (F'13) received the Ph.D. degree from cole Polytechnique de Montréal, Canada, in 1991. From 1987 to 2004, he was with IREQ (Hydro-Québec) working on research and development activities related to the simulation and analysis of electromagnetic transients. In December 2004, he joined the Faculty of Electrical Engineering at Polytechnique Montreal.

Simon Dennis received the H.N.D. degree in electrical engineering in 2015. Since 2011 he has been working as a Field Technician for National Grid UK specialising in Condition Monitoring and HV Cable fault analysis. He is a member of the IET.

A. M. Haddad (M'13) received the degree of Ingnieur d'tat in electrical engineering in 1985 and the Ph.D. degree in high-voltage engineering in 1990.

He is currently a Professor of Electrical Engineering with Cardiff University responsible for research in high-voltage engineering. He has authored an IET- Power Series Book entitled Advances in High-Voltage Engineering. His research interests are in overvoltage protection, insulation systems, insulation coordination, and earthing of electrical energy systems. He is a member of several CIGRE Working Groups and a member of the BSI PEL1/2, the IEC TC37 MT4 and MT10 and the IEC ACTAD committees. He serves on the scientific committees of several international conferences.

Dr. Hadad is a fellow of the IET and the Learned Society of Wales.

Stephen Robson received the M.Eng. degree in 2007 and the Ph.D. degree in 2012. Between 2007 and 2008, he worked as a graduate engineer with National Grid UK.

In 2013, he was appointed as a Lecturer in Electrical Engineering with Cardiff University, Cardiff, UK. His main research interests are in power line communication, fault location, condition monitoring, and simulation of transients on electrical networks. He is a member of the IEEE.