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Featured in this Issue:

- Transient and Steady-State DC Behavior of Oil-Impregnated Pressboard
- Partial Discharge Characterization of Cross-Linked Polyethylene Medium Voltage Power Cable Termination Defects at Very Low Frequency (0.1 Hz) and Power Frequency Test Voltages
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- Using a Field Probe to Study the Mechanism of Partial Discharges in Very Small Air Gaps Under Direct Voltage

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FEATURE ARTICLE

Diagnosis and Location of Faults in Submarine Power Cables

Key words: power cable, submarine, high voltage DC, fault location, fault diagnosis

Manfred Bawart
BAUR GmbH, Raiffeisenstrasse 8, 6832 Sulz, Austria

Massimo Marzinotto
TERNA, Via della Marcigliana 911, 00138 Roma, Italy

Giovanni Mazzanti
Department of Electrical Energy Engineering and Information, University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy

The article reviews the methods for diagnosing and locating faults in submarine power cables with case studies relevant to long AC cables and very long high voltage DC cables.

Introduction

Nowadays, when compared with overhead lines, power cables are becoming increasingly attractive for the delivery of electrical power. Their reduced environmental impact complies with the public concern on the compatibility of electrical infrastructures in residential areas. The lower fault rate of high voltage DC (HVDC) cables matches the need of transmission and distribution system operators for high reliability in power delivery [1], [2], and sometimes they are the only solution, e.g., submarine links. In general, the growing demand and dependency on offshore produced renewable energy makes submarine cables essential, and they have become critical infrastructures for the reliable delivery of electrical power [1]–[3].

Whereas an overhead fault is often transient and self-restoring, and can be singled out quite easily and quickly, a cable fault is permanent and normally involves long times for fault location and repair. For this reason the need for high reliability and availability increases proportionally with higher cable voltages [4], [5].

Attaining high reliabilities and availabilities is more difficult for submarine cables than for land cables. For land cables, the main focus is on the electrical and thermal design of cable insulation, on the electrothermal and thermomechanical design of cable accessories, and on quality manufacturing and installation of cables and their accessories, to ensure long life. However, for submarine cables, in addition to design, manufacturing, and installation, more issues arise, some related to the operating environment, whereas others are even more troublesome that are associated with man-made activities. Indeed, on the one hand, submarine power cables are subjected to high mechanical stresses during laying and critical service conditions in their working ambient; on the other hand, submarine cables are continuously exposed to random mechanical damage caused by ship anchors; fishing gear; off-shore rigs for wind farms; and natural hazards such as hurricanes, tides, landslides, and earthquakes [3], [6], [7].

The longer the length and expected life of a submarine cable, the higher is the probability that the cable will experience one or more faults over its service life due to human activities. Based on worldwide submarine cable failure data, it can be concluded that for long submarine cable links, the likelihood of experiencing at least one fault is high during the life of the cable. Statistically, most cable faults are caused by human activities, whereas only a low percentage are caused by natural conditions [8], [9]. The repair of submarine power cables requires specialized ships and expert teams to hoist the cable from the sea bed and to repair the cable fault. Another critical aspect is that a fairly long time is needed for the repair. For this reason, fast and efficient fault

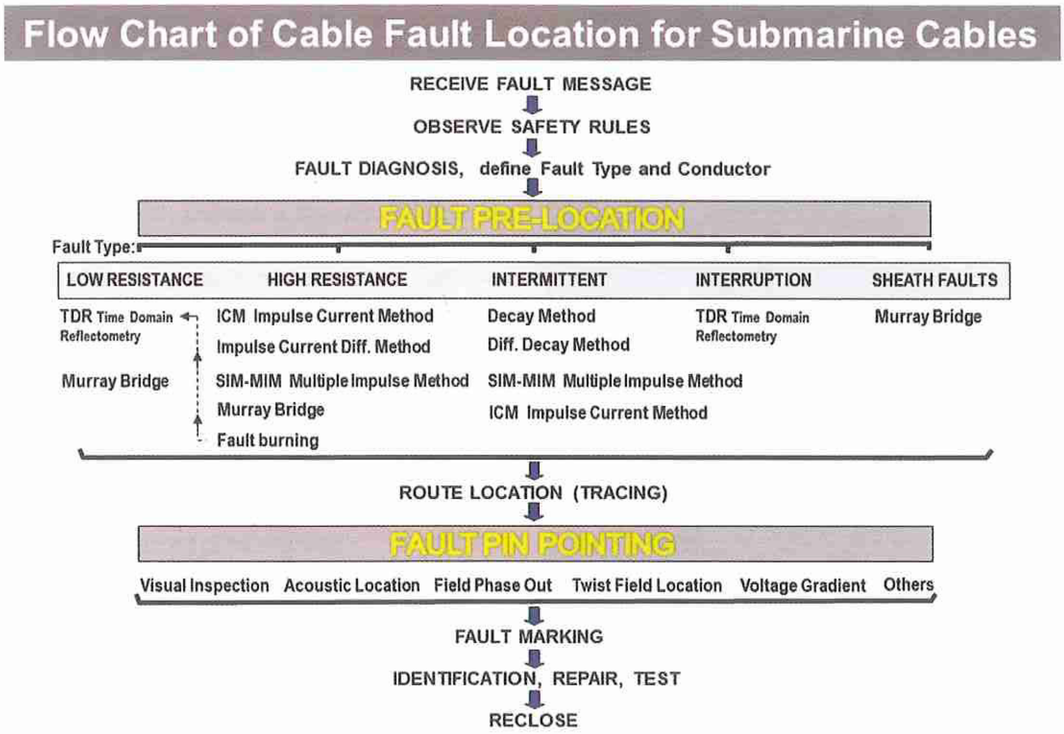

Figure 1. Flow chart of cable fault location for submarine cables (after [10], [11]).

detection is beneficial in reducing the overall outage time [3], [6], [7].

All of these aspects are discussed in this article. First, the various stages of fault location are described and summarized. Thereafter, the time domain reflectometry (TDR) fault location technique is dealt with in detail, and the relevant theoretical background is outlined because this is the basis for the other pulse-based cable fault detection techniques. A few TDR case studies are given, and the TDR-based splice fault location is discussed. This is followed by a discussion of other cable fault location methods. These methods are exemplified, with applicative cases to submarine power cables given. Finally, a few noteworthy case studies relevant to fairly long submarine AC cables and long and very long HVDC submarine cables are discussed. In addition, other important and nontrivial aspects of fault location, such as fault pinpointing and safety aspects of fault location, are discussed in the article, particularly on very long HVDC links.

Fault Location Flow Chart for Submarine Cables

The fault location procedure for submarine cables follows a sequence of stages that are outlined in the flow chart shown in Figure 1 (after [10], [11]).

First, a fault message is received. At this first stage the operator is required to follow applicable safety rules for ensuring that the cable is dead and secure for the duration of the fault location and repair work. The user is responsible for securing the front end termination as well as all locations along the cable run right through to the far end termination. As an example, the so-called "five safety rules" from the European Standard EN 50110-1 [12] (see also German Standard VDE 0105-100 [13]) are performed in the specified order.

1. Disconnect from the mains.
2. Secure against reconnection.
3. Verify that the system is dead.
4. Carry out earthing and short circuiting.
5. Provide protection from adjacent live parts.

This is followed by diagnosis of the fault, which is important for a successful and fast location of the fault. The fault diagnosis consists of

- identifying the faulty phase in three-phase AC cables or the faulty pole in HVDC cables and
- classifying the fault type.

The fault type can be classified according to the following five categories:

1. low resistance faults, with a resistance below 100 Ω (TDR technology defines a threshold of 100 Ω);
2. high resistance faults, with a resistance in the kiloohm range;
3. intermittent faults, that become active above a threshold voltage, typically below the cable operating voltage;
4. interruptions, when the cable is cut into two or more sections; and
5. sheath faults, where the cable jacket (normally polyethylene) is damaged. The cable metallic shield is normally insulated to prevent water or moisture ingress that can

Table 1. Fault Detection Methods according to the type of fault

Method	Fault characteristic
TDR, time domain reflectometry	Low resistance fault, cable interruption
Fault burning	High resistance fault, wet fault
MIM, multiple impulse method	High resistance fault, intermittent fault
ICM, impulse current method	Low resistance fault, high resistance fault, intermittent fault
Impulse current differential method	High resistance fault
Differential decay method	Intermittent fault
Decay method	Intermittent fault
Murray bridge method	Low resistance fault, high resistance fault, wet fault, cable sheath fault

damage the metallic shield. To detect faults at the earliest possible stage, DC sources are used to test the sheath insulation [14] and DC impulse signals are applied for locating the sheath faults [15], [16].

Next, the fault prelocation is performed, which consists of singling out the electrical distance of the fault from cable ends with some degree of uncertainty, normally to within 1% of the cable length. In principle several methods are available for fault prelocation, such as [10], [11]

1. TDR,
2. impulse current method (ICM),
3. secondary impulse method (SIM) and multiple impulse method (MIM),
4. decay method,
5. impulse current differential method,
6. differential decay method, and
7. Murray bridge method.

The application range of the listed fault detection methods, according to the type of fault, are summarized in Table 1.

TDR works only for low resistance faults and for cable interruptions, whereas the other methods require a HV source for breakdown/arcing at the fault location. The Murray bridge method can be used on resistive faults, up to about 10 MΩ, with units having an internal HV source, but it requires a healthy return line.

Intermittent faults are not common on submarine cables, but if they appear, they cannot be found by neither TDR nor the Murray bridge. This fault type may occur in internal insulation of the cable as well as in joints and terminations but also in the land section of the cable.

Traditional fault location methods like the SIM, MIM, arc reflection method, and ICM for fault location on high resistance and intermittent faults are limited to short cable lengths up to a few kilometers. Special HV fault location systems are required for the location of intermittent faults on long and extra-long submarine cables. There, the decay method and the differential decay method perform best [6], [7], [10], [11].

Referring to Figure 1, after the prelocation of the fault, the route location (tracing) follows. For cable tracing, an AC current with tone frequency is injected into the cable. The AC current induces a magnetic field that can be located with an appropriate pick-up coil and a receiver. The tracing procedures can be used to establish the position and depth of the cable using the so-called "minimum or maximum method." This is followed by fault pinpointing to determine the exact position of the fault. Several techniques are available for fault pinpointing, depending on the type of fault [10], [11]:

- visual inspection may be possible and local dredging may indicate the location;
- acoustic location as applied to land cable using special seismic microphones for fault pinpointing in shallow water;
- field phase-out using a boat with a nonmetallic keel that measures the magnetic field induced by the fault current, and as soon as the magnetic field phases out, the fault position is located;
- twist field location can be used for three-core land portions of the cable;
- voltage gradient or voltage drop method using galvanic probes and capacitive probes for sheath fault location.

Despite the various techniques available, pinpointing is still a problem for submarine cables. However, once pinpointing has been carried out, fault marking and identification take place for faults on the land cable section. Fault sections of submarine cables have to be identified while on board the repair vessel. Care is needed in recovering the cable from the seabed, avoiding bending, kinks, and unnecessary mechanical stress on the cable. In deep water, a remotely operated vehicle from a vessel is used for recovery. The identification of the faulted cable in a bundle of cables is a safety-specific activity that is necessary before cutting a cable, and computer-supported procedures are used for land cables [10], [11].

Repair of the cable is undertaken in a controlled environment aboard the vessel, and proof tests are done after the repair before the cable is laid back into the seabed trench, which is reclosed. A voltage withstand proof test is performed in accordance with one of the following standards, IEEE 400-2012 [16], IEEE 400.2-2013 [17], IEC 60502-2014 [18], IEC 60840 [19], or IEC 62067 [4]. The integrity of the oversheath on a land cable section is tested according to IEC60229:2007 [20].

Sophisticated cable diagnosis is often used to diagnose the cable repair on submarine links up to 15 km in length. This technology is based on very low frequency dissipation factor (tan delta) and partial discharge (PD) measurements as recommended by IEEE 400-2012 [16], IEEE 400.2-2013 [17], and IEC 60502-2014 [18]. Long HVAC cables are tested by applying a near power frequency voltage withstand test or often a 24-hour soak test. This test can be combined with a partial discharge test, but partial discharge signals cannot be detected on very long cables. Very long HVDC cables are tested with DC voltage according to Cigré 496 recommendation [5].

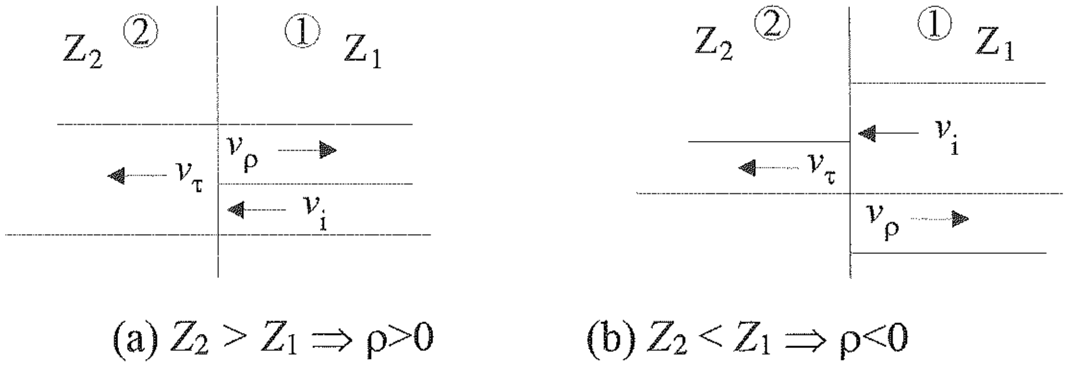

Figure 2. Reflection of a step voltage wave of amplitude v_i: (a) positive reflection, (b) negative reflection.

However, fault location on submarine cables differs much from classic fault location on land cables in that

- fault location in submarine cables is a hard task, especially if the cable is very long;
- no universal fault detection method exists. The fault type needs to be analyzed and diagnosed carefully to apply the most useful method;
- sophisticated apparatus that supports all indicated measuring methods and a very skilled and experienced staff are always required;
- fault prevention with proper techniques remains fundamental for cable link reliability and availability [3], [10], [11].

TDR

Theoretical Background

TDR is a fairly old technique; it dates back to shortly after World War II, and it is the basis for understanding the other methods for cable fault detection. The theoretical background of TDR is the theory of reflection and transmission of traveling voltage waves, discussed in detail in reference books and papers, for example in [21]–[29], and briefly outlined here.

In illustrating the theory behind TDR, it is usual to consider a voltage step wave of amplitude v_i that is injected at one end and propagates down the cable to the point where a discontinuity in the surge impedance takes place, for example, at a splice, termination, or fault (Figure 2). Because of the impedance discontinuities, Z_1 before and Z_2 after the discontinuity, part of the impinging wave v_i is transmitted, v_τ, and part is reflected, v_ρ, as follows:

$$v_\rho = \rho v_i, \tag{1}$$

$$v_\tau = \tau v_i = v_i + v_\rho, \tag{2}$$

where ρ is the reflection coefficient and τ is the transmission coefficient, which are defined as

$$\rho = (Z_2 - Z_1)/(Z_2 + Z_1), \tag{3}$$

$$\tau = 1 + \rho = 2Z_2/(Z_2 + Z_1). \tag{4}$$

According to (3), ρ can be either positive or negative, thus τ can be either greater to or less than one, depending on the values of the surge impedances. So, if $Z_2 > Z_1$, then $\rho > 0$, hence the reflected wave is positive, which adds to the impinging wave (Figure 2a); for example, an open-circuited cable or at the end of the cable $Z_2 >> Z_1$ ($Z_2 \to \infty$), thus (3) yields $\rho = 1$. If $Z_1 > Z_2$, then $\rho < 0$, hence the reflected wave is negative, which reduces the impinging wave (Figure 2b); for example, a low resistance fault or a short-circuited cable $Z_2 << Z_1$ ($Z_2 \to 0$), thus (3) yields $\rho = -1$.

A cable fault gives rise to a change in the surge impedance. In fact the fault impedance acts as a shunt impedance in parallel with the cable surge impedance, that finally lowers the total impedance. In practice, if the fault impedance is high, it does not change the cable surge impedance appreciably, and no reflected wave is generated from the fault; on the contrary, a low resistance fault gives rise to a decrease of surge impedance, and a negative reflected wave is generated from the fault that can be detected. The principle of the TDR is based on this theory, which is illustrated in Figure 3. The TDR device, also known as time domain reflectometer or TDR echometer, injects a high frequency, 20- to 160-V pulse, to one end of the cable with an oscilloscope connected in parallel to detect the reflected waves.

It must be emphasized that the above theory does not take into consideration the loss parameters of series resistance and shunt conductance of the cable which attenuate the traveling

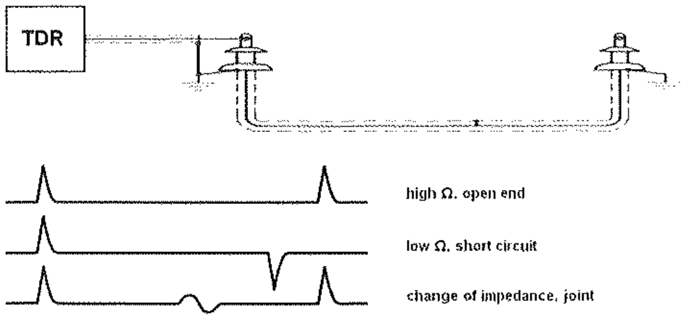

Figure 3. Schematic for time domain reflectometry (TDR) method and reflected waves depending on the fault impedance [10], [11].

voltage waves; thus the longer the cable, the higher are the losses and the greater the attenuation. In addition, cable splices cause reflections that are mainly caused by the change in geometry and/or material types. However, as these positions are generally known to the operator, they can help to detect the location of the fault with higher precision by referencing the known positions of the splices.

The fault location is estimated from the TDR echogram, or the oscilloscope voltage versus time plot, by measuring the elapsed time from the injection of the pulse to the arrival of the reflected component. Indeed, the distance, l, between the fault and the injection point is related to the time, t, by the following:

$$l = (v/2) \cdot t. \tag{5}$$

Of course, this involves the knowledge of the propagation speed of voltage waves in the cable, v, given by

$$v = \frac{1}{\sqrt{\varepsilon\mu}} = \frac{1}{\sqrt{\varepsilon_r \varepsilon_0 \mu_r \mu_0}} = \frac{1}{\sqrt{\varepsilon_r \mu_r}} c, \tag{6}$$

where ε and μ are the dielectric permittivity and magnetic permeability of the cable insulation, respectively; ε_r and μ_r are the relative permittivity and relative permeability of the cable insulation, respectively; ε_0 and μ_0 are the permittivity and permeability of the free space, respectively; and c is the speed of light in vacuum.

For cables, $\mu \cong \mu_0$, but the dielectric permittivity changes remarkably from insulation to insulation, e.g., $\varepsilon_r = 2.3$ for cross-linked polyethylene, $\varepsilon_r = 4.2$ for mass-impregnated nondraining insulation, and $\varepsilon_r = 2.6$ for ethylene propylene rubber. Hence, the propagation speed of voltage waves in cables depends basically on ε_r. Moreover, splices alter the propagation speed locally, and the wave attenuation with cable length has to be considered as well.

For this reason, the propagation speed is typical of a certain type of cable and has to be estimated carefully in its healthy state. This estimation, also referred to as TDR calibration or TDR fingerprint, needs to be performed during commissioning of the cable by injecting the TDR pulse at one end of the cable, with the other end either open or short-circuited, and measuring the time, T, elapsed from the injection of the pulse to the arrival of the reflected wave. Of course it holds that

$$v = 2L/T, \tag{7}$$

where L the length of the cable. Where more than one type of cable is used in the link, each cable section must be calibrated with its known section length. The gross propagation speed is applicable only for the full cable length, whereas the individual cable sections transfer the TDR pulse with individual velocity.

Errors or inaccuracies in the estimation of the propagation speed translate into errors in the fault prelocation. For this reason, the propagation speed that plays the role of a calibration constant must be estimated with great care.

The TDR echogram of a cable in its healthy state includes the wave attenuation with length and the secondary or multiple reflections from splices, and for this reason it is also referred to as the cable fingerprint. An accurate determination of the cable fingerprint is essential for the prelocation of the fault. Indeed, the prelocation of the fault relies essentially on the comparison of the TDR echogram of a faulted cable with the cable fingerprint.

The fault resistance is a limitation of the TDR method, as if the resistance is not low enough, the reflected pulse is too low for detection. Nowadays, TDR equipment amplify the received signal, but also other reflections caused by splices and multiple reflections often mask the small reflected wave received from a high resistance fault. A further limitation is the attenuation of the TDR pulse in a very long cable. A wide voltage pulse with amplitude up to 160 V often overcomes this second limitation.

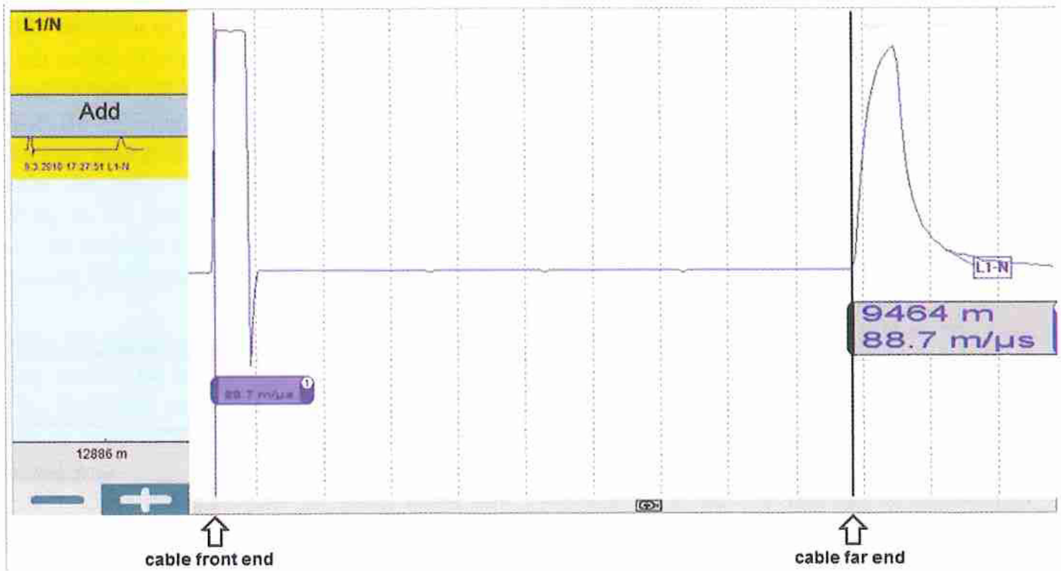

Figure 4. Time domain reflectometry fingerprint of a healthy cross-linked polyethylene–insulated, 132-kV AC submarine cable; voltage on the abscissa and time on the ordinate [10].

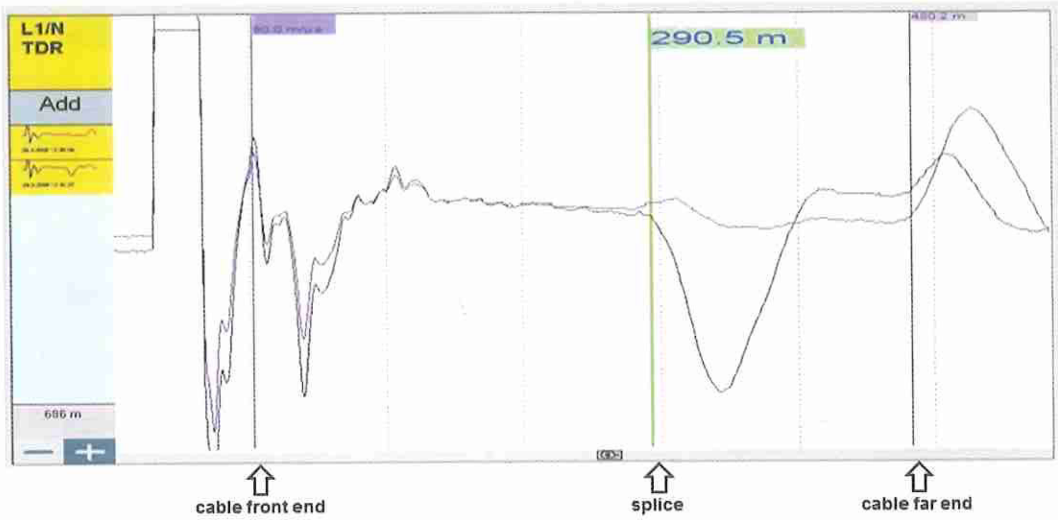

Figure 5. Time domain reflectometry (TDR) echograms of a low resistance fault at 290.5 m due to a faulty splice (large negative pulse) superimposed on the fingerprint of the same cable when healthy [10].

Fault Conditioning—Fault Burning

As high resistance faults cannot be detected by TDR, a powerful DC source offering a high arcing voltage and a high current supply is used as a burner to convert the high resistance fault into a low resistance fault, which then allows location by TDR. Cable fault burning is quite successful on cables with laminated paper–oil insulation; however, the technique is quite limited on extruded cable insulation.

Examples of TDR

The TDR echogram in Figure 4 illustrates the fingerprint of a healthy 9,464-m-long (one type) submarine cable. The pulse at $t = 0$ is the injected TDR pulse, and the reflected pulse from the open cable end is at $t = 106.7$ µs, which is twice the travel time for a calibrated cable propagation speed of 177.4 m/µs.

The superimposed TDR echograms in Figure 5 are for a faulted 20-kV AC paper-insulated lead-covered cable that is 480.2 m in length and that of the cable fingerprint obtained when healthy. The cable fingerprint shows the TDR pulse at $t = 0$ is followed by a few narrow closely spaced positive going pulses corresponding to the transition from the test lead to the cable, a small positive pulse at 290.5 m corresponding to a splice, and the reflected pulse from the open cable end at 480.2 m. The echogram of the faulted cable shows the same except that the large negative going pulse is from the faulty splice at 290.5 m.

The second example shows that the interpretation of a fault becomes much easier when comparing the faulted TDR to the fingerprint TDR. However, often TDR fingerprints are not available and then a comparison with other healthy cables may be helpful.

High Voltage Fault Location Techniques

ICM

The ICM is the conventional location method for high-resistance cable faults, which is mostly the case for extruded cables. Apart from situations of severe damage to the cable that exposes the conductor to sea water, giving rise to a low resistance fault, the usual faults are internal to the cable and do not expose the conductor to sea water. Partial restoration of the dielectric strength may take place due to melting of the extruded insulation by the fault current, and thus faults in extruded cables are mostly a high resistance or intermittent fault. This also occurs in land sections of the cable.

The method is illustrated in Figure 6 [10]. A surge generator, commonly referred to as a thumper, injects repetitive pulses, of 30 kV or higher, by discharging a capacitor (5 to 90 µF) into the cable, delivering peak currents of up to 25 kA with energy in the range of 3 kJ. The high energy impulse creates an arc at the fault spot, thereby generating impulse current waves to travel toward both ends of the cable. A high frequency current coupler, connected to a TDR at the thumper end, detects the current wave. As for the TDR method, the fault position is determined from the time elapsed from the injection of the pulse to the arrival of the current wave from the arcing fault. However, due to a time delay of up to a few microseconds for an arc to occur at the fault (ionization delay time), which depends on the characteristics of the fault (resistance) and pulse voltage level, a time shift t_i must be applied to (5), thus

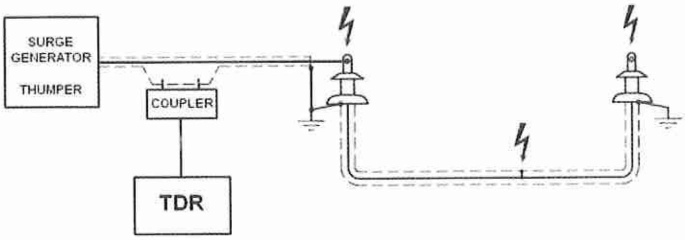

Figure 6. Impulse current method schematic. TDR = time domain reflectometer.

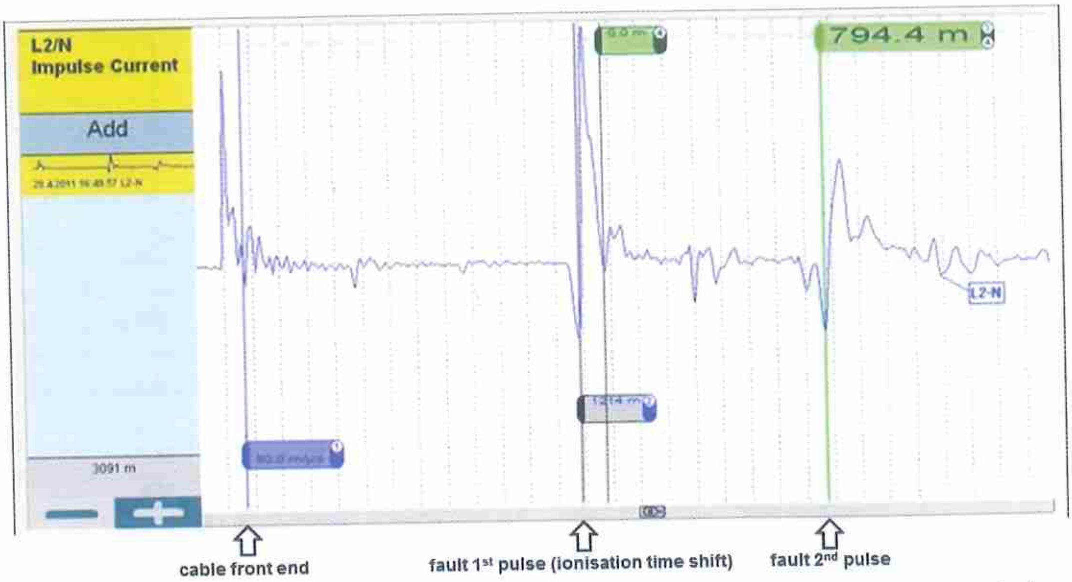

Figure 7. Impulse current method echogram of a faulty AC cable with a high resistance fault at 794.4 m (note the time/length shift due to the ionization delay time) [10].

$$l = (t - t_i)v/2. \quad (8)$$

As a consequence of the uncertainty in the delay time t_i, the ICM is not as accurate as the TDR method. But, experienced users often omit the first measuring period; instead they select the second period as it typically provides much reduced time delay and consequently offers an accurate distance measurement.

The polarity of the recorded pulses depends on the direction of the high frequency current coupler. However, because of polarity reversal of the arriving pulse at the fault, and again polarity reversal of the reflected pulse arriving back at the coupler, the recorded pulses are always the same polarity as the thumper pulse, as shown in Figure 7. This continues until the traveling pulse is completely damped out and the reflection frequency is limited to only a few periods [14].

The ICM echogram shown in Figure 7 is for a faulty AC cable, 1,200 m in length. The first positive pulse is from the thumper, which is followed by a small reflected signal from a splice and its multiple reflections. Clearly, the time from the first pulse to the second pulse is much larger than from the second to the third pulse, which is indicative of the ionization delay time in developing an arc at the fault position. This time is reduced on the subsequent pulses, and the time between the second and third pulses is taken for prelocation, which is at

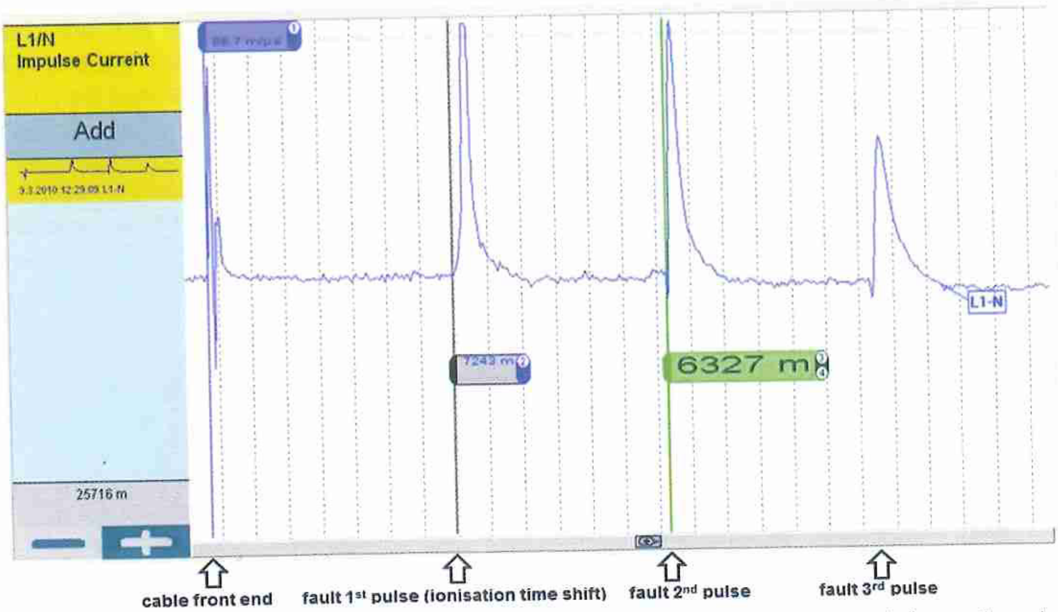

Figure 8. Impulse current method echogram of a faulty 132-kV cross-linked polyethylene submarine cable with an intermittent fault at 6,327 m [10].

794.4 m. The cable end is indicated with a negative pulse at 1,180 m distance.

The ICM echogram shown in Figure 8 is for a fault in a 132-kV XLPE submarine cable with an intermittent fault. The echogram shows the first positive pulse and a large ionization time delay, which if considered, would indicate the fault to be located at 7,243 m, whereas in fact, the fault location is at 6,327 m.

MIM

In this concept, a single shaped high voltage pulse is applied to the faulty cable, which creates an arc at a high resistance or intermittent fault. During arcing, the fault resistance is reduced to a low resistance fault, at least during the short arcing period. A superimposed TDR pulse is applied during the arcing period, which can then detect the fault.

This SIM, developed by Bawart in the early 1980s, and the MIM, a further sophisticated variant developed by Bawart in the late 1980s, are the basis of today's commonly applied fault location methods for prelocating cable faults. The basic setup for SIM/MIM consists of a surge generator, TDR, pulse shaper, and filter (coupling unit; Figure 9). The coupling unit couples the low voltage TDR pulse to the high voltage circuit.

In advance of the pulse from the surge generator, the TDR records a fingerprint of the cable indicating the splices and the cable end termination. At this stage the fault has high resistance and the fault location is not indicated. Then the HV pulse is applied to arc the high resistance or intermittent cable fault. Slightly delayed to the surge generator pulse, the TDR echograph is recorded and superimposed onto the fingerprint trace, which simplifies the interpretation of the fault location (Figure 10).

There are several factors that affect the effectiveness of this method, namely, water in a joint and oil reflow in oil filled cables either shorten the duration of the fault arcing or cause a delay in the fault ignition time. These factors require that the trigger delay settings are manually adjusted, thus skilled operators of the equipment are needed. To overcome these difficulties, the MIM is used.

The great advantage of MIM is that during the fault arcing process several TDR records can be obtained within the few milliseconds of arcing. In the case that arcing is interrupted due to one of the reasons mentioned, the operator can view all the TDR traces and select the appropriate fault echogram.

The particular benefits of this method are the simple handling, universal application, and extremely simple interpretation of the echograms. High-resistance faults are ignited by a surge voltage impulse, the fault distance is measured repeatedly by the TDR within a single discharge, automatically stored, and displayed. Thus, the fault distance evaluation is fully automatic.

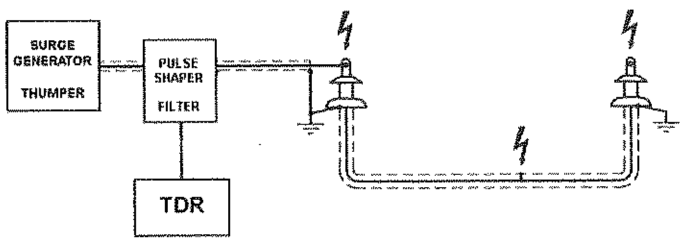

Figure 9. Schematic connection for secondary and multiple impulse methods. TDR = time domain reflectometer.

SIM and MIM are mostly used for detecting high resistance faults. Intermittent faults can be located in SIM/MIM DC mode, where the voltage is gradually increased until the fault appears. The method is known for its efficiency in cable fault location on land cables but limited to cables of short and medium length. Depending on cable length, fault type, and arcing behavior of externally damaged submarine cables, this fault location method is limited to typical application of land cables.

Decay Method

In the method, a HVDC source is used to charge the cable, which acts as a large capacitor, and as such, extreme care in discharging the cable is necessary because of the high energy stored. In charging, when the voltage exceeds the fault breakdown voltage, the fault spot arcs and transient waves are generated that are picked up by a capacitive coupling sensor. The voltage oscillation signals are recorded and analyzed on the TDR. The method is used to locate breakdown faults and intermittent cable faults with a high breakdown voltage particularly on long XLPE- or paper-insulated cables. However, the method is not suitable for wet types of faults.

The decay method relies on the continuous detection of a sequence of voltage waves, and the location of the fault is estimated from the echogram by measuring the time t elapsed from the first pulse to the arrival of a pulse of same polarity to the TDR. But, one recorded pulse cycle, from one positive peak to the subsequent positive peak, lasts four times the travel distance of the pulse. Therefore, the fault distance calculation is based on the following formula:

$$l = (v/4) \cdot t. \tag{9}$$

For accurate distance measurement the position of the transient pulse edges should be used, as peak to peak measurements may falsify the results. Considerable pulse attenuation occurs in extra long cables, and the numbers of wave cycles are limited. In this case, a half cycle may be used for fault distance measurement.

The echogram shown in Figure 11 is an example of the decay method applied to AC XLPE-insulated submarine cable with an intermittent fault. Note the distance measurement applied to the leading edge of the first cycle of the damped reflected wave.

Differential Methods

For these methods one healthy cable is required as a reference, and as such, these methods can be used on three-phase AC cables and 2 poles of DC cables. As voltage is simultaneously applied to the faulted and one reference cables, high frequency couplers that are similar in design to the ICM coupler, installed on both cables, are used as a differential coupler.

For fault location of high resistance faults the impulse current differential method is applied. First, a pulse is applied simultaneously to the two cables, and the couplers detect and cancel all common mode reflected pulses such as from splices that are at the identical location. However, the reflected pulse from the

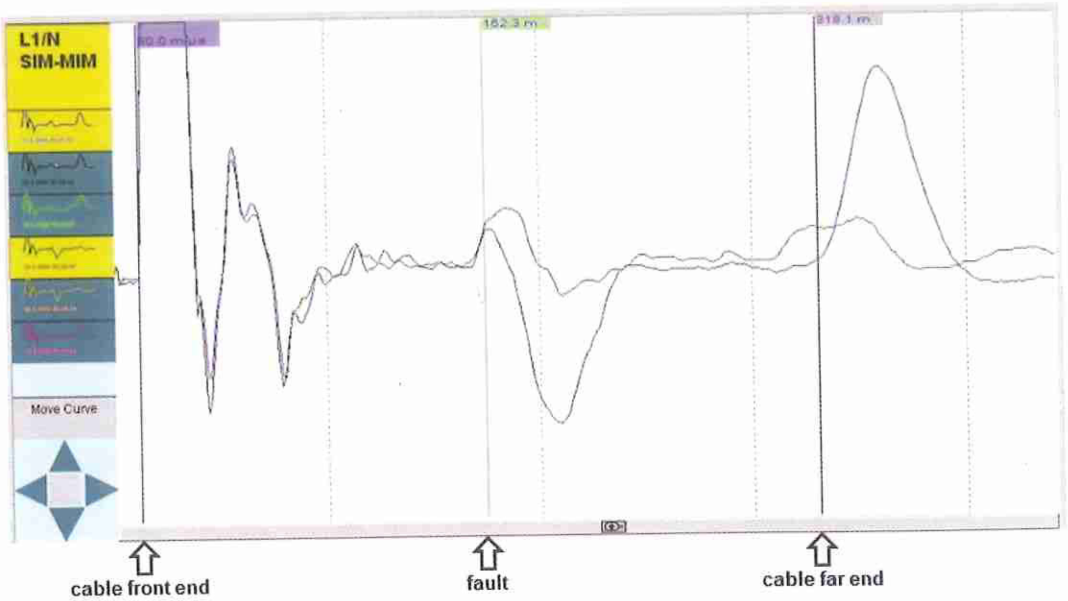

Figure 10. Secondary and multiple impulse methods (SIM-MIM) echogram of a faulty AC cable with high resistance wet fault at 162 m.

faulty phase is recorded. Next, the far ends of the cables are connected together and the test is repeated. This time the reflected pulse from the arcing fault now returns to the couplers via both cables, reaching the coupler first on the faulty phase and then later on the reference phase. The two echograms are superimposed, and the distance to the fault is determined from the far end of the cable.

The method works well on long cables and offers accurate location results as the ionization time delay does not cause an inaccuracy. The method has also been successfully used on T-branched medium voltage cables. However, for breakdown faults and intermittent faults on long submarine cables, the differential decay method is the best option.

In the differential decay method, two cables are required, the faulted and a reference cable and both are fitted with couplers that are connected in a differential mode. A HVDC source is used to energize both cables, and when an arc develops at the fault, a pulse is generated that is detected by the coupler and displayed by the TDR device. As in the case of the impulse current differential method, a second measurement is required where both cables are linked at the far end allowing the fault pulse to propagate in both the faulty and reference cables to the coupler.

Figure 11. Echogram of the decay method applied to an AC cross-linked polyethylene–insulated submarine cable with an intermittent fault at 730.4 m [10].

Figure 12. Connection of the Murray bridge method for fault location.

The two echograms are superimposed, and the distance to the fault is determined from the far end of the cable. The differential decay method offers easy interpretation, good accuracy, and a unique cable length capability.

Murray Bridge Method

The Murray bridge method is at least 100 years old and relies on having one good cable of the same type as the faulted cable to be used as a return line as the method is based on the fact that cable conductors have uniform per-unit length resistance and that the fault resistance is low compared with the cable insulation resistance. The method is illustrated in Figures 12 and 13, whereby it can be argued that the Murray bridge is essentially a modified Wheatstone bridge of resistors that can be balanced by a potentiometer. This enables the evaluation of the proportion between the conductor resistance of the cable section prior to the fault and that past the fault, including the return cable line. The measuring result is indicated in percentage of the cable length and can easily be converted into meters as the total cable length is known. A typical measuring accuracy within 1% of cable length can be achieved, on condition that data are carefully entered into the menu of the Murray measuring bridge.

As shown in Figure 13, the Murray bridge setup consists of a DC voltage supply, V_{DC}; adjustable balancing resistors, R_1 and R_2; and a shorting jumper at the far end to link the two cables (the Murray loop). Because both cables are of the same type, and the shorting jumper is short in length and assumed to have zero

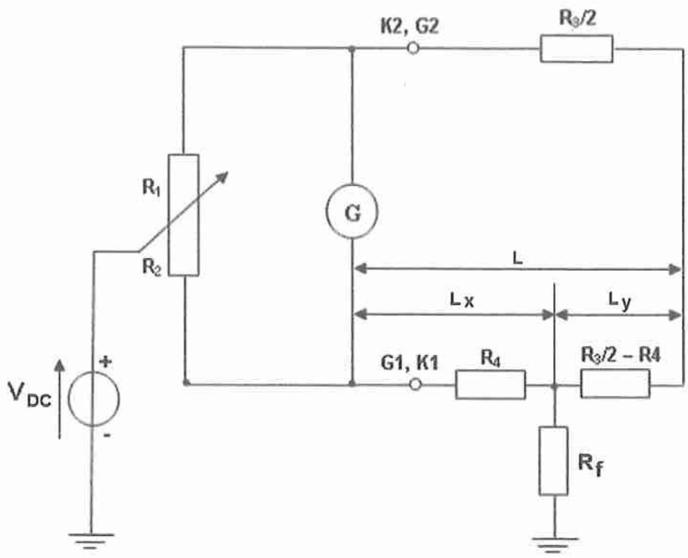

Figure 13. Electrical scheme for the Murray bridge method of fault location [14].

resistance, the total resistance of both cables, R_3, can be split into two equal resistances, $R_3/2$, for the healthy and faulted cables, respectively. The fault resistance R_f divides the faulted cable of length L into two sections: lengths L_x, having an unknown resistance of R_4 on the voltage source side, and L_y, having a resistance of $R_3/2 - R_4$ on the jumper side. A null detector (galvanometer G) is for balancing the bridge.

The value of the unknown resistance R_4 is proportional to the distance of the fault from the cable end where the DC voltage source is located, namely L_x, thus

$$L_x = 2L\frac{R_2}{R_1 + R_2}. \tag{10}$$

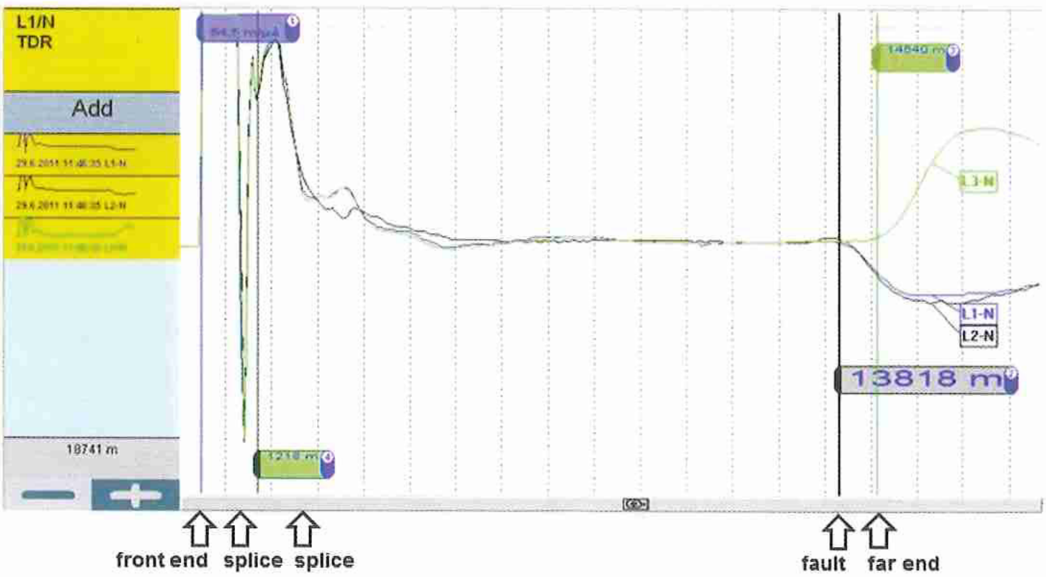

Figure 14. Time domain reflectometry (TDR) echograms of phases L1, L2, and L3 of an AC cross-linked polyethylene–insulated submarine cable 14,640 m in length [10].

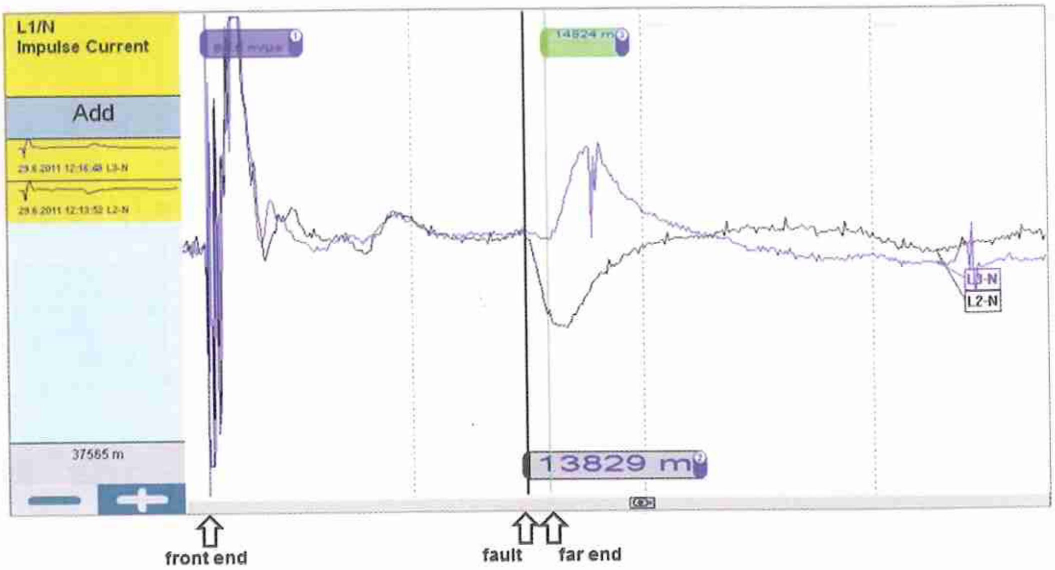

Figure 15. Impulse current method echograms of phases L2 and L3 of an AC cross-linked polyethylene–insulated submarine cable 14,640 m in length [10].

The method is applicable to resistive faults and ideally suited for fault location detection on DC bipolar links with one healthy pole or to monopolar links with a healthy return, and it offers an accuracy of 0.5 to 1%. However, a change of conductor cross section or of conductor material along the submarine cable needs to be factored in for accurate fault distance evaluation.

The Murray bridge method enabled successful fault location of low and high resistive cable faults, for instance on the 580-km long NORNED cable (a 450-kV mass-impregnated nondraining–insulated HVDC link connecting Norway and the Netherlands) [6], [7], [10], [11].

Case Studies

AC XLPE-Insulated Submarine Cable

Figure 14 shows TDR echograms for the three phases of a 14,640-m-long AC XLPE-insulated submarine cable. The comparison of the echograms shows L1 and L2 phases are faulty, at a distance of 13,818 m, and close to the end of the cable, whereas phase L3 is healthy. At the calibration stage on the healthy L3 phase, the propagation speed of voltage waves was determined to be 129 m/µs. The transition splice from the land to submarine cable is indicated at 1,218 m, and another splice at about 2,800 m can be recognized.

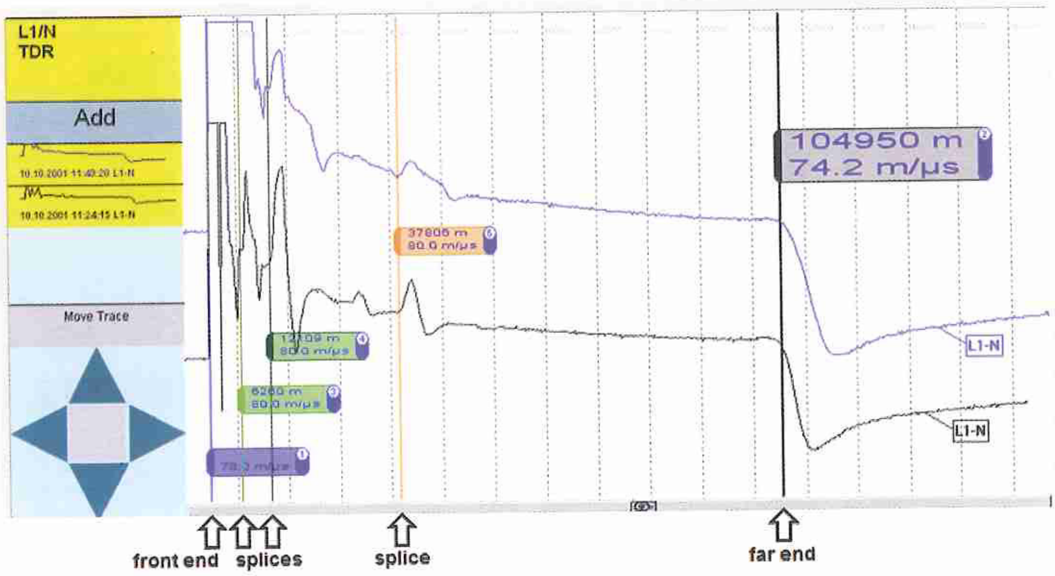

Figure 16. Echograms showing the effectiveness of a narrow pulse width which provides a fine resolution in a narrow zone and is effective for locating splices [10].

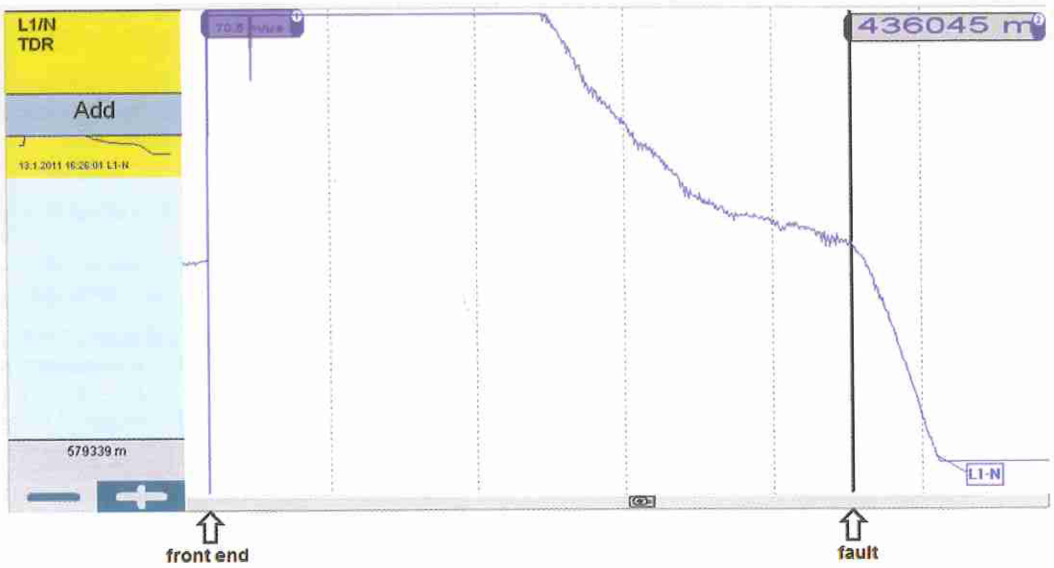

Figure 17. Sardinia-Italian Peninsula 500-kV submarine cable indicating a fault 436 km from the test setup [10].

The negative waves reflected from the faults correspond to a reflection coefficient tending to −1, which implies a low resistance fault. The diagnosis of the TDR echograms is confirmed by the ICM echograms shown in Figure 15 for L3 the healthy phase and L2 one of the faulty phases. The location of fault from the ICM echogram is estimated at 13,829 m, in excellent agreement with the location at 13,818 m according to the TDR echogram.

When comparing the echograms in Figure 14 with Figure 15, it can be noted that the abscissa has been extended to much longer times/distances in order to account for the ionization time delay. Nevertheless, since the fault is of a low resistance, the ionization time delay does not take place, and a first negative peak is immediately detected from the faulty cable.

Sardinia-Corsica-Italy (SACOI) ±200-kV Mass-Impregnated Nondraining–Insulated Submarine Cable

This link is 105 km in length. The echograms shown in Figure 16 demonstrate the effectiveness of adjusting the pulse width for locating splices. A narrow TDR pulse width provides a fine resolution in a narrow zone, whereas a larger pulse width is required for detection of splices at a far distance. The negative pulse reflection at 104,950 m relates to the safety short circuit at

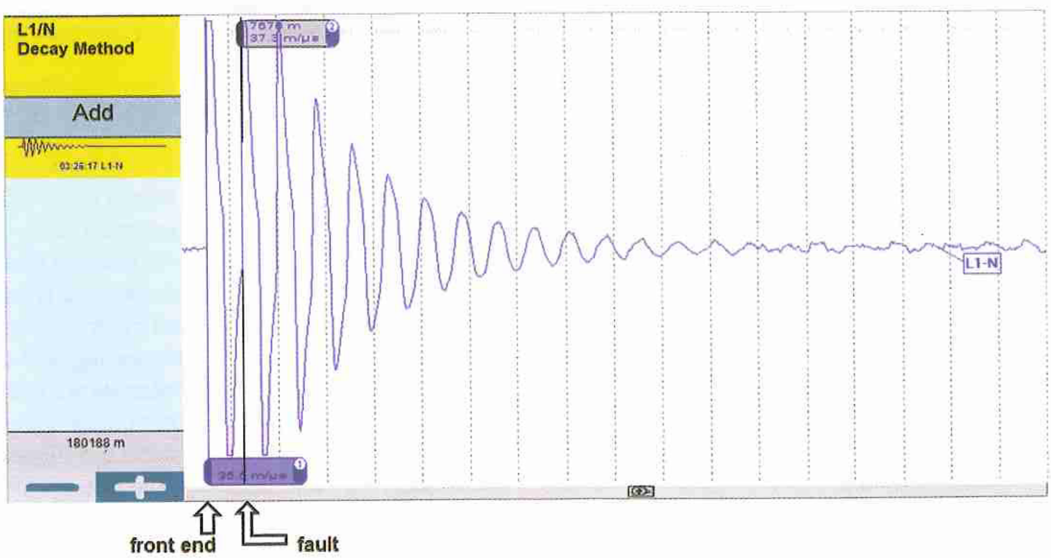

Figure 18. Decay method echogram revealing a 10-kV breakdown voltage intermittent fault at 7,586 m of distance from the front end of the cable [10].

the cable end. For accurate measurements, the TDR needs to be calibrated to its known cable length.

Sardinia-Italian Peninsula (SAPEI) 500-kV Mass-Impregnated Nondraining–Insulated Submarine Cable

This link is 442 km long and is the world's longest 500-kV submarine cable. The TDR echogram shown in Figure 17 shows a low resistance fault at 436 km, which is only a few km from the end of the cable. In this case, a burner was used to convert the high resistance fault to a low resistance fault.

In another case, the SAPEI link developed an intermittent fault. In this case, the decay method was used to locate the fault (Figure 18). The echogram shows an intermittent fault with 10-kV breakdown voltage at a distance of 7,586 m from the front end of the cable.

Summary

A cable fault on a submarine cable poses a difficult task for the transmission system operator because the shortfall in electrical power and the time for repair are often problematic. Fault diagnosis and fault location on long submarine cables requires a knowledgeable team of experts and specialized fault location equipment as the speed of the repair is dependent on both. The experience proves that the overall outage time for repair can be reduced significantly with good fault location accuracy.

The article emphasizes the differences in the conditions and methods between locating a fault on a submarine cable from land cables, and the best practices for diagnosing and locating these types of faults are discussed. Some field results on submarine AC and HVDC links are provided as examples.

Finally, it is emphasized that long submarine cables store large amounts of electrical energy that pose safety issues for field personnel and can damage sensitive equipment.

References

[1] G. Mazzanti and M. Marzinotto, *Extruded Cables for High Voltage Direct Current Transmission: Advances in Research and Development*, IEEE Press Series on Power Engineering. Hoboken, NJ: Wiley, 2013.

[2] R. Bartnikas, Ed., *Power and Communication Cables,* IEEE Press Series on Power Engineering. New York, NY: Wiley, 2000.

[3] T. Worzyk, *Submarine Power Cables*. Berlin, Germany: Spinger-Verlag, 2009.

[4] Power Cables With Extruded Insulation and Their Accessories for Rated Voltages Above 150 kV (Um=170 kV) up to 500 kV (Um=550 kV)—Test Methods and Requirements, IEC Standard 62067, Ed. 2.0, Nov. 2011.

[5] Working Group B1.32, *Recommendations for Testing DC Extruded Cable Systems for Power Transmission at a Rated Voltage up to 500 kV.* Cigré Brochure 496, Apr. 2012.

[6] M. Bawart, M. Marzinotto, and G. Mazzanti, "A deeper insight into fault location on long submarine power cables," in *Proc. 2014 Cigré Session*, 2014, paper B1_201_2014.

[7] M. Bawart, M. Marzinotto, and G. Mazzanti, "Challenge of fault location on long submarine power cables," in *Proc. 9th Int. Conf. Insulated Power Cable (Jicable'15)*, 2015, paper B3.5.

[8] Working Group B1.10, *Update of Service Experience of HV Underground and Submarine Cable Systems*. Cigré Brochure 379, Apr. 2009.

[9] Working Group B1.21, *Third-Party Damage to Underground and Submarine Cables*. Cigré Brochure 398, Dec. 2009.

[10] M. Bawart and M. Marzinotto, "Fault location on long submarine power cables," presented at the Insul. Conduct. Commit. ICC/IEEE-PES—C11D Submarine Cables, St. Petersburg, FL, 2012.

[11] M. Bawart, "Fault location on long submarine power cables and offshore wind farms," presented at the Insul. Conduct. Commit. ICC/IEEE-PES—C11D Submarine Cables, Pittsburgh, PA, 2013.

[12] Operation of Electrical Installations—General Requirements, EN Standard 50110-1, Ed. 2.0, Mar. 2013.

[13] Operation of Electrical Installations—General Requirements, DIN Standard VDE 0105-100, Oct. 2009.

[14] T. Neier, *Cable Fault Location in LV, MV and HV Underground Cable Networks. Practical Experience*. Sulz, Austria: BAUR GmbH, Ed. 1.04, 2009.

[15] IEEE Guide for Bonding Shields and Sheaths of Single-Conductor Power Cables Rated 5 kV Through 500 kV (Revision of IEEE Standard 575-1988), IEEE Standard 575-2014, 2014-06-12.

[16] IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems Rated 5 kV and Above (Revision of IEEE Std 400-2001), IEEE Standard 400-2012, 2012-05-05.

[17] IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF) (less than 1 Hz), IEEE Standard 400.2-2013, 2013-03-08.

[18] Power Cables With Extruded Insulation and Their Accessories for Rated Voltages From 1 kV (Um=1.2 kV) up to 30 kV (Um=36 kV)—Part 2: Cables for Rated Voltages From 6 kV (Um=7.2 kV) up to 30 kV (Um=36 kV), IEC Standard 60502, Ed. 3.0, Feb. 2014.

[19] Power Cables With Extruded Insulation and Their Accessories for Rated Voltages Above 30 kV (Um=36 kV) up to 150 kV (Um=170 kV)—Test Methods and Requirements, IEC Standard 60840, Ed. 4.0, Nov. 2011.

[20] Electric Cables—Tests on Extruded Oversheaths With a Special Protective Function, IEC Standard 60229, Ed. 3.0, Oct. 2007.

[21] C. Lo and C. Furse, "Noise-domain reflectometry for locating wiring faults," *IEEE Trans. Electr. Compat.*, vol. 47, pp. 97–104, 2005.

[22] J. Chesnoy, Ed., *Undersea Fiber Communication Systems*. San Diego, CA: Academic Press, 2002, p.171.

[23] P. Smith, C. Furse, and J. Gunther, "Analysis of spread spectrum time domain reflectometry for wire fault location," *IEEE Sensors J.*, vol. 5, pp. 1469–1478, Dec. 2005.

[24] L. V. Bewley, *Travelling Waves on Transmission Systems*. New York, NY: Dover, 1963.

[25] A. R. Hileman, *Insulation Coordination in Power Systems*. New York, NY: Marcel Dekker, 1999.

[26] A. Greenwood, *Electrical Transients in Power Systems*. New York, NY: Wiley-Interscience, 1991.

[27] E. W. Greenfield, "Transient behaviour of short and long cables," *IEEE Trans. Pow. App. Syst.*, vol. PAS-103, pp. 3193–3203, Nov. 1984.

[28] M. Marzinotto, "Relationship between impinging and stressing overvoltages statistical distributions in power cable lines," in *Proc. 2007 IEEE Pow. Tech.*, 2007, pp. 1911–1916.

[29] M. Marzinotto and C. Mazzetti, "Overvoltage attenuation in power cable lines—A simplified estimation method," *Electr. Power Syst. Res.*, vol. 80, pp. 506–513, May 2010.

Manfred Bawart (M '12), Austrian citizen, is an internationally renowned expert in cable fault location and cable diagnosis. His core competence is based on 30 years of first-hand experience in cable fault location, cable testing, and cable diagnosis. His main interests are focused on continuous innovation in cable fault location and cable diagnosis techniques. He is a member of IEEE-PES and IEEE-SA and is active in several IEEE-ICC WGs as well as Cigre WG B1.52. He has been a speaker at several international conferences and author and coauthor of several publications on cable fault location and cable diagnosis.

Massimo Marzinotto (S '97, M '00, SM '09) received the master's degree and the PhD degree in electrical engineering at "La Sapienza" University of Roma in 2000 and 2006, respectively. From 2001 to 2008 he was with the Electrical Engineering Department at "La Sapienza" University of Roma. Since 2008 he has been with TERNA (the Italian TSO) in the Engineering Department. His main interests are high polymeric materials, power cables, insulators, applied statistics, insulation coordination, and transients. He is a member of IEEE-DEIS, IEEE-PES, EPRI, CIGRE, and CEI (Italian Electrotechnical Committee), and he is active in different IEEE committees and CIGRE WGs. He is EPRI METT (manager of EPRI technology transfer) for TERNA. He is author and coauthor of different international publications on IEEE transactions and conferences and coauthor of the book *Extruded Cables for High Voltage Direct Current Transmission: Advances in Research and Development*, John Wiley-IEEE Press, 2013.

Giovanni Mazzanti (M '04, SM '15) is an associate professor of HV engineering and power quality at the University of Bologna, Italy. His interests are life modeling, reliability, and diagnostics of HV insulation; power quality; renewables; and human exposure to electro-magnetic fields. Since 2009 he has been a consultant of TERNA (the Italian TSO) in the HVDC and HVAC cable systems area. He is a member of IEEE-DEIS, IEEE-PES, and IEEE-SA. He is author and coauthor of more than 240 published papers and coauthor of the book *HVDC Extruded Cable Systems: Advances in Research and Development*, Wiley-IEEE Press, July 2013. He is chair of the IEEE DEIS TC "HVDC Cable Systems" and of the IEEE DEI/SC/HVDC Cable Systems Working Group.