# CHALLENGES AND SAFETY ASPECTS FOR EFFECTIVE FAULT LOCATION ON LONG HVAC AND HVDC CABLES

***Robert Probst[1], Ahmed El-Rasheed[2]***

*[1]Megger Germany Product Management, Baunach, Germany*
*[2]Megger Group Industry Director Renewables, Dover, United Kingdom*

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## Abstract

Long cables are now in the spotlight as a means of power transmission and distribution and are quite crucial both for building the European supergrid and for driving the green energy transition towards renewable generators. As has been unsightly demonstrated repeatedly in recent years, these long cables are much more fragile than expected, and outages caused by cable faults show significant negative impacts on the security of supply and the economics of operating resources. The problem is not expected to diminish given the exponential addition of offshore wind generation worldwide and due to HVDC corridor projects such as Südlink or SüdOstLink. Such cable routes, especially transnational interconnectors, which are mainly HVDC cables, therefore require an approach adapted to the problem. Faults must be measured as quickly as possible so that they can be repaired and reconnected in a timely manner. In contrast to the conventional medium-voltage cables of the distribution networks, however, fault location on long cables cannot utilize the same equipment utility companies and service contractors use on medium-voltage cables.

## 1 Introduction

In contrast to the conventional medium-voltage cables of DSO systems, long HVAC and HVDC cables cannot be treated with conventional fault location equipment from the medium voltage world. They have longer lengths, bigger capacitances, much higher fault voltages, among other differences. Yet, it is still possible to locate faults safely and quickly on HVAC and HVDC cables when using a systematic, heuristic problem-solving approach. This paper reviews real-world results based on applying the right method to the fault identified.

### *1.1. Requirements of cable fault location*

The number one requirement of cable fault location is finding the fault. It must be found safely and quickly. This is especially tricky for HVAC and HVDC cables because they tend to be very long transmission assets.

Very long cables are associated with very high amounts of stored energy and considerable safety risks for personnel and equipment, which must be managed. And, offshore fault locating is especially time-sensitive with involved logistics and generation/transmission losses posing a large financial impact on top of the logistics costs.

### *1.2. Safety Considerations*

Safety is paramount. When working with such HV assets, it is critical to be aware and follow all safety procedures to protect personnel, protect equipment, and continue to manage a productive workflow.

In pursuit of Safety, it is essential to follow all established company work rules and procedures. These include ensuring the Cable is de-energised and earthed before testing. There is a risk of back-feed causing damage to personnel and property if the cable is not de-energised and earthed.

It is also important to be aware of all the sources of hazardous voltages during testing and fault location. The three main sources are the operating voltage of the site, induced voltages that charge the cables, and the test equipment used.

### *1.3. Basics of Fault Location*

Long HV cables are big capacitors, considerable low pass filters, and extremely distributed assets. Therefore, a toolbox approach is essential for fault location. As seen in Fig. 1 long HV cables have several parameters in their equivalent circuit,

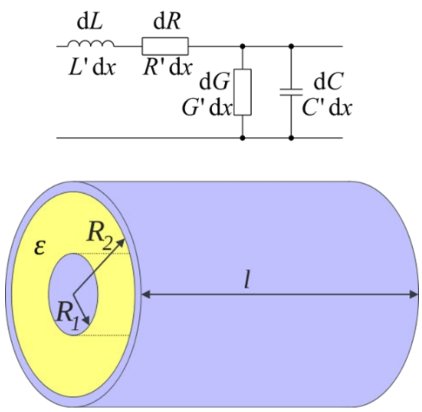


Fig. 1 Cable Parameters and Equivalent Circuit [1]

where cable capacitance, impedance, and velocity of propagation are dictated by the cable's parameters. Equation 1 shows the proportionalities regarding cable capacitance. Equation 2 is cable impedance, and Equation 3 is the cable's velocity of propagation.

Equation 1: $C \sim \varepsilon\,,\ \ell\,,\ \frac{1}{\ln\left(\frac{R_2}{R_1}\right)}$

Equation 2: $Z \sim \sqrt{R' + \mathrm{j}\omega L'}$

Equation 3: $v \sim \frac{1}{\sqrt{\varepsilon}}$

There are four requirements in the process of HV cable fault location. Testing and identification, which are the essential initial assessments of the fault characteristics. Conditioning and Conversion, where, when required, the fault is changed to more favourable characteristics. Pre-location, where the distance to the fault is identified and multiple methods can be used to handle different types of faults. And Pinpointing, where the exact position of the fault is identified.

### *1.4. Testing Locations*

The tests carried out were done on offshore wind turbine platforms, on HVDC marine interconnect cables, and on training centre HVAC and HVDC cables. The tests demonstrate the viability of the testing methods covered.

## 2. Methodology: Fault Locating Techniques

The methodology used has proved adept at locating pinhole faults, low resistance faults, intermittent faults, chargeable faults, and at distances of up to 80 km. The cables tested were single core.

### *2.1. Safety*

There are no short cuts when it comes to safety. And there are five basic rules to follow [2]:

1 Switch off power
2 Lock against reclosure
3 Check that lines and equipment are dead
4 Earth and short circuit phases
5 Cover, partition or screen any adjacent line sections

These five steps help protect personnel from the operating voltage and from induced voltages. Additionally, the test equipment used must have safety precautions inbuilt. This includes but is not limited to:

- Emergency stop to shut down hazardous events
- Status indicator lights to visually signal the Earthing state of the system
- Loop resistance and system Earth monitoring to check for good operational and protective Earth connections
- Mains input protection device installed to prevent damage from surges, overvoltage or undervoltage
- Use of isolation transformers

In addition, it is essential to have a single point Earthing connection. One system Earth is the only true Earth-ground used to avoid Earth loops. An Earth loop is where there are two different connections to Earth and there is a voltage drop between them. This system Earth is the first point of connection between the test equipment and the cable under test. Usually, there are three connections between the cable under test and the test equipment, which are done in sequence of:

1 Test equipment safety Earth connected to the system Earth

2 HV return of the test equipment connected to the return path of shield or concentric

3 HV connection to the conductor of the cable under test

These are the main precautions completed during testing. However, all work safety procedures of each site must be adhered to.

### *2.2. Identification.*

The next step is the check and identification. This is to confirm which cable has the fault as well as identify the type of fault and the minimum voltage that shows the fault. This is normally done with two methods of Insulation Resistance test or Ramped DC Breakdown test

*2.2.1. Insulation Resistance Test:* The Mega-Ohm test is the quickest way to identify a low resistance fault or short in the cable circuit. It is a short duration DC test that provides a pass/fail indication based on the resistance value measured. Also, a cable that cannot hold the Mega-Ohm test charge shows a low resistance fault which is a valuable piece of information.

*2.2.2. Ramped DC Breakdown Test:* This is a DC High-Potential test and can reveal more detail than the Mega-Ohm test. The test lasts less than 60 seconds and involves increasing the applied test voltage up to a level just above the operating voltage. A faulty cable should breakdown before reaching the operating voltage. If the cable does not breakdown, then it might not be the faulty cable.

The other important piece of information from this test is the actual voltage level that reveals the fault. It is imperative and very helpful to know that voltage level because it becomes useful in the next phases of the fault location methodology.

### *2.3. Pre-location*

This stage is about finding the distance to the fault. The toolbox of methods available includes:

- TDR/Cable Radar
- Arc Reflection Methods (ARM, ARM Live Burning, etc.)
- Transient Methods of ICE and Decay
- Complementary Methods like HV Bridge measurement.

*2.3.1. The TDR:* Time Domain Reflectometry works like radar, where a signal is transmitted and the time for its reflection to arrive is measured. A good TDR device will measure several properties such as signal shape, delay, and polarity.

A TDR sends out well-defined transmitter impulses and starts a stopwatch. And, measuring the time delays of returning reflections while analysing their shape, usually utilizing low voltage (LV) high frequency (HF) pulses as transmitter pulse. Local impedance changes in the cable are measured using the known properties associated with the propagation of pulses through the cable to measure.

The TDR pulse propagation requires two parallel metallic conductors. And the impedance measured is a function of cable geometry, while the local impedance changes are proportional to the distance between wires. Finally, a good TDR will visualise impedance as a trace, and displaying key signatures related to distinct irregularities, and applies software algorithms for automatic cable end recognition, denoising, and averaging.

Long cables need special measures for the TDR technique to work, because the long lengths and low pass filter properties attenuate the TDR pulse. As seen in Fig. 2, long cables attenuate as well as disperse TDR signals.

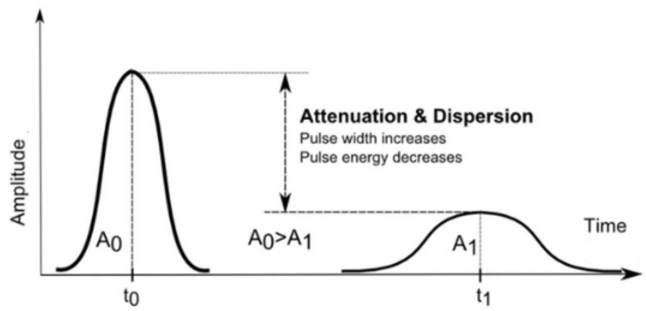

Fig 2 Long cables cause attenuation & dispersion of TDR signal [3]

Therefore, to achieve sufficient long-range performance on transnational submarine interconnectors, the signal-to-noise ratio (SNR) is the most important, dominating quantity since cable radar reflections from the far end of the cable are attenuated to some ten Millivolts while the injected transmitter pulse was in the hundreds of Volts.

TDR for long cables must have de-attenuation technology that can deliver +40 dB dynamic compensation or better to deal with the exponential attenuation of TDR impulses due to the cable behaving like a low pass filter. De-attenuation significantly improves signals which originate far away from the connection point, e.g., the cable end. At the same time, and in contrast to a general Y gain, the signals from the near field remain unaffected for the most part.

Experiences in the field have shown that de-attenuation is an indispensable feature to be able to work effectively on very long onshore and offshore HVAC and HVDC cables. Other applications which benefit from such a feature are cables with many joints as well as cable systems with cross-bonding joints.

Another technique for improving performance is Noise Suppression which is done through a new signal path design and new techniques for interference suppression such as bipolar impulse generation. The TDR injects ± 250 V impulses of 30 µs impulse width into "any" cable impedance without any thermal restrictions regarding repetition rate or duration of continuous operation. This allows for significant De-noising where the TDR sends out a positive transmitter pulse followed by a negative transmitter pulse. Any noise will be averaged out by a subtraction of the two signals, not by an addition.

Signal-to-noise ratio (SNR) can be improved even more, by applying averaging. From field testing, the averaging of 32 bipolar impulses into one averaged block produced good noise suppression. While the averaging into even longer blocks of 64 or more bipolar impulses produced a great amount, but a moving average of several averaged blocks produced the greatest level of noise suppression. Additionally, a pulse compression and autocorrelation technique allowing for Signal Boosting has provided a lot of improvement in the lengths that TDR's can measure.

All these techniques came together to produce a very good TDR measurement of the submarine HVDC cable on North Sea Link, 720 km. Fig. 4 shows the TDR screen of this measurement.

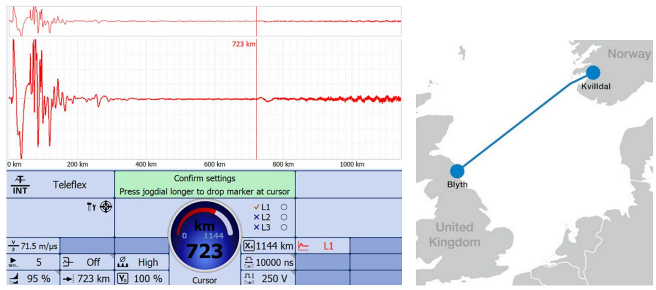

Fig. 3 TDR screen (left) measuring ~720km HVDC of North Sea Link (right)

2.3.2. *Arc Reflection Method (ARM)*: The arc reflection method (ARM) was originally introduced by HDW Elektronik in 1965 [4]. It is an overlay and direct comparison of two distinct TDR traces, one recorded as low voltage reference trace, colour coded in blue in Fig. 5, and another TDR trace recorded as high voltage fault trace, colour coded in dashed red, after the fault has been ignited by capacitor discharge through an arc reflection filter.

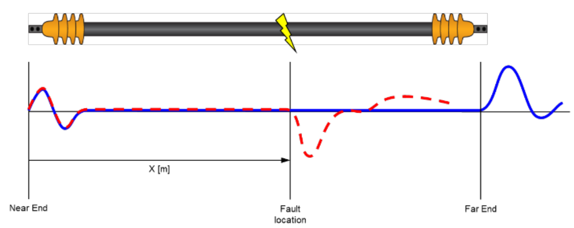

Fig. 4 ARM method showing low voltage TDR trace (blue solid line) and HV trace (red dashed line) superimposed

With offshore and onshore HVAC and HVDC cables, it is preferrable to have a higher voltage output, to be able to handle more high resistance faults directly with ARM and to have enough voltage for handling paper-insulated cable designs.

By experiences in the field, it has become evident that the ability to go up to 50 kV is helpful to successfully find a larger number of high resistance faults on HV cables, specifically in the shallow water zone and the onshore segments.

One innovative change to ARM is the double surge concept, where once the 50 kV stage has been discharged and ignited the fault, an auxiliary capacitor will be switched in, dumping an additional energy of 2000 J at 12 kV into the fault as well. This energy is considerably higher than the remaining and rapidly declining energy associated with the collapsing voltage at the fault. This inductive-active stabilization leads to a favourable behaviour of the arc and produces very clean traces, even on difficult-to-find faults.

Today, ARM is the industry's standard method for solid dielectric cables. However, it is range-limited to approximately 30-40 km due to the bandwidth of the signal coupling circuitry, and the method itself may be challenged by issues regarding arc ignition or difficult fault characteristics.

In those cases, other methods should be applied, such as current decoupling (ICE) or voltage decoupling (Decay).

2.3.3. *Impulse Current Decoupling (ICE):* Impulse current decoupling is a transient HV pre-location method and an alternative to ARM [5]. The TDR visualizes the impulse current component of a travelling wave which is initiated after the fault has been ignited by capacitor discharge, as shown in Fig 6.

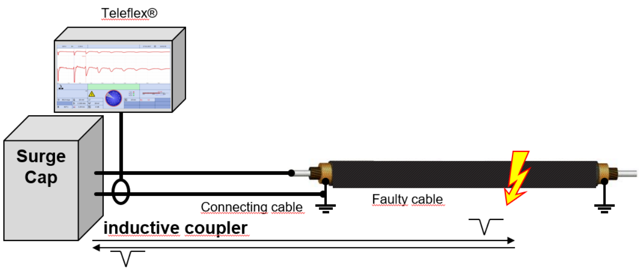


Fig. 5 ICE setup for cable fault pre-location

In brief, the cable under test is not charged and a travelling wave is initiated by capacitor discharge into the uncharged cable under test. The fault location system is configured for obtaining an impulse current trace where the surge generator is set up for single shot release. The TDR is passive, just capturing signals like a transient recorder. There is no arc reflection filter and the coupler to measure the current component of the travelling wave is a current transformer or a Rogowski coil.

Signal oscillates by repeated reflection of the travelling wave between the burning arc at the fault position (low impedance) and the earth point of the surge capacitor (low impedance) inside of the test system until all energy is dissipated. The physical limit for measurable fault distances becomes 80 km maximum.

It is important to remember that the setting for the measurement range $X_R$ should be five to ten times the electrical length of the cable under test to be able to see and not miss parts of the oscillation (not relevant on transnational submarine interconnectors). Also, as a transient pre-location method ICE overestimates distances to the fault by up to 10%. And there is the ionisation time problem that must be monitored. The cable under test is not charged, and the fault might not ignite during the first pass of the surge wave.

The ICE trace contains the distance to the fault as 1 period of the oscillation. The length of the test leads must be subtracted. The first oscillation is typically too poor to be of any use. And manual adjustment is sometimes needed to determine the distance to the fault.

ICE is a useful method for applications like difficult to ignite faults such as PILC/MIND cables, wet XPLE faults, long cables, and to a certain extent faults which are not chargeable.

2.3.4. *Voltage Decoupling (Decay):* Voltage decoupling is a transient HV pre-location method and another alternative to ARM [6].

A TDR visualizes the voltage component of a travelling wave which is initiated after the fault has been ignited by DC charging until breakdown occurs. In brief, the cable under test is not charged and a travelling wave is initiated by DC charging of the cable under test until the fault ignites. The fault location system is configured for obtaining a Decay trace while the DC source (DC hipot) is charging via a DC ramp. The TDR is passive, just capturing signals like a transient recorder, there is no arc reflection filter. And as seen in Fig. 7 the coupler for measuring the current component of the travelling wave is a capacitive voltage divider

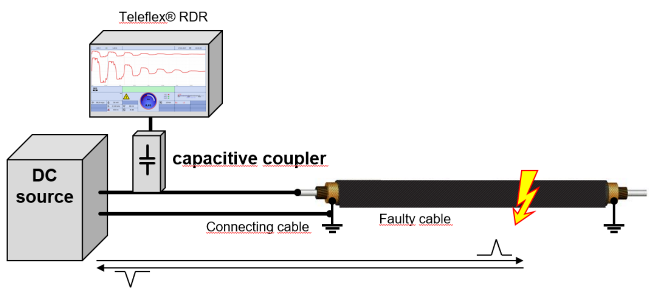


Fig. 6 Decay setup for cable fault pre-location

Oscillation in Decay test is the repeated reflection of the travelling wave between the burning arc at the fault position (low impedance) and the DC source (high impedance) inside of the test system. Oscillation continues until all energy is dissipated. The physical limit for measurable fault distances using Decay is 80 km maximum.

Important things to keep in mind include, setting for the measurement range $X_R$ should be five to ten times the electrical length of the cable under test to be able to see and not miss parts of the oscillation (although it is not relevant on transnational submarine interconnectors). And as a transient pre-location methos Decay overestimates distances to the fault by up to 10%, but it has no issues with ionisation time.

The Decay trace contains the distance to the fault as 1 period of the oscillation divided by 2. The length of the test leads must be subtracted from the trace. And the first oscillation is sometimes too poor to be of any use.

The Decay method is great for locating chargeable faults in general, specifically high resistance faults with a high ignition voltage, but it does not work on non-chargeable faults.

*2.3.5. Fault Conversion by high power burner in conjunction with ARM Live Burning*: The physical limitations of the HV pre-location methods ARM, ICE and Decay is a fault distance of approximately 80 km. There is not a single conventional technique that can obtain workable results beyond this horizon.

An approach to pre-locate faults at distance beyond 80 km is to use a long-range TDR in conjunction with the capability to condition faults to a very low impedance by means of high-power burning.

As a good approximation, a TDR can measure low resistance faults up to 10 times the cable's surge impedance. However, while on MV cables this normally means 300-400 Ω, very long HV cables often have smaller surge impedances. Therefore, an effective fault location system must not only be equipped with an optimized long-range TDR but must also produce sufficient power to change the characteristics of faults below the threshold at which the TDR can actually measure the impedance change and visualize it.

The lower the cable's surge impedance the more difficult it becomes, and the more burning is required to create the proper fault characteristics.

Typical burn-down units in medium-voltage fault locating equipment are too weak to provide the necessary active power into the fault, and are also not designed for more than a few 10 min of intense duty.

*Fig. 7 Heavy duty burn transformer* 40 kV DC, P = 20 kW, capable of for 24/7 duty, S = 80 kVA.

ARM Live Burning is one of the most versatile and most beneficial pre-location technologies for difficult faults and HV cables. Instead of igniting the fault with the capacitor discharge unit (surge generator), the heavy duty burn transformer (see Fig. 8) charges the cable until a breakdown occurs and an arc is forming. The burner will not be stopped but it will keep going to stabilize the arc. At the same time the TDR is continuously coupled in, via a special separation device, so that a continuous live arc reflection measurement can be recorded. The impedance change can be observed live by the operator. As soon as the characteristic low impedance signature of a fault is identified then the trace is frozen, the distance to the fault is determined, and the burner is stopped.

ARM Live Burning is therefore suitable on wet faults, paper cables, oil cables, subsea cables, and faults which are generally very difficult to ignite and to stabilize.

## *2.4. Pinpointing*

Pinpointing is still necessary after all the pre-location (using TDR, ARM, ICE, etc..), because it is difficult to accurately identify velocity of propagation, the cable path and depth. Therefore, a more accurate technique for fine tuning the fault location is necessary after the pre-location work.

Pinpointing on onshore and offshore HVAC and HVDC cables is a much bigger challenge than pinpointing on typical medium-voltage distribution-type cables. Problems are often directly related to logistics and the installation itself, for example, concrete joint vaults buried under several meters of soil, or offshore cables covered by mud or sand in the shallow water zone near to the shore.

Experiences have shown that a high voltage surge generator with a voltage of 100 kV can be very useful for successful pinpointing on HV cables. High surge voltages make it possible to ignite faults with a high breakdown voltage, and therefore provide another method for users in case breakdown voltages exceed 50 kV.

A high surge energy of 4000 J facilitates magnetic-acoustic pinpointing via a pinpointing system. In these tests a single-stage surge extensions of 100 kV with 4000 J was used.

All this energy is necessary because pinpointing is done by the coincidence method, correlating magnetic pulses to sound waves. The method can be thought of as a "thunder and lightning" metaphor. It is necessary to create a big enough arc to create both an audible and electromagnetic effect at the fault location. The "sound" and "light" generated allows for precise pinpointing of the fault location by coinciding them.

In pinpointing the physical quantity measured is time in milliseconds. The pinpointing device has two channels with one measuring electromagnetic pulses and the other measuring acoustic pulses. The time delay between the pulses is the indication of distance to the fault. When the time difference is at its shortest, then the fault is directly beneath that point. This system works for deep-water as well as conduit covered cables.

## 3. Conclusion

The information presented is a summary of the latest testing technique developments that brought fast accurate fault locations on HVDC and HVAC cables. It is built on known procedures and methods but modified for use with long HV cables. The difficulty with fault location on long HV cables demands a review of the process. This successful methodology, presented, has four phases of Safety precautions, Identification testing, fault pre-location, and pinpointing.

Safety is paramount and critical with such enormous discharge potential from the cables and the test equipment which may be equivalent to a considerable amount of TNT explosive. It is vital to take all precautions to keep personnel safe and equipment protected. Finding a way to ensure safety while maintaining a productive workflow is necessary to find cable faults safely and quickly. Speed is needed because of the power loss impact from HV cable faults, but not at the cost of safety.

Identification testing is crucial for ensuring that the faulty cable is the one that is worked on. This testing is relatively simple and quick, but highly important. Successful identification provides confirmation of a fault on a cable as well as the voltage level that the cable fails at. This piece of information allows setting of the equipment for the next phase.

Fault pre-location is a well know activity in MV cable work, but it must be modified for long HV cables. The popular ARM technique must be used at higher voltages of 50 kV, and its filter technology must be inductive to utilize its maximum physically possible range of about 40 km. Resistive ARM filters lead to poor results. Although the higher voltage helps improve the usefulness of ARM, it is still limited. The methods of ICE and Decay allow for an increased pre-location distance of up to 80 km. This is a significant improvement. Moreover, another very useful method in the fault locating toolbox is ARM Live Burning, in contrast to ARM, ICE and Decay a continuous pre-location method. It is able to deal with difficult to ignite and difficult to stabilize faults, as well as tricky intermittent faults. Lastly, fault conversion using a high-power burner equipment in conjunction with the direct TDR method provides an even greater range for pre-location and is the only approach capable of exceeding fault distances of 80 km.

Pinpointing is done with the popular magnetic-acoustic method coincidence but modified for HV cables. The modification described allows for using this method on deep-water and conduit covered cables.

Overall, fault location on long HVDC and HVAC cables is a challenge, but it can be met with innovative modification of well-known techniques, and dedicated, specialized HV fault location equipment that should be part of the planning considerations of any long cable project right from the start.

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