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A Deeper Insight into Fault Location on Long Submarine Power Cables

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SUMMARY

This paper provides a deep insight into fault location on long Submarine Power Cables.
Several field results on submarine power cable faults are provided.
For land cables the main focus is on the electrical and thermal design of cable insulation and on the electro-thermal and thermo-mechanical design of cable accessories, in order to grant sufficient endurance performances and reliability to the whole cable systems [1]. In submarine cables more issues arise, some related to the harsh laying environment, some others – even more troublesome – associated with man-made activities. Indeed, on the one hand submarine power cables are subject to strong mechanical stresses during the laying operations and critical service conditions in their working ambience. On the other hand, submarine cables are continuously exposed in all water depth to random mechanical damages caused by fishing gears, anchors and natural hazards [2,3].
The longer the expected life and the longer the path of the submarine cable link, the higher is the probability of facing one or more faults due to human activities. Based on surveys about submarine cable failure data recorded worldwide over long periods, it can be concluded that the probability of experiencing at least one fault during lifetime is close to certainty for long submarine links. Statistically most damages to submarine cables are caused by human activities; only a low percentage is caused by natural hazards.
Based on growing energy demand and dependency on offshore produced renewable energy, submarine power cables become essential for reliable electric power supply and often can be classified as critical infrastructure [4].
Repair of damaged submarine power cables requires specialized ships as well as experts to recover the cable from the sea bed and replace the faulty cable section. Another critical aspect associated with long submarine cables is that, whenever a fault occurs, a fairly long time is spent for repair. For this reason, fast and efficient fault detection is essential in order to reduce the overall outage time as much as possible.
All these aspects are discussed in this paper. The best practice commonly employed for classifying submarine power cable fault types are included in the paper, together with the results of measurements carried out in the field.
The paper points out that fault location on submarine power cables differs by much from classical cable fault location on buried land cables as to both conditions and measuring methods, thereby illustrating the most efficient cable fault location methods. Some field results on submarine power cable faults are provided, measured on AC submarine cables as well as on HVDC submarine links.

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A unique case study of fault location on longest HVDC Submarine Link will illustrate TDR based measurements on cable lengths above 400km. The case studies further focus on TDR diagram analysis in order to explain how to identify cable joints.
The results prove that the overall outage time for repair activities can drop significantly if the fault location system is peculiarly designed for detecting faults in very long submarine cables with a good measuring accuracy.
The hazards for operators and instruments connected to the huge amount of electrical energy that may be stored in very long links are also tackled in the paper, thereby addressing the particular safety issues involved by extra-long submarine cables.

KEYWORDS
Submarine power cables
Cable fault location
Long HVDC Cable
Long length power cable
TDR on long power cables
Murray Bridge Method
Offshore wind park submarine cable
Wet type low resistance fault
High resistance cable fault
Dry type flashing fault, intermittent fault
Cable joint detection

INTRODUCTION

Developments of long submarine cable links are strongly motivated by today´s growing demand on electrical energy. The growth in energy demand requires fundamental re-engineering of the electrical grid structure for availability of electric energy, secure power supply, balance of peak power consumption as well as linking low cost energy production sites to regions with high electric energy consumption.
Especially investments in technical infrastructures for linking international electric grids and the drive towards sustainable use of renewable energy generated by offshore wind parks lead to investment in long submarine cables. With growing reliance on offshore based renewable energy, submarine power cables become more important for the power infrastructure.
Likewise the demand for electric power supply of oil and gas production platforms increases.
For protection against external damages the submarine cables are usually buried into the sea bed [3,4,5]. Submarine power cables are designed to withstand extreme conditions for very long periods of time.
Despite the mechanical precaution against damage and the reinforced cable armoring, cable faults on submarine cables may occur during operation causing expensive power outages. Cable faults on submarine cables are mostly caused by human activities. Even the most robust designs can't always survive the natural and manmade mechanical forces present. Ship anchors, fishing gear and dredging are common causes as emphasized in Table1 [6.] Submarine cables are also exposed to a range of natural hazards in all water depths and these include submarine earthquakes, submarine landslides, seabed erosion, turbidity currents, current waves, hurricanes, volcanic activity free hanging cable sections, fish and mammal bites (e.g. sharks) and others natural hazards.[3,4].

Table1. Submarine cable fault distribution [6]

Cause	Pre 2007	2007 - 2008
Fishing	67%	33%
Anchors	8%	48%
Dredging	2%	0%
Other	23%	19%

FAULT LOCATION ON LONG SUBMARINE CABLES

Statistically the amount of cable faults increases by the number of installed submarine cables.
A cable fault once appears then paralyzes the entire energy transport in the submarine cable. Often the required electrical energy cannot be substituted by other available energy sources or alternative supply routes, and thereby creating a difficult task for the Transmission System Operator (TSO). Once a submarine cable fault occurs the time to find and repair the fault is critical.

Fast response and efficient fault location based on available and well proven fault location equipment can be applied on buried land cables of short length.

On the contrary a cable fault on a submarine cable confronts the TSO with a difficult task.

Based on standard fault location equipment and standard operator´s knowledge cable faults on submarine cables are difficult - and often unfeasible - to locate.

Especially faults on long cable length may cause unsolvable problems. In particular it has to be understood that cable faults on submarine cable are inaccessible.

Short and medium-length submarine power cables are designed as AC cable systems.

For transport of large energy amounts over long distance HVDC systems are required. Therefore long power cables are designed as HVDC link.

Cable fault location on long and extra-long cables is a particular challenge. On long submarine cables most of the commonly used measuring methods developed for application on short cable distance of buried land cables do not lead to success.

A submarine cable typically consists of a number of sections, starting from a HV termination connected to a HV land cable from there connected with a special transition joint to a submarine cable. Depending on cable length and laying depth the submarine cable may consist of different sections and the cable design may change passing from shallow water to deep water. On the far end the submarine cable is commonly connected to a land cable with HV termination.

Experience has confirmed that once a cable fault occurs, most probably the fault appears in the submarine cable section and to a lower percentage in the land section.

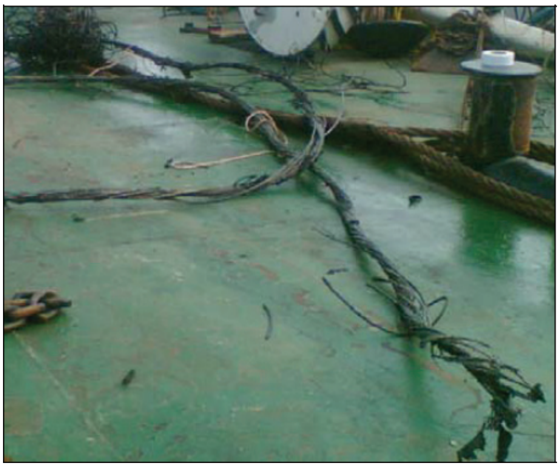

Fig.1. Typical result of anchor damage to a submarine cable [6]

The damage to a submarine cable by an anchor can be evidenced over an extended length of cable. The point of contact can usually be lacalised by a typical deformation of the armour wires but the strain induced can cause damages hundreds of meters in both directions. The typical result of anchor damage to a submarine cable is shown in Fig.1 [6].

CABLE FAULT LOCATION METHODS AND APPLICATION

Conditions and methods for cable fault location on submarine power cables differ heavily from classical cable fault location on buried land cables.

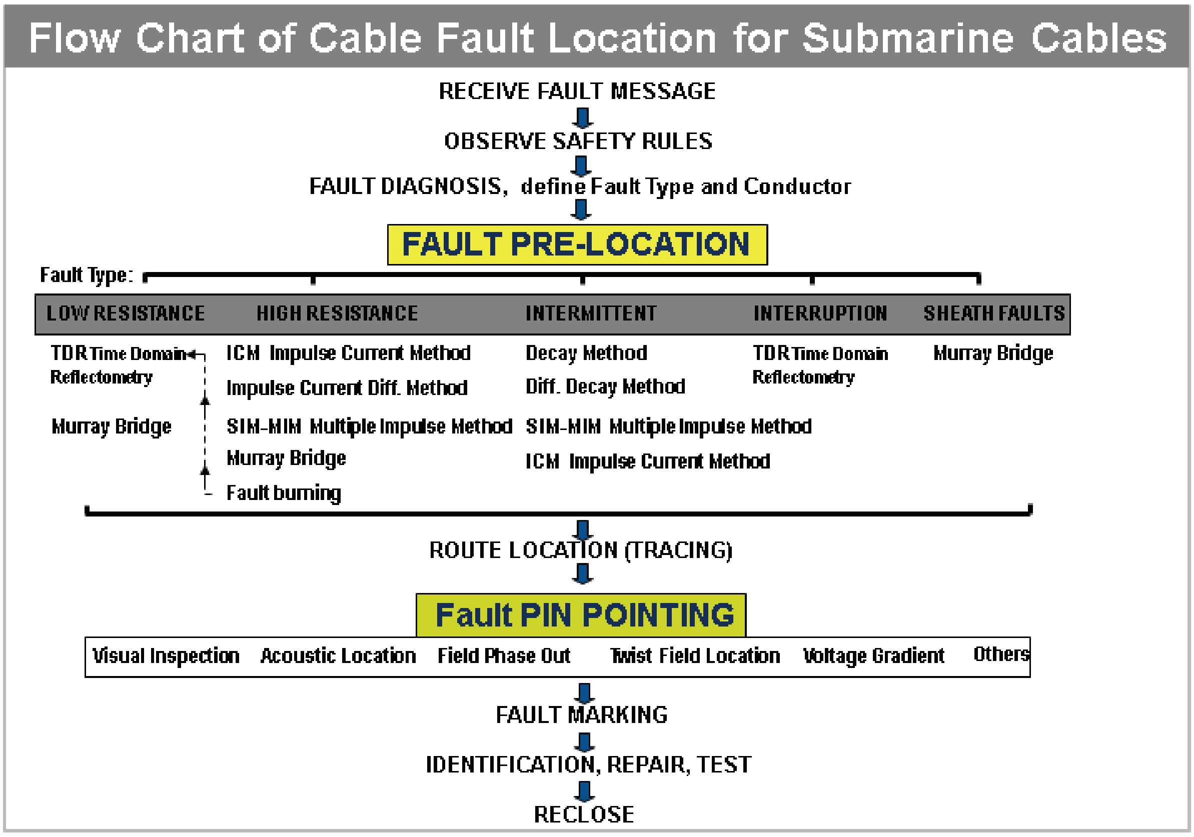

Fig.2. Flow chart of cable fault location for submarine cables [2]

CABLE FAULT LOCATION METHODS AND APPLICATION

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Wet Type Low Resistance Faults

Often the cable fault is caused by an external mechanical damage that allows water ingress and thereby leads to an insulation fault.

Especially ingress of salt water facilitates, due to its high conductivity, the fault location process.

Depending on type of cable fault, specific fault location methods can be applied which are listed in Fig.2.

For this characteristic type of cable fault the classic Time Domain Reflectometry (TDR), (see Fig 3) as well as the Murray Measuring Bridge Method can be applied.

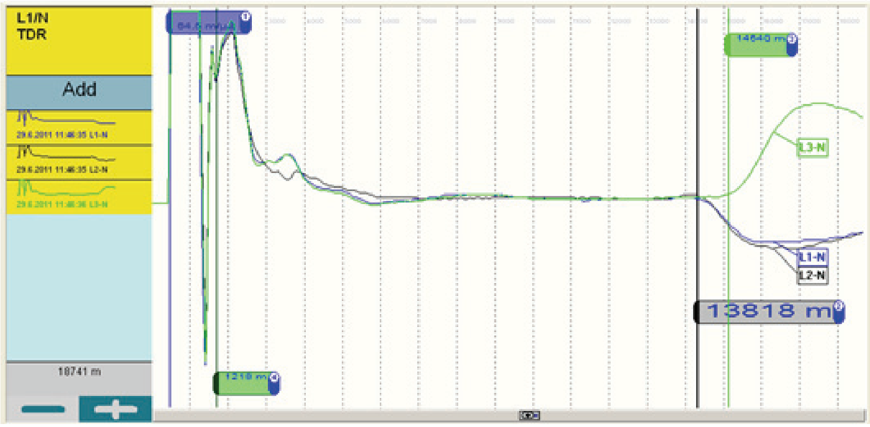

Fig.3. TDR trace of an AC submarine cable, Italy Main Land -Ischia [2]

Particularly long cables tend to attenuate the TDR pulse heavily.
On long and extra long cables special high performance TDR are applied and provide best technical features to overcome the high pulse attenuation and thereby allows successful detection and distance measurement of a low resistance cable fault, as well as identification and distance measurement of cable joints and cable end.

One of worlds earliest laid HV DC submarine cable, installed between Italy-Tuscany and the Island Corsica commissioned in 1967(SACOI Intertie), faced during its long life time several damages due to ship anchors and fishing gears. The actual TDR case study indicates several repair joints in the Tuscany shallow water zone (Fig.4).

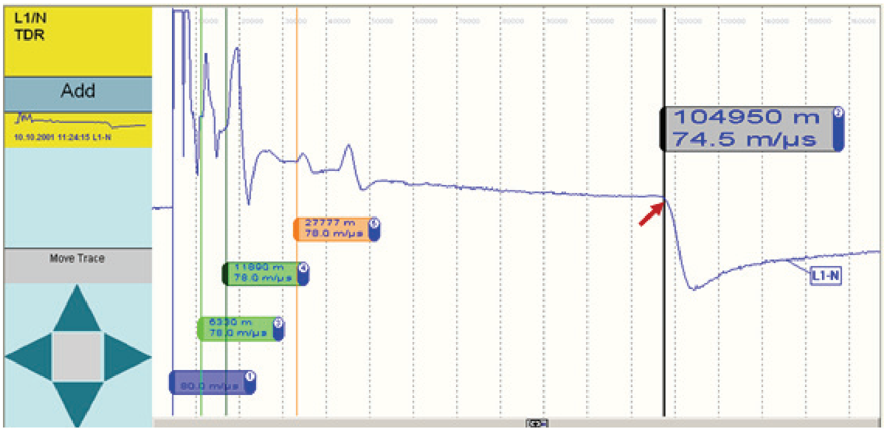

Fig.4. TDR trace of a long HVDC submarine cable,
SA.CO.I (SArdinia - COrsica - Italy Intertie) Total cable length between Italy mainland to Corsica about 105km, length of Submarine cable section 102km [7]

The negative pulse reflection at 104950m relates to the safety short circuit at the cable end. For accurate measurements the TDR needs to be calibrated to its known cable length. Thereby the pulse propagation (V/2) will be aligned to match the exact cable length. It is highly recommended to store this TDR graphics with its corresponding pulse propagation as a TDR Fingerprint.

The unique case study (Fig.5) on world's longest 500kV HVDC link (SAPEI) installed between Italy and the Island Sardinia, proves the capability to apply TDR on an extremely long cable of 442km. The TDR trace clearly and accurately indicates the positive pulse reflection at 442032m caused by the open circuit cable end.

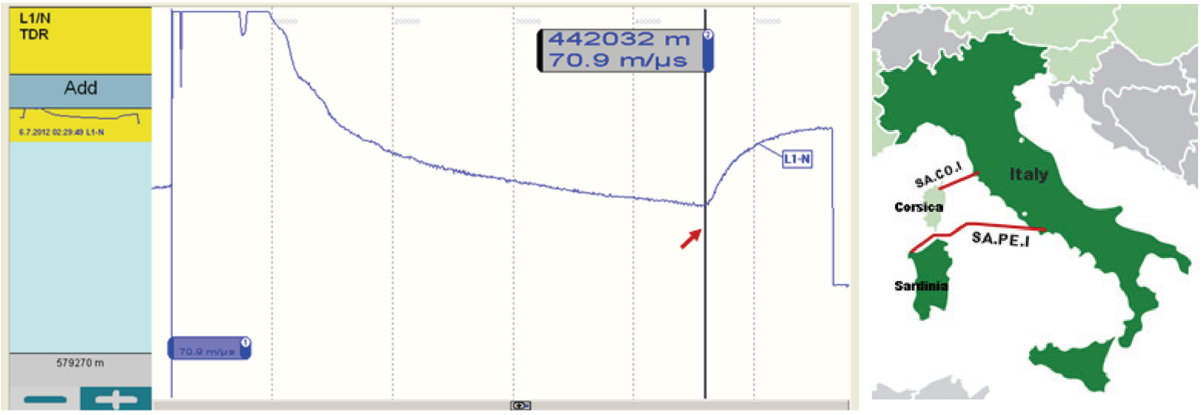

Fig.5. TDR trace shows open circuit on a long HVDC submarine cable 442km SAPEI (SArdinia - Peninsula - Italy) [2].

On the contrary high resistance cable faults cannot be detected by use of a TDR. There a powerful burner is used to convert the high resistance cable fault into a low resistance fault which then allows location by TDR. Cable fault burning is quite easy to use on cables with laminated paper-oil insulation, while the application is limited on extruded cable insulation.

Constant High Resistance Faults

Non convertible high resistance faults can only be measured by application of a dedicated high voltage Measuring Bridge according to Murray Method (Fig.6). The Murray Bridge method is based on a modified Wheatstone Bridge Circuit evaluating the proportion of conductor length resistance from cable section prior to fault, comparing the conductor length resistance past the fault including return line. The provided measuring result is indicated in percent (%) of cable length and can easily be converted in meters as the total cable length is known. A change of core cross section or of conductor material type along the submarine cable needs to be considered carefully for accurate fault distance evaluation. Once this data are carefully entered into the menu of a Murray Measuring Bridge, a typical measuring accuracy better than 1 % of cable length can be reached.

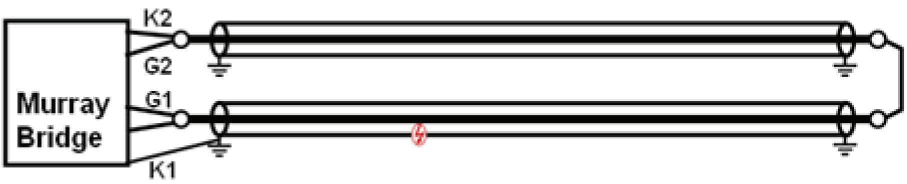

Fig.6. Murray Bridge connection diagram

Fig.7. Murray Bridge, Method application on NORNED HV DC Link 580km [2]

Murray Bridge Method requires a healthy return line. Murray Bridge Method is applicable for low resistance fault type as well as for resistive faults. Special units powered by an internal HV source can be applied to locate high resistance faults up to a range of 10 MOhm.

Dry Type Flashing Faults, Intermittent Faults

Dry type flashing faults, also called intermittent faults, are not common on submarine cable, but if they appear, they cannot be detected and located by TDR and Murray Measuring Bridge.

This fault type may occasionally occur on internal insulation defects of a submarine cable as well as in joints and terminations and also in the land cable section.

Most of the commonly used measuring methods traditionally applied on buried land cables will find severe restriction when applied on long submarine cables.

Traditional fault location methods like Secondary Impulse Method (SIM), Multiple Impulse Method (MIM), Arc Reflection Method (ARM) and Impulse Current Method (ICM) used for fault location on high resistance and intermittent faults are limited to short cable length up to a few km.

Special high voltage fault location systems are required for location of intermittent faults on long and extra long submarine cables. There the Decay Method (Fig.8) and the Differential Decay Method offer best performance [2].

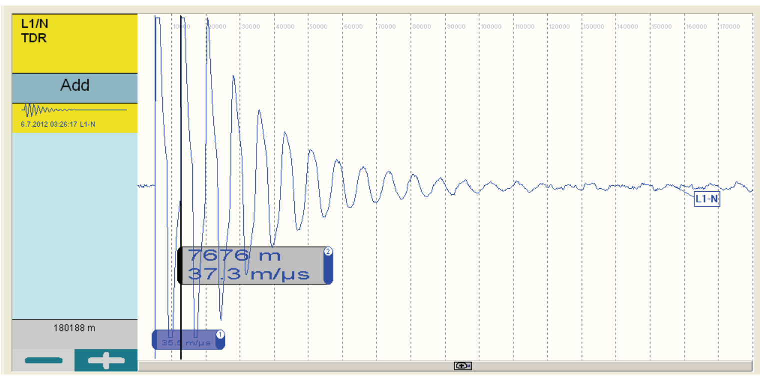

Fig.8. Decay Method, applied on long submarine cable

Route Tracing and Pin Pointing:

Nowadays detailed cartographic records are available from all main submarine cable installations allowing the repair vessel to follow the cable all along the laying route. The on board navigation system guides the repair vessel along the cable run until the fault place is approximately reached, accepting a reasonable tolerance due to various factors like accuracy of the fault distance measurement, on board navigation and accuracy of cartographic records.

From fault prelocation the distance to the fault is known and the repair crew will check on their records the estimated depth of the laid cable. Cables in shallow water are then recovered from sea bed by the repair vessel. Application of audio frequency field detection can support the cable route tracing. Thereby a transmitter is connected to the cable end and induces a magnetic AC signal all along the cable. A dedicated signal pick up coil and its receiver on a search vessel can pick up the signal and follow the submarine cable all the way long. Further on this method often allows detecting the fault position by field phase out of the AF signal.

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Cable Recovery and Repair:

Cable repair in offshore zone is known to be very time consuming and may take several weeks depending on location, weather conditions, cable laying depth, availability on a spare cable and jointing material, availability of a cable repair vessel with experienced repair crew and required permission from a costal state.

In shallow water the cable can be picked up by ROV from sand or mud. Subsequently the cable will be lift up by crane and guided over the repair vessel stern sheaves.

Once available on the vessel, the submarine cable is accessible to the repair crew for visually inspecting the cable surface in order to detect the mechanical damage. During visual inspection process the repair vessel needs to be moved backward and forward until fault spot is recognized. A Surge Generator may help to indicate the exact fault spot by acoustic location.

If the fault cannot be recognized the cable needs to be fastened on the vessel before cut. A TDR is used to determine the exact distance from cable cut to the close-by fault. The fault spot will then be replaced by a few hundred meter new cable, depending on laying depth, water ingress on fault into the cable and severity of further mechanical damages along the cable. Submarine repair joints are used to link the new cable section. Subsequently the repair crew will gently return the submarine cable back to the sea bed.

Cable recovery from deep water zone is a challenging and expensive undertaking as often Submarine cables cannot be recovered from deep water zone in order to avoid mechanical overstress. In this case the cable will be cut by a ROV down at the sea bed and the cable end recovered by a crane. The cable will be cut back and connected to a repair cable. Then the other cable end will be recovered, cut back and reconnected to the repair cable [5].

Significant higher repair time and costs are considered if the submarine cable cannot be picked up from deep water zone. In this case the cable lift-up takes place in the shallow water zone and rolled up over the cable vessel stern sheaves all along the cable until the fault spot is reached.

In case the fault is on the land cable section it is easy accessible for the repair crew.

SAFETY AND SAFETY MEASURES

Highest priority should be set for safety of the operator and safety design of equipment.
Especial safety precaution must be set for the operator and his crew, as he has to act in high voltage ambience. He needs clear safety rules and also full information for control of the cable system and the related switching and grounding. Surely to be considered the operator and his crew need to connect and operate high voltage equipment for fault finding.
Cable terminations of HV submarine cables links are designed for their rated voltage and often reach a dizzying height of 5 to 10m altitude above ground: the fault location equipment needs to be connected at this altitude. Fault location on submarine cables is complicate and often requires the operator to follow a test sequence of several measurement methods and also sequential reconnection of testing instruments. Reconnecting the individual fault location devices at this altitude is difficult and should be considered as a specific safety risk for the crew.
Special fault location systems with central control for easy instrument selection and single HV test lead without risky reconnection in dizzying altitude have been developed to provide highest safety for the operator (see Fig 9).

Fig. 9) SAPEI HV Hall, test lead connection at 9m height

Important information to be observed for long and extra-long submarine cables are as follows: When operated for HV withstand testing and for fault location on intermittent faults, the long submarine cable will be charged with high voltage, then the cable acts as a HV capacitor and stores the charged energy. The stored energy can reach extremely high and risky levels.

As an example, let us consider a cable length L=442km, yielding a cable capacitance C=150µF. Then the following energy will be stored in the cable when charged at U_{DC}=32 kV:
$Q = C (U_{DC})^2/2 = 150\ \mu F \times (32000\ V)^2/2 = 76800\ W\,s = 76.8\ kJ$

The stored energy at U_{DC}=100 kV reaches the extremely hazardous value of 750 kJ!

Common available cable fault location equipment is designed neither to cope with such extraordinary high energy levels, nor for safe discharge of such high energy. Moreover, common available equipment is not safe to cope with transients waves of such high energy content.
The Transmission System Operator is responsible for the safety of his crew and the authors may advice considering the above mentioned safety issues including safe discharge of high discharge energy and protection against transient waves.

CONCLUSIONS

The paper summarizes the main fault location techniques that can be used for cable fault location in long submarine cables depending on the various types of faults. It is shown that advanced instruments, detecting techniques and skilled crew are required in order that the detection can be effective in the various cable fault conditions.

Measurements performed in field shows that a fault location system especially designed for very long cables can detect faults with a good error accuracy helping in this way to reduce the outage time for repair activities.

The hazards for operators and instruments connected to the huge amount of electrical energy that may be stored in very long links are also tackled in the paper, thereby addressing the particular safety issues involved by extra-long submarine cables as extra long submarine cables may store a tremendous amount of electrical energy that can cause high risk for operator and instruments.

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