DAMAGE LOCATING OF 6-500 kV CABLES IN POLYMER PIPES

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In the previous issue of the magazine was published an article, which considered the difficulties that arise when testing cable lines laid in polymer pipes. The new article is designed to develop the topic and is devoted to the cable damage locating. It should be noted that the damage locating and related problems are so important that in September 2019, the international Council of CIGRE devoted to them a whole technical brochure No. 773, numbering 152 pages.

Keywords: cable line, cross-linked polyethylene, cable screen, outer sheath, sheath testing, damage locating, fault locating

INTRODUCTION

A large number of different designs of high-voltage cables are known in the world. According to the type of current, there are cables for transmitting electrical power by alternating current (AC) and cables for transmitting electrical power by direct current (DC). According to the number of current-carrying cores of the AC cable, they are subdivided into three-phase cables and three-phase groups of single-core cables. According to the type of cable insulation, cables with solid insulation (cross-linked polyethylene XLPE, ethylene propylene rubber EPR) and cables with paper-oil insulation (oil impregnation, low-pressure oil, high-pressure oil) are widely known.

On the cable route, there may be sections laid by one or another of the methods:

- above the ground on various structures;
- in the ground (directly in the ground or in pipes);
- along the bottom of reservoirs (in the bottom soil or in pipes).

The causes of cable line damages are very diverse:

- manufacturing defect;
- careless installation;
- poor-quality repairs;
- unsuccessful cable or cable coupling (joint, termination) design;
- route design errors;
- mechanical damage;
- other factors.

Cable damage can be single or multi-place. Each of the cable damages can have a low or high transient resistance, and therefore they are called, respectively, low-resistance or high-resistance (more than 100 ohms). Unstable damage is also possible, having an arc character or having a "floating" character (when the cable is capable of self-healing for a certain period of time, after which the damage re-manifests itself).

Damages can be longitudinal (breakage of the cable core, screen, entire cable) and transverse (violation of the main insulation of the cable or its outer sheath). For transverse, both damage between phases and damage to the ground are possible. From the point of view of the place of damage occurrence, there are:

– directly in the cable;
– in the cable coupling (joint or termination);
– in additional equipment (for example, in a cable screen link-box).

The listed variety of cable designs, their laying conditions and types of damage suggests that locating a specific place of cable damage is a serious task, for which there can hardly be any one universal method. At the same time, the timing of the repair of the line and the restoration of its normal operation, as well as the amount of water that has managed to penetrate the cable insulation from the external environment and can cause new accidents in the future, depend on the speed and accuracy of locating the place of damage. Considering the above, one should not be surprised at the increased attention of the scientific community and practical engineers to the damage locating topic. In particular, in September 2019, the International Council of CIGRE published a technical brochure [1], in which it considered almost all the main known ways to find and locate places of cable line damages.

Since the number of 6-500 kV cables laid in polymer pipes has grown significantly in recent years, the applicability of known methods of locating damage places to such changed cable placement conditions is of interest. In the new CIGRE brochure, a separate paragraph 3.7.1 is devoted to pipe cases, which indicates that modern polymer pipes prevent the search for cable outer sheath damage, since they do not allow the test current to escape from the cable into the ground (to ensure the possibility of locating, it is necessary to open the pipes and divide their sections). As for cable main insulation damage, even here the pipes interfere with the locating procedure, for example, if we are talking about locating using the acoustic method (see paragraph 2.4.2 of the SIGRE brochure [1]). Thus, the problems with pipes, which are described in detail in the article [2], really deserve attention. It is quite possible that a clear awareness of the existence of these problems will serve as an impetus for the emergence of new methods of cable damage locating that can complement the already wide range of devices and equipment available on the market.

Let's consider the main ways of cable damage locating mentioned in [1], and explain which of them will not be able to work effectively in the case when the damage occurred on the pipe section.

LOCATING THE CABLE DAMAGE

The locating procedure of cable damage place can be divided into two main stages: preliminary locating and accurate locating. A preliminary locating allows you to determine with an error of up to several tens of meters the problematic section of the route, where you should send a stuff to perform an already accurate locating for the place where the damage occurred and where excavation and repair work is to be carried out.

Preliminary locating is carried out on a line that has been taken out of operation, by attaching to the cable core special equipment implementing a particular locating method. Most often, it is enough to connect only to one of the cable ends, however, in some cases, to increase accuracy or for other reasons, it may be necessary to repeat the procedure by attaching equipment also at the opposite line end. As for the accurate locating, it involves the arriving of specialists to the route section indicated by the preliminary locating, and the well-coordinated joint work of people on the route and people remaining at the ends of the cable and responsible for the locating equipment connected there to the cable.

The cores of 6-500 kV cables usually have a significant cross-section, and therefore breakage is a rare event and is rather typical for cases of marine laying, where the danger comes from anchors. Thus, it should not be surprising that not all methods are suitable for core locating. Most damages – are either the main insulation or the outer sheath. Consider first the damage of the main insulation of the cable, and then – of the sheath.

PRELIMINARY LOCATING

The most well-known preliminary methods for locating the cable main insulation damage according to [1] are:

– wave method;
– pulse-wave method;
– oscillatory discharge method;
– bridge method.

The wave method (Time Domain Reflectometry, TDR), like many other methods of preliminary locating, is based on the theory of wave processes in a cable having a given wave resistance Z_C and wave propagation velocity V_C. At the end of the cable, a waves generator is connected to it, which propagate along the core and are reflected from places where there is some kind of heterogeneity (Fig.1). The reflection of waves occurs according to a well-known law:

– if the resistance in the path of the wave exceeds Z_C (the end of the cable or its breakage), then the wave is reflected with the same sign (Fig.1a, Fig.1b);
– if the resistance in the path of the wave is less than Z_C (low resistance damage), then the wave is reflected with the opposite sign (Fig.1c).

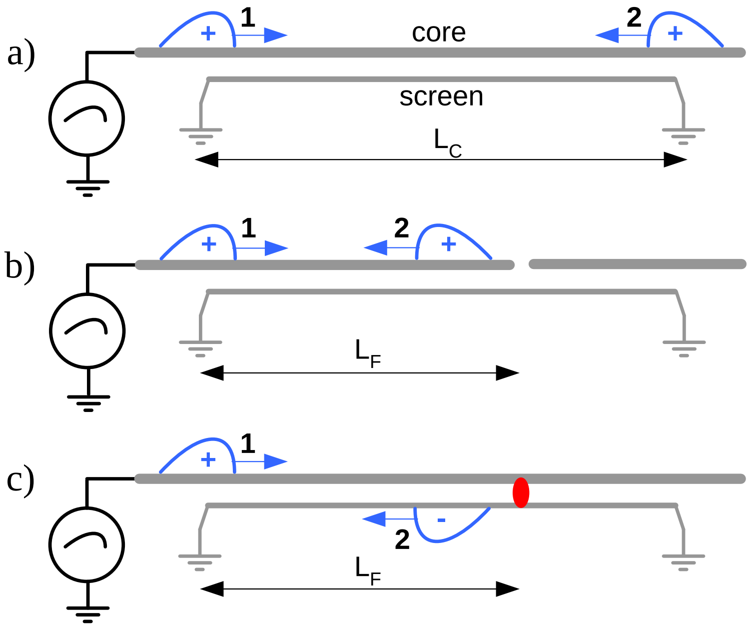

Fig.1. Wave method of damage locating:
a) cable without damage;
b) cable with a core breakage;
c) cable with insulation damage

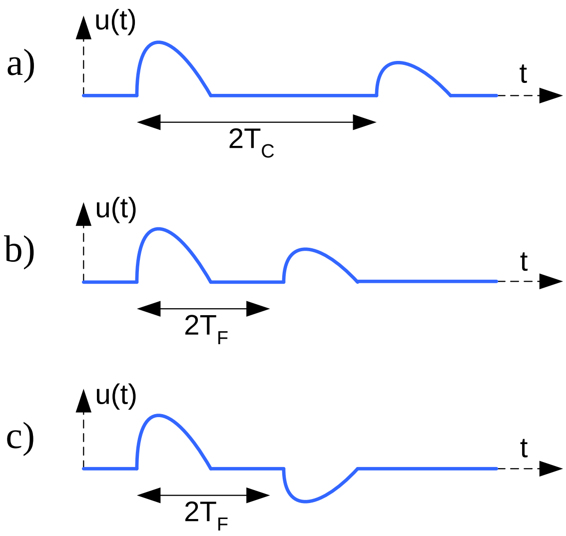

Fig.2. Oscillograms of wave method:
a) cable without damage;
b) cable with a core breakage;
c) cable with insulation damage

By the nature of the waveforms that are fixed at the connection point of the wave generator, it is possible to determine the type of damage (Fig.2). The distance to damage (to fault) L_F can be found by the time interval between neighboring oscillations, which is visible on the oscillogram. This time interval is equal to the sum of the T_F time of the wave run from the generator to the damage place and the T_F time of the wave return back. Having received $2T_F$ from the oscillogram and thus determining the T_F further, knowing the speed of the V_C wave, the distance to the damage place can be calculated as $L_F = T_F \cdot V_C$.

Unfortunately, as the waves propagate along the cable, they deform and attenuate. Also, some wave reflections occur at the location of the cable joints. All this requires certain qualifications from specialists in order to correctly interpret the waveforms and at least approximately find the distance L_F to the damage (to the fault). The use of the wave method for preliminary locating, rather than the accurate one, is also due to the fact that, as a rule, the speed V_C of wave propagation along the cable is known only with an error of up to 5-10%.

High-resistance cable damages are not capable of causing noticeable waves reflection or refraction, and therefore they are difficult to detect using the wave method. In this case, before using the wave method, it is recommended to transfer this damage from high-resistance to low-resistance, which can be done by burning (Burn down technique). The burning is carried out in several stages – at the first stage, an increased DC voltage is applied to the cable, leading to a breakdown of the damaged insulation. At the next stage of burning, it is no longer the voltage that is controlled, but the current, by the thermal action of which the insulation is burned. As the resistance decreases at the place of cable insulation damage, a lower source voltage is required to maintain the current (Fig.3).

It is important to note that according to paragraph 2.3.3 of the SIGRE brochure [1], insulation burning can be used for cables with oil insulation, and its use is not recommended for cables with XLPE insulation, since it can lead to a significant increase in the size of the damage place. Therefore, a special pulse burn has been developed for the XLPE insulation, implemented in the pulse-wave method of damage locating.

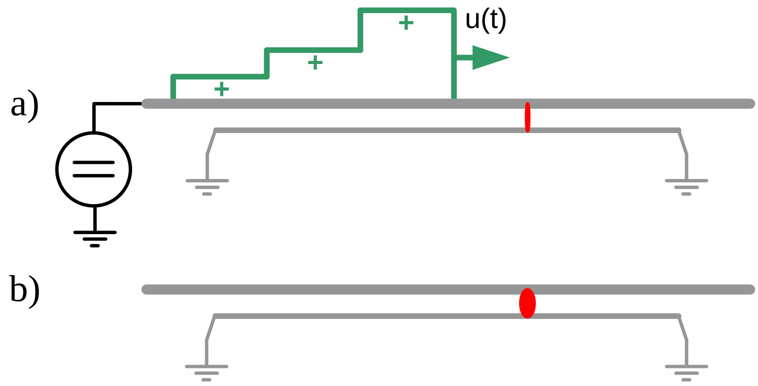

Fig.3. Burning method:
a) impact on high-resistance damage;
b) the transition of damage to low-resistance

The pulse-wave method (Arc Reflection Method, ARM), also called the electric arc stabilization method, can be considered some combination of the burning procedure and the wave method. This method is specially designed for XLPE insulation and consists in the following: a generator connected at one end of the cable sends a voltage pulse to the cable, which causes a breakdown of the cable insulation damage (Fig.4) for a time of up to several milliseconds, which does not pose a danger from the point of view of overheating of the XLPE insulation. Following the power pulse, a probing wave is sent to the cable by analogy with how it happened in the wave method (Fig.1). The force pulse and the probing wave must synchronize in such a way that the wave arrives at the damage place at those moments in time when the force pulse has already caused a breakdown of the insulation, but the arc has not yet gone out. There are modifications of this method, when not one, but a series of several probing waves are sent to the cable at once, after which the most "successful" of the received waveforms is selected on the oscilloscope screen.

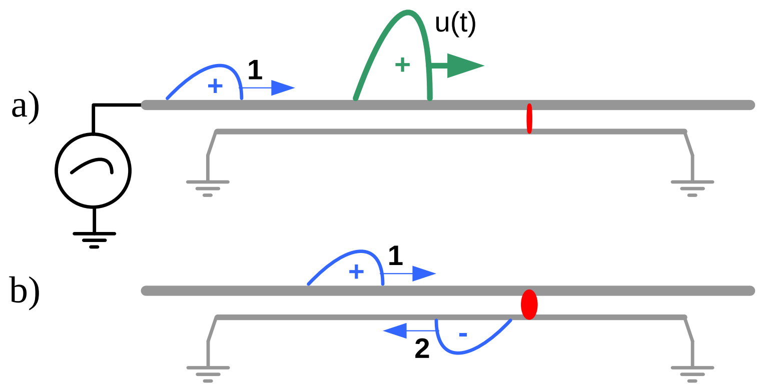

Fig.4. Pulse-wave method:
a) generation of a force pulse and a wave;
b) wave transients

The oscillatory discharge method is another method that is used to locate for high-resistance damage. If in the pulse-wave method, the force pulse and the probing wave were separate effects on the cable, and each of these effects had its own function, then with respect to the oscillatory discharge method, we can say that these functions are combined in one common effect on the cable (Fig.5). According to [1], there are two main modifications of the oscillatory discharge method:

– "Current connection" (Impulse Current Method);
– "Voltage connection" (Decay Method).

In the first case, a powerful high-voltage power pulse is sent to the cable from a source having a charged high-capacity capacitor (Fig.5a), which provides a breakdown of a place with weakened insulation strength, after which an oscillatory transient occurs in the cable in the area between the source and the breakdown place. The analysis of the oscillograms of this process and the determination of the oscillation period allow us to obtain information about the distance to the damage.

In the second case, the source is a charger, and the capacity of the cable line acts as a charging capacitor. As the cable is charged, the constant voltage on its capacitance increases (Fig.5b), and at some point, it becomes sufficient to break through a place with weakened insulation strength. An oscillatory transient occurs in the area between the source and the breakdown site. The waveforms analysis gives an idea about the distance to the damage.

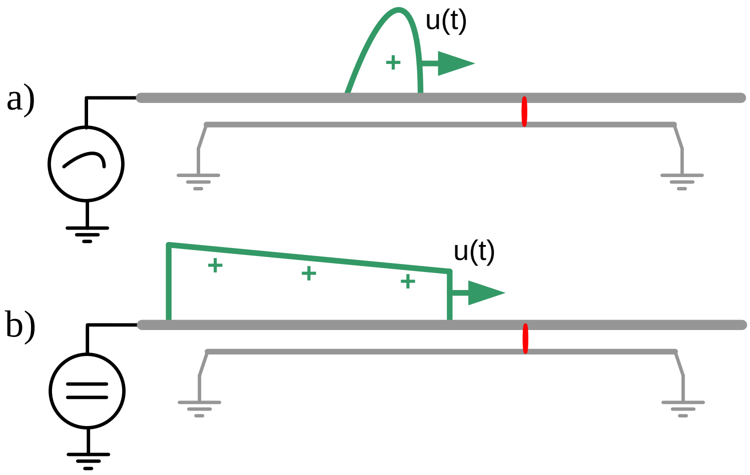

Fig.5. The method of oscillatory discharge:
a) the discharge is initiated by a pulse;
b) the discharge is initiated by a constant voltage

The Bridge Method, unlike all previous methods, does not use the theory of wave processes in a line. The scheme for locating the cable main insulation damage is shown in Fig.6 and, as can be seen, the use of the method requires the presence of at least one intact line phase. Access to both ends of the cable is also required to install a set of jumpers, which makes it difficult to apply the bridge method in cases where the cable enters a gas-insulated switchgear (GIS).

The principles of operation of an electric bridge (Murray Bridge, Glazer Bridge) are in many literary sources, but here, in order to simplify, we will explain the operation of the bridge differently. When using the bridge method (Fig.6), in fact, the currents I_1 and I_2 fixed in the two arms of the bridge are compared with each other. The comparison of currents I_1 and I_2 allows us to estimate the ratio of the total length of the cable L_C and the distance to the place of damage L_F – it makes possible to locate the place of damage. For example, the case $I_1=I_2$ means that the damage occurred near the end of the cable $L_F=L_C$, and the case $I_1>>I_2$ means that the damage occurred near the beginning of the cable $L_F<<L_C$.

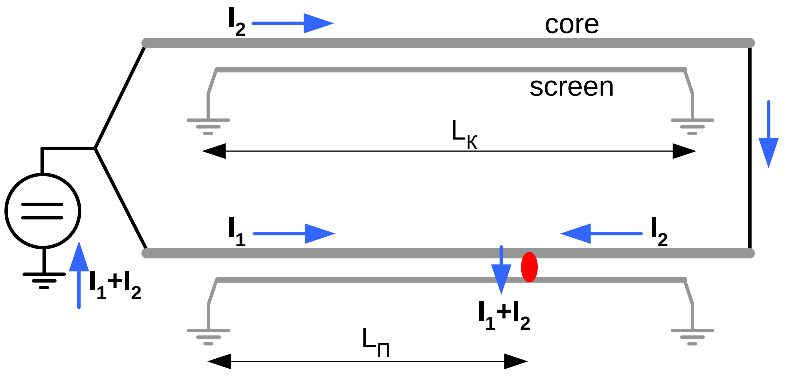

Fig.6. Bridge method of cable main insulation damage locating

Other methods. Among the group of preliminary methods for cable damage locating, Frequency Domain Reflectometry (FDR) is also known; a method for measuring cable insulation capacity; various methods that are based on the analysis of information received from the optical fiber embedded in the cable.

Note that polymer pipes, in which cables are increasingly laid, interfere with the flow of current from the cable into the ground. However, most of the considered methods of preliminary cable damage locating do not require the output of current into the ground, and therefore their applicability will not deteriorate in any way with the appearance of pipe sections on the cable route.

ACCURATE LOCATING

Preliminary methods make it possible to find the approximate location of the damage place along the line route, after which this place must be clarified by additional measurements carried out directly close to the damage place. Most often, the following methods are used for accurately locating the cable main insulation damage according to [1]:

– acoustic method;
– induction method;
– step voltage method.

The acoustic method assumes that power pulses are fed into the cable from one of the ends, leading to breakdowns at the damage place, which is why claps are heard in this place. A specialist with a receiver of sound signals passes along a section of the route located near the damage and observes the force of the claps. The greatest magnitude of the force of the claps will reach when the specialist is directly above the place of damage (Fig.7a).

It is important to note that breakdowns of the damage place, accompanied by claps, are impossible with low-resistance insulation damage, and therefore the acoustic method is applicable mainly to locating high-resistance damage. It is also important that the acoustic method does not work well if the cable does not touch the ground, but is laid in a polymer pipe. The fact is that the air in the pipe provides much less sound attenuation than the ground, and therefore the claps are clearly audible even at a considerable distance from the desired damage place, and this does not allow you to find the location of the sound source.

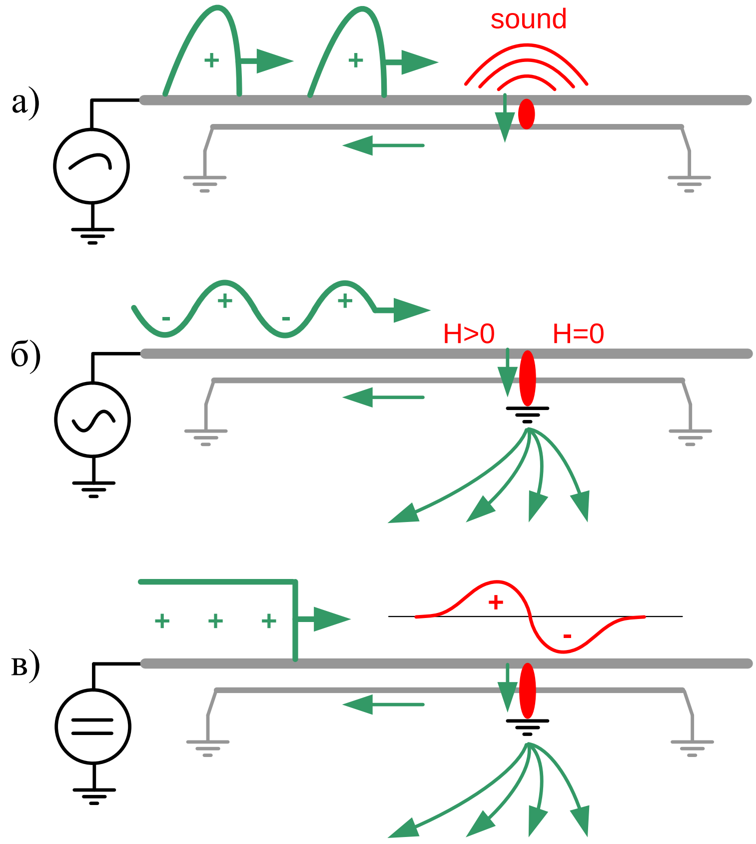

Fig.7. Methods of accurate search:
a) acoustic;
b) induction;
c) step voltage

The induction method (Magnetic field method) assumes that an alternating voltage is supplied to the cable from one of the ends, and in order to detach from interference, the voltage frequency should not be a multiple of 50 Hz. You also need an antenna configured to measure the magnetic field of the frequency that is set at the cable connected source.

Alternating current from the source passes through the cable core and creates a magnetic field H>0 around it. Having reached from the source to the insulation damage, the current enters the cable metallic screen and the surrounding ground. Thus, there will no longer be a core current and the associated field H=0 behind the damage place. To find the damage, it is necessary for a specialist with an antenna to walk along the cable route and record the level of the magnetic field of the current flowing through the cable. The place of the route, starting from which the observed magnetic field H will begin to weaken up to H=0, will be located just above the cable damage (Fig.7b).

It should be understood that for the induction method to work, it is important that the current at the point of damage leaves the core not only into the cable screen, but also at least partially goes into the surrounding ground through the damaged cable sheath. If the sheath is intact and does not pass the current from the screen into the ground, then in this case the "forward" current of the core and the "reverse" current of the screen will be close to each other in magnitude and opposite in sign, that is, the magnetic field of the cable will be absent not only to the right of the accident place (H=0 in Fig.7b), but also to the left of it (where H>0 now shown in Fig.7b), which will make the induction method useless.

Even if the cable sheath is damaged, in some cases the current still cannot escape into the surrounding ground, which creates obstacles to the use of the induction method – this happens when the cable is laid in a polymer pipe.

The step voltage method consists in measuring the step voltage along the cable route near the damage place (Fig.7c). At the end of the cable, a DC voltage source is connected to it, under the influence of which the current from the cable through the insulation damage goes into the surrounding ground, where it spreads and thereby creates a step voltage. The specialist walks along the cable route and with the help of two metal electrodes stuck into the ground along the cable at a distance of 0.3-0.5 m from each other, measures the step voltage with the device. The place of the route where the sign of the step voltage changes to the opposite – is the desired place.

The principle of measuring the step voltage can be applied only when the current from the damage place has the ability to pass into the surrounding ground. If the cable is laid in a polymer pipe, the current will not be able to get into the ground, and therefore the step voltage method will not work. An exception will be the situation when the pipe is filled with water, and this water helps the current to reach from the place of cable damage to the ends of the pipe and there go into the ground – it will be possible to fix a change in the sign of the step voltage at these pipe ends, but such information will hardly be useful when locating for the exact place of damage along the pipe section of the cable route.

CABLE OUTER SHEATH DAMAGE LOCATING

The methods shown in Fig.1-7 are related to locating the place of the cable main insulation damage or the cable core breakage. The applicability of these methods to locating cable outer sheath damage should be specified separately.

Preliminary search. Wave methods work well precisely when locating for cable insulation damage, since waves propagate between the core and the cable screen at a known constant speed determined by the dielectric constant of the insulation, and the attenuation of such waves remains within acceptable limits. If the task is to locate the cable outer sheath damage place, then the waves must be launched not into the cable core, but into the screen, and thus they will no longer propagate between the cable core and its screen, but between the screen and the ground. Unfortunately, determining the speed and attenuation of a wave in the ground is a complex engineering task, the solution of which depends on many influencing factors. Therefore, the use of wave methods to find the place of sheath damage is difficult.

Having discarded wave methods, only the bridge method remains to search for cable outer sheath damage, the scheme of which is given in Fig.8. As you can see, to use the method, a current pass into the surrounding ground is needed, which means polymer pipes will interfere with the search procedure.

Accurate search. To find the cable outer sheath damage place in the ground, you can use the same accurate locating methods that were considered for the cable insulation (Fig.7). The difference lies in the fact that the installations must be connected not to the cable core, but to its metallic screen, and the test current will not exit from the core into the cable screen, but from the screen into the surrounding ground.

The appearance of pipe sections on the cable route interferes with the output of the test current from the cable screen into the ground, and therefore the use of known precise methods (acoustic, induction, step) turns out to be ineffective for sheath damages [1, 2].

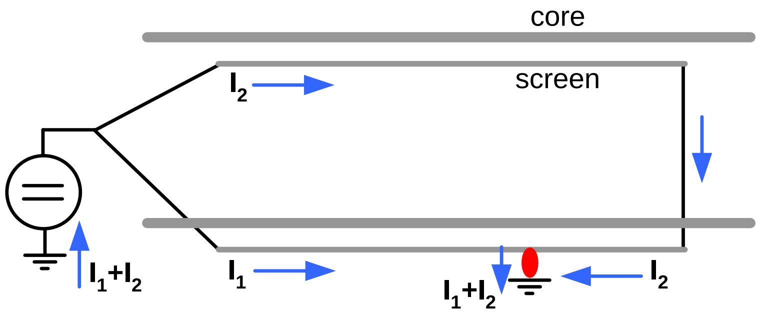

Fig.8. Bridge method of cable outer sheath damage locating

CONCLUSIONS

Based on the CIGRE brochure [1] and other sources, the article provides an overview of the main methods for cable damage locating and shows why polymer pipes interfere with:

- accurate locating for the place of cable main insulation damage;
- both preliminary and accurate locating for the place of cable outer sheath damage.

Thus, despite the considerable variety of methods, the materials of the article confirm the conclusions of the international commission of CIGRE [1] that the locating for damage on those sections of the route where cables are laid in polymer pipes is a serious problem.

REFERENCES

1. Fault location on land and submarine links (AC & DC) // Cigre Technical Brochure № 773, September 2019.152 p.
2. Dmitriev M.V. Methods of reducing the voltage induced on the 6-500 kV cable line // ELECTRIC POWER. Transmission and Distribution, 2019, No.4(55), pp.82–85.