

Cable fault location in medium voltage of Sonelgaz underground network

Recherche de défaut de câblé dans le réseau souterrain de Sonelgaz

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ABSTRACT

Power supply networks are growing continuously and their reliability is becoming more important than ever. The complexity of the whole network comprises numerous components that can fail and interrupt the power supply. Underground distribution systems are normally exposed to permanent faults, due to specific construction characteristics. In these systems, visual inspection cannot be performed. In order to enhance service restoration, accurate fault location techniques must be used.

The present paper describes the different faults affecting the underground distribution system of SONELGAZ, and cable fault location procedure using Time Domain Reflectometry (TDR) method. This method is based on the analysis of the cable electromagnetic impulse response that allows cable fault pre-location. Results obtained from real tests conducted on underground distribution feeders of electrical network of Energy Distribution Company. The objective of these tests is to know the influence of cable characteristics on the types and frequency of faults, and how the TDR method contributes in obtaining an accurate fault location.

RÉSUMÉ

Les réseaux électriques de distribution se développent continuellement et leur fiabilité est devenue indispensable que jamais. Les composants du réseau électrique peuvent échouer et interrompre l'alimentation électrique. Les réseaux de distribution souterrains sont toujours exposés à des défauts permanents, vue leurs caractéristiques de construction spécifiques. Dans ces systèmes, l'inspection visuelle ne peut être effectuée. Afin d'améliorer la qualité de service, des techniques précises de localisation des défauts doivent être appliquées. Cet article décrit les différents défauts qui affectent le réseau de distribution souterraine de SONELGAZ, et la procédure de localisation de défaut de câble avec la méthode d'échométrie basse tension(TDR), basée sur les analyses de la réponse du câble à l'impulsion électromagnétique, qui permet la pré-localisation des défauts de câble. Des résultats sont obtenus à partir des essais réels dans des dépôts souterrains du réseau électrique de la société de distribution de Souk-Ahras, afin de connaître l'influence des caractéristiques des câbles dans les types et la fréquence des défauts et comment contribue la méthode TDR à leur localisation précise.

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1. INTRODUCTION

The urban development zones and environmental considerations have preferred the use of underground power cables instead of overhead lines. Underground cables have many advantages compared to overhead lines. In fact, they do not require practical maintenance and they are particularly not affected by the weather and climatic conditions. However, in the case of underground cable fault, it takes usually more time to repair it, due to the various stages of fault location, identification and classification [1], [2]. In order to guarantee the continuity of power energy, the electricity distribution companies need to identify and locate rapidly and precisely the faulted segment to reduce outage time [2], [3]. Methods based on the principle of time domain reflectometry (TDR, or PE: Pulse Echo) [4], [5] are currently used for faults location in cables and lines. Time Domain Reflectometry (TDR) is a well-known technique that is usually used for measuring the impedance discontinuity as a function of time (or distance) in electronic systems [6], [7].

This paper presents TDR method for easier and faster faults location in a medium voltage underground power cable. The methodology used to locate faults, including fault type classification and exact fault location is presented. All required steps are illustrated in the diagram shown below. Finally, results of real tests conducted on different faulted sections of underground network in Distribution Company are presented as well as the results of the TDR method applied in these sections.

2. CABLE TYPES AND CHARACTERISTICS

Cable types are basically defined as low, medium and high voltage cables. According to the cable type, different requirements to cable testing, cable fault location as well as maintenance strategy are defined. The tendency within the last years shows a shifting to single-core systems as they are less costly, reduced in weight and maintenance cost. Furthermore oil impregnated or oil filled cables are used less and less, as the environmental sustainability cannot be guaranteed. Especially in industrialized countries, these types of cables have been replaced and are no longer installed.

Today PE insulated cables are mainly used. The improvement of the PE insulation material combined with modern design of the cable enable to manufacture cables even for extra high voltage level. Figure 1 illustrates the equivalent circuit of underground cable.

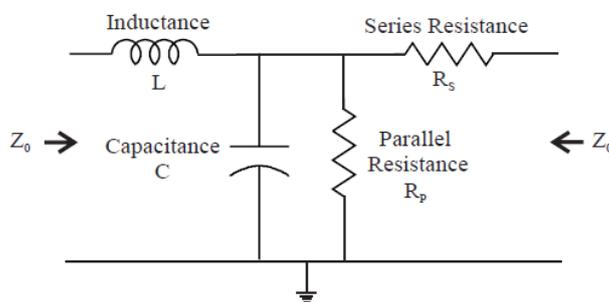


Figure 1 : Equivalent circuit of healthy cable

The different types of cables used by the SONELGAZ company are noted in Table 1.

Table 1 : Cable types used in Sonelgaz

Voltage	Type of cable	Nature and style of conductive core	Type of insulating material
10 kV	Unipolar Three-pole	Aluminum 185 mm ² Aluminum 240 mm ² Copper 120 mm ²	Impregnated paper (IP)
30 kV		Aluminum 120 mm ² Aluminum 185 mm ² Copper 70 mm ²	Synthetic Insulation (PRC, PVC, PE)

3. TYPES OF CABLE FAULTS

Cable faults can be categorized into three main types: open conductor faults, shorted faults, and high impedance faults [8], [9].

3.1. Open Conductor Fault

An open conductor fault occurs where the cable conductor is completely broken or interrupted at the location of cable fault. It is possible to have a high resistance shunted faults (to ground) on one or both sides of the faulted conductor’s location.

3.2. Shorted Fault

A shorted fault is characterized by a low resistance continuity path to ground (insulating fault). The resistance from the conductor to ground is lower than the surge impedance of the cable for a shorted low resistance fault.

3.3. High Impedance Fault

A high impedance fault contains a resistive path to ground (shunted fault) that is large in comparison to the cable surge impedance. This type of fault may also demonstrate non-linear resistive characteristics which allow the apparent resistance to vary with the level of applied voltage or current.

4. IDENTIFICATION OF FAULT TYPES

A multimeter is used as ohmmeter or insulation tester to determine the fault type. This is important to decide which method of fault location is best suited.

Tow values of fault resistance R_d are important to know the type of fault (Table 2):

Table 2 : Values of fault resistance

Category	R_d value
1	< 130 to 150 Ω
2	between 130 to 150 Ω and some megohm
3	More than some megohm

If the resistance value is situated in category 1, then it can be confirmed that it is an insulation fault, but if R_d value is situated in category 2 or 3 then the continuity measure or dielectric test have to be used (Fig. 2 & Fig. 3).

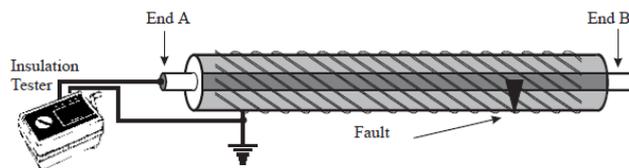


Figure 2 : Test for insulation (fault) resistance using an insulation tester

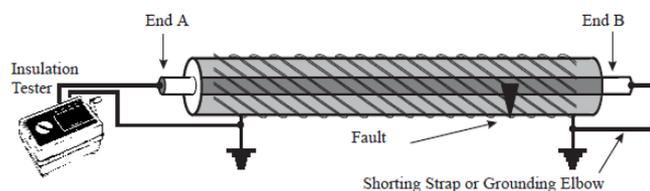


Figure 3 : Loop test for continuity using an insulation tester

5. TYPES OF FAULTS DETECTION (PRE-LOCATION METHODS)

The faults occurring in the power lines and cables can be classified into four main categories: short circuit to another conductor in the cable, short circuit to earth (ground), high resistance to earth and open circuit.

Not all approaches provide satisfactory results for each type of fault. Four methods that are mostly used for detecting fault location are described hereafter.

- A-Frame
- Thumper
- Bridge methods
- Time Domain Reflectometer (TDR)

A persistent short circuit to earth fault can be most easily located using the A-Frame method. For high resistance earth faults, the A-Frame method is not always sufficient. In this case, thumper method has to be used to reduce fault resistance. Thumper method alone may be sufficient for fault location but when applied for a longer duration, it may damage the cable insulation. A-Frame is not useful for locating faults which are not connected to the ground. Time Domain Reflectometer (TDR) is suitable for determining the locations of most faults.

5.1. A-Frame Method

In A-Frame method, a pulsed direct current (DC) is injected into the faulted cable and earth terminal to locate the ground fault. The DC pulse will flow through the conductor and returns via earth from the earth fault location back to the ground stake as shown in Figure 4.

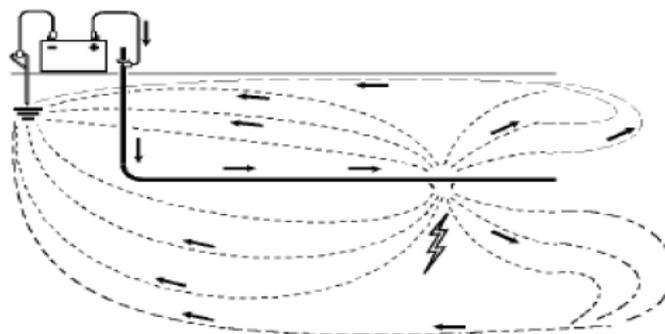


Figure 4. An A-Frame method for finding cable fault location

The flow of pulsed DC through the ground will produce a small DC voltage. A sensitive voltmeter is used to measure the magnitude and direction of the DC voltage in segments of the earth along the cable route. Analyzing the results of the measuring voltage along the route, the location of the fault in the cable can be pinpointed.

A-Frame is an accurate method but it is not the fastest, since the operator has to walk along the length of the cable from the transmitter to the ground fault. This method may face a problem if the return DC finds some easier path back to the earth stake of transmitter instead of returning through the ground. If the ground is sandy or paved, which provides high resistance and consequently, less current flows through the ground. In this case, the voltmeter fails to measure the voltage and fault detection becomes complicated.

5.2. Thumper Method

The Thumper technique is basically a high voltage surge generator which is used to apply a reasonable high voltage to the faulty core of an underground cable to generate a high current arc resulting in a loud noise to hear above the ground. This method requires very high current thump at voltages as high as 25 kV to make underground noise loud enough to be heard from the ground.

As the A-Frame method, the thumper method requires an operator who has to walk along the path of the cable and listen to the sound from above the ground. Different ground conditions, nearby traffic and noises may make this sound hard to listen to make a clear distinction.

5.3. Bridge Method

Bridge methods used for locating faults in underground cables are based on modified Wheatstone circuit where direct current is used to measure the resistance in order to calculate distance of the fault in percentage of the total line length. Murray and Glaser bridges [8] use the similar principal for calculating the distance of the fault. Brief description of these bridges is given below.

Figure 5 shows the Wheatstone bridge circuit where R_1 , R_2 , R_3 are the known resistances and R_x is unknown resistance.

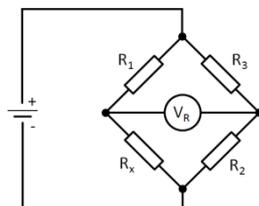


Figure 5: Basic Wheatstone bridge

When the galvanometer represented by the circle in the figure shows zero current flow, the unknown resistor R_x value can be found from the other known resistances value using the following equation:

$$R_x = \frac{R_1 \times R_2}{R_3} \quad (1)$$

A variation on the Wheatstone bridge is the Murray Loop Bridge. Figure 6 shows the adjacent resistances, RC_1 of a faulted cable in a loop with RC_2 of a good cable designed to represent R_x and R_2 of the Wheatstone bridge. Similarly, corresponding portions of a slide wire resistor RB_1 and RB_2 can be designed to represent the resistances R_1 and R_3 . At balance in the Murray Loop Bridge, RC_1/RC_2 is equal to RB_1/RB_2 .

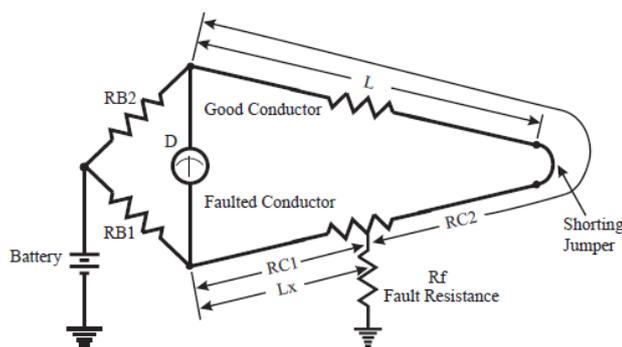


Figure 6 : Murray Loop Bridge application

When it is assumed that the resistance of a uniform conductor is linear and proportional to its length, and the total length of the cable section under test is L , the distance to the fault, L_x , is calculated as follows:

$$L_x = 2L \frac{R_{B1}}{R_{B2}} \quad (2)$$

5.4. Time Domain Reflectometry (TDR)

The TDR method is the most established and widely used measuring method for the determination of:

- the total length of a cable
- the location of low resistive cable faults
- the location of cable interruptions
- the location of joints along the cable

In the Time Domain reflectometry (TDR) method, a low energy signal is sent through the cable where the perfect cable with the uniform characteristic impedance returns the signal within a known time and with a known profile. This time and profile of the signal is altered once the cable has an impedance variation due to any fault. The impedance variation causes a portion of the signal reflected back to the source.

1) Velocity of Propagation

Certain information must be provided to the TDR before it can provide distance information. The most important quantities are: the velocity of propagation (*VP*), the speed at which the transmitted pulse travels down the cable under test. This value is used by the analyzer to convert its time measurement to distance.

The approximate velocity of propagation of cable is given by:

$$V = \frac{V_0}{\sqrt{\epsilon_r}} \tag{3}$$

Where :

V_0 is the light speed: 300×10^6 m/s or 300 m/ μ s

ϵ_r is the relative permittivity or the dielectric constant of the insulating material.

Table III presents the velocity of propagation for different cable types:

Table 3 : Propagation velocity for different types of cables

Cable type	VP m/ μ s
Impregnated paper (IP)	140 - 155
Polyethylene (PE)	170
Ethylene propylene (EPR)	136 - 166
Polyvinyl Chloride (PVC)	155

2) Characteristic Impedance

If we consider that a cable is a line with distributed parameters, where:

l : linear inductance H/m

c : linear Capacitance F/m

The characteristic impedance of a cable is given as follows:

$$Z_c = \sqrt{\frac{l}{c}} \tag{4}$$

The characteristic impedance of power cables generally ranges from 10 to 40 Ω .

3) Reflection factor

A voltage pulse V_i is sent into the cable and it is reflected at any changing in the cable impedance (joints, fault, derivation...)

The magnitude of the pulse reflections depend on how severely the fault impedance (Z_r) differs from the characteristic impedance (Z_c). The reflection can be calculated using the following equation:

$$r = \frac{Z_r - Z_c}{Z_r + Z_c} \tag{5}$$

For a short circuit, $Z_r=0$ and $r = -1$ this means that the pulse is reflected in the form of a negative pulse. For an open circuit, Z_r is infinite and $r = +1$, signifying that the pulse is reflected in the form of a positive pulse.

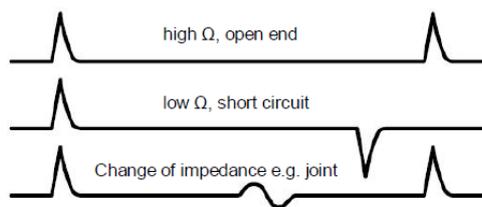


Figure 7 : Schematic diagram of TDR reflection graphs

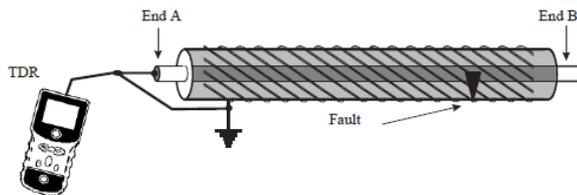


Figure 8 : TDR test for cable length

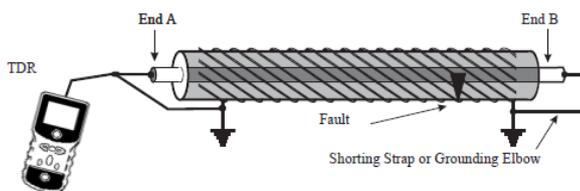


Figure 9 : TDR test for continuity

A low voltage TDR is an excellent tool for the pre-location of open circuits and conductor to conductor shorts. Cable faults with a resistance higher than 150 Ω are almost impossible to distinguish from normal clutter reflections on the cable. And almost all faults on underground distribution cable are high resistance faults in the area of thousands of ohms or even megohm. Due to the reflection characteristics of these high resistance faults it is impossible to see using only the low voltage TDR. In this case, we use the high voltage method to reduce this resistance to make it easier to know the fault location using the TDR method.

- **Arc Reflection Method (ARM)**

The standard conversion of a high-impedance to a low-impedance fault with a high-capacity burn down unit is used in decreasing cases. Today, high-power burns down units are used for the modification of the fault resistance faulty cables for prelocation in connection with ARM burning (arc reflection burning).

In the ARC reflection method, a TDR is coupled through a power separation filter to a high-voltage surge generator (Fig. 10). The filter protects the pulse reflection instrument from the applied high voltage while allowing the low energy TDR pulse to pass.

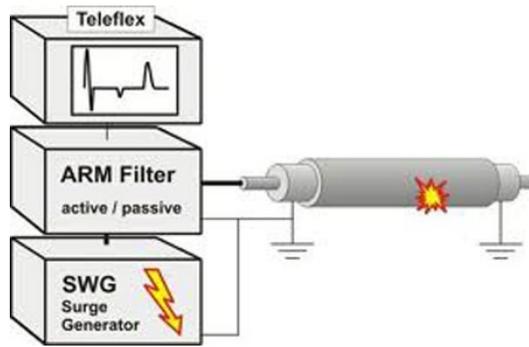


Figure 10 : Arc Reflexion fault location

- **Decay Method**

The Decay Method is the conventional fault location method for high resistance cable faults with a flash over voltage higher than 32kV.

The Decay Method is based on voltage decoupling by a capacitive voltage divider. The faulted cable is charged by applying DC or VLF voltage (Very Low Frequency voltage) up to the level of the breakdown. This breakdown creates a transient wave (due to discharge of the stored energy of the charged cable) which travels between faulted point and the high voltage (HV) generator. This transient wave is recorded by the echometer via the capacitive voltage divider (Fig. 11).

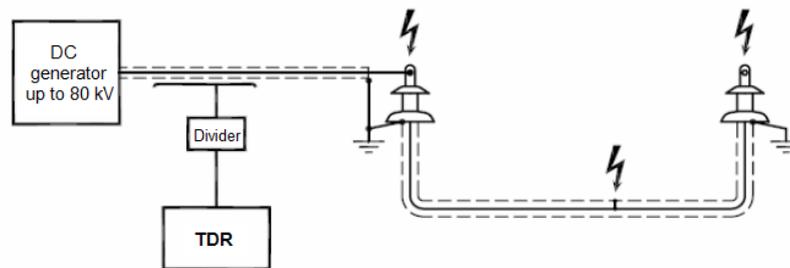


Figure 11 : Decay Method

- **Impulse Current Method (ICM)**

The ICM is the conventional location method for high resistance cable faults, especially on long cables. A high voltage impulse is sent into the cable under test up to the level of the breakdown (Fig. 12). This high voltage impulse ignites an arc at the faulted position. The created current impulse travels along the cable and is recorded by an echometer via an inductive coupler (current converter).

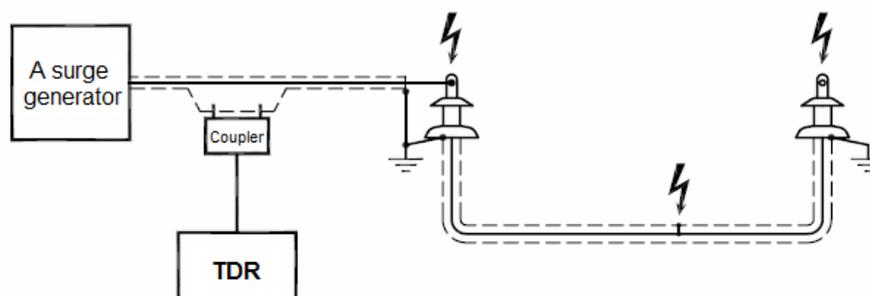


Figure 12 : Impulse Current Method

6. LOCATING OR PINPOINTING METHODS

6.1. Acoustic Fault Location

For pinpointing high resistive and intermittent faults in buried cables the acoustic method is used to spot the exact fault location. As signal source, a surge generator is used in repetitive pulsing mode. High energy pulses which are released by a surge generator force a voltage pulse to travel along the cable. At the fault, the flashover happens. This causes a high acoustic signal that is locally audible. These noises are detected on the ground surface by means of a ground microphone, receiver and headphone. At the fault position the highest level of flashover noise can be detected.

6.2. Methods of audible frequencies

Approximately 2% of cable faults require such method [10]. We use this method when the resistance fault R_d is less than 5Ω . It was not possible to locate the cable fault with the acoustic method.

7. ALGORITHM FOR LOCATING CABLE FAULT

In this section, we propose an algorithm for different steps of fault location. The bloc diagram that we made to follow steps in faulty cables is presented in figure 13.

The tests were conducted with SONELGAZ Company, Distribution Company of electric and Gas of Souk-Ahras. Several tests were conducted on different underground cables with different section core and insulation, with two different voltages 10 kV and 30 kV, using the steps presented in the block diagram (figure 13).

The results of the tests are shown in next section.

The proposed algorithm is divided into three principal parts:

1) Identify the type of faults:

- Isolating test
- Continuity test
- Dielectric test

2) Cable fault pre-location:

With TDR method or thumper method (Arc reflection method, direct voltage method or direct shock wave method)

3) Cable fault pinpointing: with acoustic method or audible frequencies method.

When a fault happens, the isolating measure is first put to use. If R_d is less than the range 130 to 150Ω then it can be confirmed that it is an isolating fault for which the pre-locating method is well adapted. But if R_d is beyond the range 130 to 150Ω than the continuity test can be utilized. The reflection factor is hence calculated. If $r = +1$ then it is a continuity fault the pinpointing fault is detected, or if $r = -1$ then it is an insulating fault.

If $r \neq \pm 1$, then the dielectric test is considered, if an arcing is obtained then it is a high impedance fault and the cable fault pre-location using thumper methods is implemented.

Finally if we do not have an arcing then we have to return to normal work (there's no cable fault).

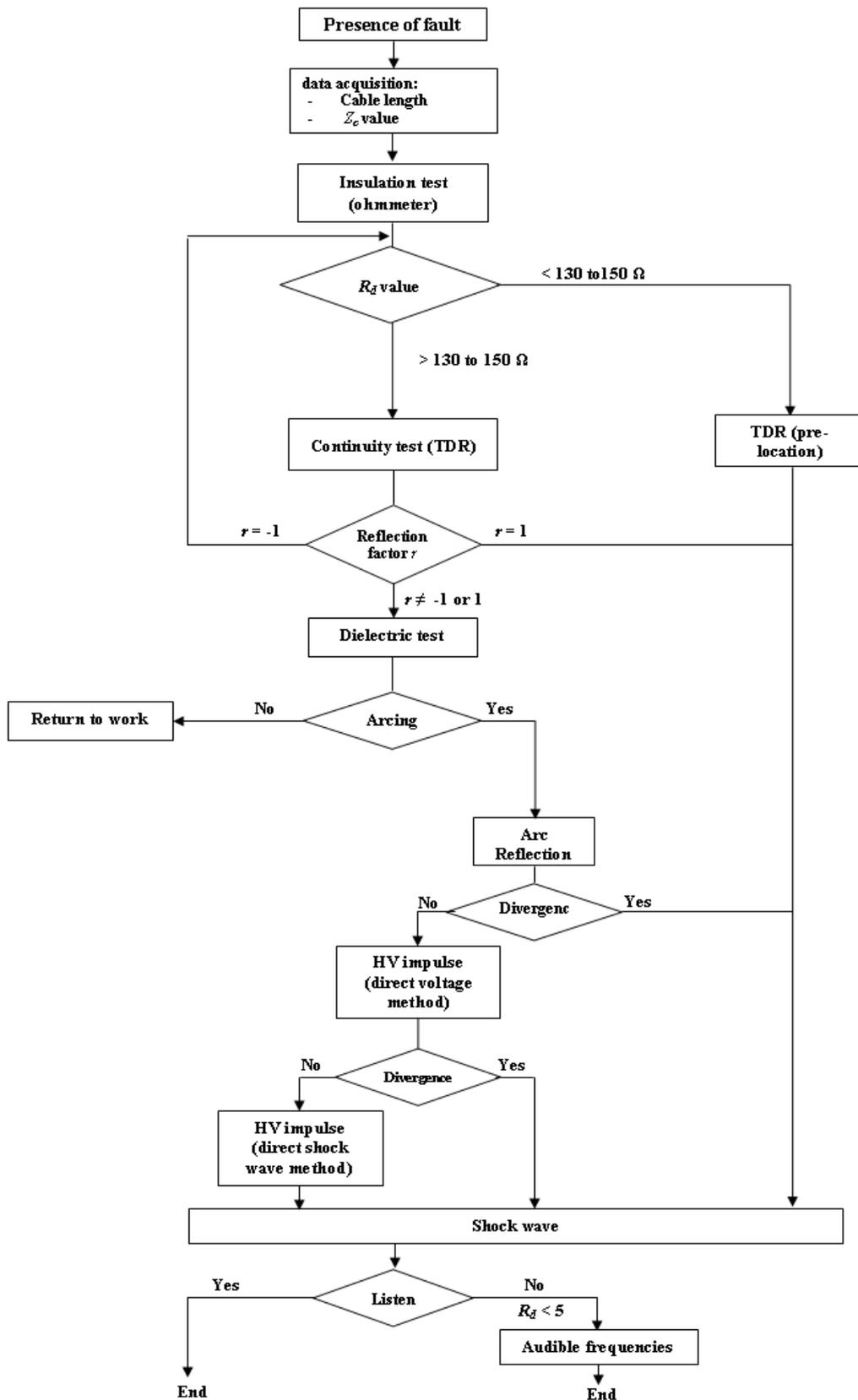


Figure 13 : Block diagram of location algorithm

8. TEST RESULTS AND DISCUSSIONS

Firstly after data acquisition, we show in table 4 the results of insulation resistance value for different sections of cables:

Table 4 : Results of insulation tests

Voltage (kV)	Cable section (mm ²)	linear resistance (Ω/km)	linear inductance (Ω/km)	Type of insulating material	Insulating resistance (Ω)
10	185	0.184	0.100	PRC	<u>62.79</u>
	240	0.140	0.100		<u>110.04</u>
	120	0.176	0.100		<u>51.97</u>
	185	0.184	0.100	PVC	<u>18.83</u>
	240	0.140	0.100		<u>33.01</u>
	120	0.176	0.100		<u>15.59</u>
30	120	0.284	0.100	PRC	<u>81.10</u>
	185	0.184	0.100		<u>49.20</u>
	70	0.300	0.100		<u>56.40</u>
	120	0.284	0.100	PVC	<u>7.00</u>
	185	0.184	0.100		<u>0.678</u>
	70	0.300	0.100		<u>18.00</u>

It is noted that R_d value is less than the standard value, so it can be confirmed that it is an insulating fault (Shorted Fault) in these sections of underground network. In this case, we use the pre-location with TDR method in one of faulted sections.

The low voltage impulse is applied in two phases, the faulted and healthy phase, for comparison between the forms of both the pulses. Figure 14 bellow shows the reflectogram obtained after the test.

The blue signal represents the reflected impulse of the healthy phase. It is observed that its length is of 480 m, and the black signal represents the reflected impulse of the faulted phase, that it is a negative reflection (insulating fault). The negative reflection is at 290.5 m from the beginning of the cable, thus we can locate the fault.

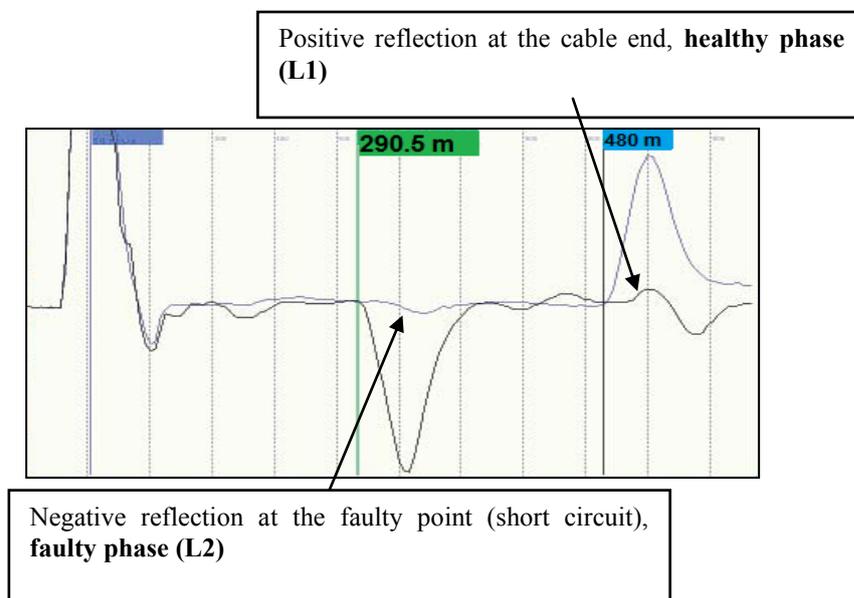


Figure 14 : Reflectogram of test result

The TDR method helps to know the pre-location of faults, and avoid walking along the length of the cable, making the fault cable pinpointing easier and faster.

9. CONCLUSION

This paper shows the importance of faults location in the distribution network and reviews some of the cable fault locating methods that are mostly used in practical fields.

The conducted work has confirmed that TDR technique can detect faults and other features along the length of the cable including joints.

This method is in general very accurate but also very manpower- and time consuming.

However, IEEE recommends that Fault locating techniques that enable the detection at the lowest possible voltage with the shortest time should be selected. Wherefore many of the offline methods are problematic to use [11]. Thus, various research studies have been conducted to develop numerical methods for fault identification and detection in underground systems by using algorithms injected into the digital relays. Nevertheless, sometimes, numerical relays in faulty network are not available, so TDR method remains necessary.

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