Identification and classification of faults in underground cables – A review

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Abstract. The need for power is constantly rising, with the current economic growth. In the power distribution system, transmission lines are the most important part as they play an indispensable role in transferring power from the power plant to the load centres. Transmission lines are done to faults which are largely caused by dampness in the paper insulation, weakness of the cable, or defects in splices or other accessories. The presence of these faults cases the power transmission efficiency to become low, giving rise to a huge annual power loss. Finding and designing new methods to identify the type of defect and its location, is the key to increasing the reliability and optimal performance of the system. This paper reviews about various approaches used for determining the location of underground cable faults and determining the faults using thermal imaging.

Keywords: Underground cables, classification, detection, locating fault.

1. Introduction:
The demand for power has grown exponentially over the years, due to the increase in industrial expansion and continuous growth in energy consumption. Power transmission is possible in both overhead as well as underground cables. Initially, transmission was carried out with overhead cables, but the performance of the cables was greatly affected by adverse weather conditions [1]. Due to their long service life and reliability, underground cables were found to be a replacement of overhead cables. However, if a fault occurs, it is very difficult to find the exact fault location as they are buried underground. Accurate detection of fault segment is required to enhance the dependability of the distribution system and to reduce the interruption time during the fault. Hence reliable fault detection techniques are needed to reduce outage time, minimize economic losses, significantly accelerate system improvement, and guarantee customer power quality [2].

Most of the transmission lines are laid by the overhead line method, but nowadays, an underground cable is widely used for the safety and small city development. Underground cable installations are expensive compared to overhead lines, but more are more reliable and also service life of underground cables is more as compared to overhead lines. Detecting faults in underground cable is difficult compared to overhead line cable. The underground cable is not affected by adverse conditions such as a rainstorm, snowfall and variations in temperature [3] - [6]. If the fault occurs in the underground cable, it becomes difficult to detect, so in this paper, the methods to determine different types of fault and its location is to be discussed.
This paperwork explains about the construction of underground cables, and the faults in underground cables and their types. It gives a brief description on why fault detection is important and describes the different methods to identify faults and techniques to locate them. Further, this paper describes how the faults can be detected using thermal imaging.

2. Overview of underground cables
An underground cable essentially consists of one or more conductors covered with suitable insulation and surrounded by a protecting cover which is shown in Fig. 1 [7]-[10].

![Figure 1. Construction of underground cable.](image)

As shown in figure 1, the following are the parts of a three-core underground cable: (i) Core or Conductors (ii) Insulation (iii) Metallic sheath (iv) Bedding and (v) Armouring.

2.1. Core
The core or the central conductor, made up of aluminium or copper is used to carry the electric current. Depending on the application, a cable can have one or more cores. They are stranded in order to reduce proximity effect and skin effect, improve its capacity to carry current, and to keep the cable flexible.

2.2. Insulation
Each conductor has a provision of insulation of suitable thickness. The thickness of the layer of insulation depends upon the voltage rating of the cable.

2.3. Metallic Sheath
A metallic sheath made up of lead or aluminium surrounds the insulation. The sheath forms a radial barrier to prevent the penetration of moisture and other damaging liquids in the soil. The moisture and chemicals degenerate the insulation and give rise to certain chemical reactions, eventually causing the failure of the insulation.

2.4. Bedding
Bedding consists of a fibrous material like hessian tape or jute. It is used to protect the metallic sheath against corrosion and also from mechanical injuries caused due to armouring.
2.5. Armouring
Good mechanical strength and protection to the cable will be provided by the layers of high resistance galvanized steel wire called armouring. This layer will be placed over bedding.

The advantages of underground cable are: Lower transmission losses, Lower maintenance and cost, less damage during severe weather and to install it requires a small band of land. The disadvantages of underground cable are: Expensive installation, susceptible to damage due to underground water and moisture in the soil and it has less heat dissipation.

3. Faults in underground cables
Underground cables are vulnerable to different faults, which compromise the continuity of power supply, and hence, its reliability. When fault occurs, the fault must be cleared, before it causes disturbances in the system which further leads to extensive outages in the firmly interconnected system working within its limits. To raise the reliability indices, techniques have been developed to discover fault symptoms and to analyse the faults, so that the same fault is not allowed in the future. The different types of fault that can exist in underground cable are discussed in this section [11] - [15].

3.1. Open circuit fault

![Open circuit fault](image)

An open circuit fault occurs due to break in conductor as shown in figure 2. In that case, there will be zero current flows in the conductor. The Megger is used to check for open circuit faults. It can be checked using three conductors of the three-core wire at the end is shorted and grounded. Megger is used to measure resistance between conductor and ground. It is known to be not broken when megger indicates zero resistance in the conductor circuit. But when it indicates infinite resistance, it means the conductor it is broken and needs to be replaced.

3.2. Short Circuit fault

![Short circuit fault](image)

The two multi-core cable wires come into electrical contact with each other due to an insulation fault as shown in figure 3, then it is referred as a short circuit fault. For this circuit, the megger is also used to check the fault. The two terminals of megger are associated with any two conductors. In this method, the fault is detected when the megger gives a zero reading between the leads. It is further classified into 2 types as symmetric fault and asymmetric fault.
3.2.1. **Symmetric fault.** In this case all the three phases unit are short circuited.

3.2.2. **Asymmetric fault.** In this case the magnitude of the current is not equal and it does not move 120 degrees.

3.3. **Earth fault**

![Earth fault](image)

Figure 4. Earth fault

When those wire goes under contact for those ground, it will be known as ground fault. This failure occurs when the outer shell is damaged due to chemical reaction with the ground and mechanical vibration and crystallization as shown in figure 4. The fault is detected when two terminals of the megger are connected to conductor and ground. The ground fault is known when the megger indicates zero readings.

4. **Importance of detection of faults**

Cable faults are cable damage that affects cable resistance. If you continue, voltage changes may occur. Fault detection is necessary for the power system to eliminate the fault before it increases damage to the power system. Any failure in these systems can stop the supply of electricity, which is a big problem in today's life. Therefore, fault detection has become essential to provide an uninterrupted power supply.

5. **Identification of fault detection methods**

5.1. **Online method**

This method uses and processes the sampled voltages and current for determining the point of failure. The online method for underground cables is less than overhead lines [16].

5.2. **Offline method**

Offline method is divided into two methods, (e.g) the tracer method and the terminal method.

5.2.1. **Tracer method.** This method tests cable service in the field using a special instrument. The tracer method is a comprehensive way to locate a bad segment by going through the cable circles. A faulty segment can be determined from acoustic or electromagnetic signals and requires dispatch of crew members to the disruption area. There have been various techniques are largely used in the industries, including the tracking approach through acoustic, electromagnetic or current. Example: 1) Tracking current method 2) sheath coil method [17].

5.2.2. **Terminal method.** It detects the fault location in a cable from either one end or both the ends without tracking. In this method, general areas of the fault are found, to speed up tracking in buried underground cables. Example: a) Murray loop method b) Impulse current method [9].

6. **Locating Underground Cable Faults**

Special techniques are required to find the exact location of the fault. The following are some of the methods used to locate faults in underground cables [18] - [21]:

a) Cable thumping

b) Time Domain Reflectometer (TDR) and

c) High voltage radar methods
The factors that affect these fault location methods include: remote source, cable length, effect of fault parameters, external faults, and load taps.

6.1. Cable thumping
Applying a high voltage supply to a faulty cable creates a high-current arc which makes a thumping sound at the fault location. The heat from this high current damages the insulation of the cable. These damages can be reduced by limiting the power supply through the cable. However, sustained cable testing can deteriorate the insulation to an intolerable level. The main advantage of cable thumping is its accuracy in detecting the location of the fault. Disadvantages of cable thumping are: i) It is infeasible for longer cables. ii) This method cannot detect short circuit faults.

6.2. A time-domain reflectometer (TDR)
A time-domain reflectometer (TDR) is used to measure the cable length and to determine the location of joints, low-resistive faults and intermittent faults. When a low voltage pulsed signal is sent by the TDR, if there is a characteristic change in the impedance, some part of the signal will reflect back to the source. Since the speed of propagation of the pulse is known, the time measured by the TDR can be converted to distance to the reflection. From this, the nature and location of the fault can be detected. Figure 5 shows a typical set up for a TDR measurement. One of the TDR leads is connected to one phase of the cable and the other TDR lead is connected to the cable sheath, which is grounded. The pulse is positively reflected at the end of the cable or at any interruption in the cable, negatively reflected at a short-circuit point, and indicated as a laid S when there is a change in impedance.

![Typical set-up for a TDR measurement](image)

Figure 5. Typical set-up for a TDR measurement

The reflection coefficient is used to determine the magnitudes of the pulse reflections. Reflection coefficient, \( r = \frac{(Z - Z_0)}{(Z + Z_0)} \), where \( Z \) is the impedance of a discontinuity and \( Z_0 \) is the characteristic impedance of the cable. For an open end \( Z >> Z_0 \) and \( r \) is a positive reflection and, for a short circuit \( Z << Z_0 \) and \( r \) is a negative reflection.

One of the major advantages of TDR is that, it does not degrade the insulation, as it sends a low energy signal. Disadvantages of TDR are: i) It cannot detect the exact location and gives only an approximate distance to the fault location. ii) TDR generally cannot detect high resistance ground faults. iii) TDR signal gets interfered by the surrounding electrical noise.
6.3. High voltage radar methods
To overcome the limitations of Time Domain Reflectometer, the following high voltage radar methods are used.

   a) arc reflection method  
   b) surge pulse reflection method  
   c) voltage decay reflection method.

6.3.1. Arc reflection method. This method requires the use of a TDR along with a thumper or surge generator, and a filter. An arc is created across the shunt fault by the thumper. This arc results in a temporary short circuit, causing the TDR to show an effective downward deflection. The TDR is protected from the high voltage surge produced by the thumper, by the arc reflection filter. This filter also directs the low voltage signal through the cable. Arc reflection technique of locating the fault in underground cable is shown in figure 6.

6.3.2. Surge pulse reflection method. This method makes use of a thumper or surge generator, a current coupler, and an analyser or a storage oscilloscope. The thumper and the underground cable are directly connected without making use of a filter. A high-voltage pulse is transmitted down the cable, by the thumper, which creates an arc at the location of the fault. This causes energy to get reflected back to the surge generator. This reflection between the thumper and the fault continues back and forth till all the energy gets exhausted. The surge reflections are sensed by the current coupler and then captured by the storage oscilloscope and displayed on a screen.

6.3.3. Voltage decay reflection method. This method requires a voltage coupler, high-voltage dc test set and an analyser. Here, the flashover of dc voltage at the fault produces reflections which are sensed by the voltage coupler. The analyser acts as a storage oscilloscope to capture the reflections and display them.
7. Detection of faults using thermal imaging

Faults in underground cables can be detected using infrared camera images while the surrounding images of the faulty device are captured using the Charge Coupled Device (CCD) camera. Practically, the infrared camera image is easily affected by the temperature of the environment. Hence, the temperature range with minimum/maximum temperatures is set up for the thermal image, in order to have a diagnosis that is reliable and accurate. From this range of temperature, one pixel of palette is determined, which represents a particular temperature.

![Image of a diagnostic program](image.png)

**Figure 7. Images of a diagnostic program. [6]**

7.1. Automatic Capturing of the Images

The infrared camera and the PC, which collects the infrared and CCD images as shown in figure 7, are connected together. The predetermined colour palette value of the thermal image between the maximum, temp\_high, and the minimum, temp\_low, is divided into 255 levels, which corresponds each RGB colour to a certain temperature. The temperature of each level of the palette is

\[
\text{temp\_level} = \frac{\text{temp\_high} - \text{temp\_low}}{256}
\]

After dividing the infrared image into 5600 pixels, the temperature of a pixel is determined by searching for the matched colour in the palette. The matched colour level is indicated as data\_RGB. The temperature of each pixel is

\[
\text{temp} = \text{temp\_low} + (\text{data\_RGB} \times \text{temp\_level})
\]

When this temperature, temp, goes above the error temperature, the CCD camera captures and saves the images, which can later be used for scheduling repairs, by the operator. [6] Figure 8 depicts the flowchart for the detection of the fault.
7.2. To classify faulty and un-faulty conductors

A model developed using Convolutional Neural Networks (CNN) with LeNet architecture is utilized as an automated decision support system for the classification of faulty and un-faulty conductors. The performance metrics of the system can be calculated using the following equations:

\[
\text{Accuracy} = \frac{TP + TN}{TP + FP + TN + FN} \\
\text{Sensitivity} = \frac{TP}{TP + FN} \\
\text{Specificity} = \frac{TN}{TN + FP} \\
\text{Positive predictive value} = \frac{TP}{TP + FP} \\
\text{Negative predictive value} = \frac{TN}{TN + FN} \\
\text{F-Measure} = \frac{2 \times (\text{Precision} \times \text{Recall})}{\text{Precision} + \text{Recall}}
\]

where, TP is True Positive, FP is False Positive, TN is True Negative, and FN is False Negative.

The adopted CNN classifier is trained using 200 thermal images from different instances and directions. In addition, 100 thermal images are made as the test image to analyse the performance of the CNN-based classification system. The 100 test images with un-faulted and faulted conductors are transferred to the CNN classifier.
Figure 9. output of the CNN-based decision support system [5]

Figure 9(a) and (b) shows the output of the CNN classifier, namely un-faulty condition and faulty condition respectively. When comparing the acquired thermal images of the faulted and un-faulted conductors, it is seen that there is a notable change, due to the generation of heat caused by the current flowing through the conductor. The quantity of current flow through the conductor varies with respect to its configuration. However, the change in thermal signatures cannot be seen or detected naturally; the CNN-based decision support system classifies faulty and un-faulty condition with a high degree of accuracy. The accuracy of the classifier can further be increased by increasing the number of test images. [5].

8. Conclusion
To enhance the power quality of the underground cables, and restore power supply in time, it is of great importance to locate and classify the fault rapidly and accurately. In this paper, various promising fault location and detection methods were discussed, which can be embedded in the existing relays. With the use of the Charge Coupled Device image, the infrared images are extensively used to detect and identify faults in underground cables. The faulty and un-faulty conductors can be classified using the output of the CNN classifier. Underground cables have been widely used in power distribution networks due to their limited environmental concerns and increased reliability. With accurate fault detection methods, the faults in underground cables can be minimized.

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