Summary: This paper describes an automatic fault location technique for permanent faults in Underground Low Voltage Distribution Networks (ULVDNs). The system pre-processes Time Domain Reflectometry (TDR) signals to eliminate reflections due to tee-offs, and to locate 3-phase open or short circuit faults. The system also uses adaptive filtering to analyse the TDR signals to locate single and phase-to-phase faults. The procedure not only minimises the interpretation skill required from a user of a typical TDR based fault location instrument, but also differentiates between single-phase tees and faults. The performance of the new method was evaluated relative to current practice, using field data that were obtained from real ULVDNs.

INTRODUCTION

Power utilities need an accurate and automatic fault location method for ULVDNs. This is due to a number of key factors, namely: reliability and quality of supply, reduction of repair costs, and the desire for low tariff charges to maintain a competitive edge.

TDR is one of the most common methods used for locating faults in underground cables and transmission lines [1-5, 9-13]. TDR based fault location techniques have been developed and successfully applied in high or medium voltage cable or overhead transmission network systems [1, 3, 4, 5 and 10], but not as successfully for ULVDNs. Because of multiple 3-phase and single-phase (service cable) tee joints in the ULVDN, the recorded TDR signals are much more complicated than those obtained from high and medium voltage underground cables, and overhead transmission lines [13].

The system developed in [1] is TDR based, but uses impulse current rather than impulse voltage to locate cable faults and requires experienced engineers to interpret the waveforms. The system described in [3] uses TDR principles to locate the fault automatically. This method can locate faults for cable network with 3-phase tees, but does not consider cable networks with single-phase tees and moreover can only be applied to cables operating at 6.6kV to 33kV. The fault location technique described in [4] uses wavelet transforms to analyse the power system fault transients in TDR signals, and was applied to 345kV transmission lines without tees only.

The system described in [5] uses expert knowledge to simplify the fault location procedures. However, it still requires significant user input, and the technique was demonstrated for high voltage underground cable without tees. The fault locating system described in [10] automates the fault locating process with the aid of a computer. It requires three stages to locate faults, and has only been demonstrated for 15kV distribution cable networks without tees.

Some of the key issues in ULVDN fault analyses are:

1. Recorded TDR signals are not easy to interpret due to reflections from the many tee connections in the network.
2. Since single-phase tees may produce reflections similar to short circuits, it is difficult to distinguish between a single-phase tee and short circuit fault from the reflections recorded.
3. When fault location is carried out on live lines, not all the access points for fault recordings are isolated from the bus bar. If the access point is not isolated from the bus bar, then it is not possible to record a good healthy phase reflected signal. This is because the pulse launched into the cable travels into other feeders as well. Therefore, the only recordings that can be made are related to the faulty phase. To record a healthy phase reflected signal, additional fuses need to be taken out, which leads to power outages for more customers.

In an earlier paper [15], results from applying the adaptive algorithm to data obtained from currently available TDR instrument were presented. The results demonstrated, although based on a small set, the efficacy of the algorithm.

Since 2003, the algorithm was integrated into a prototype TDR instrument, which was designed by the research team in the University. In addition, the instrument was designed for both automatic and manual operation, the automatic operation would be very useful when used by a non-expert in fault location. This paper, therefore, presents the results of the tests undertaken on a cable network using the new hardware. The intelligent processing used in the system is designed such that the frequent tee-offs associated with such networks do not significantly affect the ability of the system to produce a location to the fault. The basis of conventional TDR based fault location systems is discussed, and the intelligent processing that is used in the new ULVDN fault locator system is described. The results from a series of field trials demonstrate the accuracy of the new system.

TDR BASED FAULT LOCATION

In TDR, a pulse is launched into the cable network from an accessible point, and is partially or completely reflected by
any impedance mismatches in the cable network. These impedance mismatches can be a short circuit or an open circuit or tee joint. The reflected pulses (signals) are recorded for both faulty and sound (healthy) phases. These reflected signals are then used to locate any fault in the cable network either by visual comparison or after subtraction from the other. This method is used in many commercial ULVDN fault location instruments [9]. The main disadvantage of these instruments when used for ULVDN is the need for experienced engineers to interpret the results due to the complexity of the reflected signals.

A schematic diagram of a 4-core cable model is shown in Fig. 1. It comprises a 55m main 4-core cable with a tee branch at 20m of length 12m. A short circuit fault occurs at 40m along the main cable between core 1 and 2.

![Figure 1](image1.png)

**Figure 1** An ideal 4-core signal cable model [14]

Fig. 2(a) shows an interrogation pulse, representative of that used in the TDR system. Figs. 2(b) to (d) show the expected ideal TDR recorded signals. The reflected signals from three phases to Neutral (1-N, 2-N, and 3-N) have a negative pulse at 20m and positive pulses at 35m and 55m as expected. The phase signals 1-N and 2-N have a second negative pulse at 40m that are related to the short circuit fault. In Fig. 2(e) the superimposed signal 1-N & 3-N is illustrated. The bold pulses indicate that two reflected pulses are in the same position. Fig. 2(f) shows the difference signal 1-N&3-N. Only one key departure is shown at 40m in the difference signal. This is due to the short circuit fault at 40m.

![Figure 2](image2.png)

**Figure 2** Ideal TDR input signal, recorded signals, and expected results for the model of Fig.1 [14]

In the ideal situation, key departures can only exist if one of the phases under test is faulted. In the real case, this is not true because of impedance differences along the cable, noise, which cause amplitude variations in the reflected signal. These variations may show departures similar to those caused by faults.

The C&C method of fault location has three main disadvantages. First, as explained earlier, the amplitude variation may cause problems in interpreting the reflected signals. Secondly, this method can only deal with two signals at any instant. This may cause a problem if the faulty phase signal is not known. Thirdly, recording on ULVDNs is restricted because of live line testing, as mentioned in the introduction. Therefore, it is not always possible to record healthy and faulty phase reflected signals without customer power outage. The number of reflected signals recorded in a faulted 3-phase live ULVDN cable is decided as follows:

- Only three reflected signals can be recorded if a fuse is blown in a substation or pillar. For example, if the Red phase fuse is blown, then the reflected signals that can be recorded must be associated with the Red phase. Therefore, only Red-Neutral (RN), Red-Blue (RB), and Red-Yellow (RY) reflected signals can be recorded if the Red fuse is blown.

![Figure 3](image3.png)

**Figure 3** Real TDR signal of the 1-N phase for the model of Figure 1
Another fuse needs to be taken off if other reflected signals need to be recorded. This will lead to customer power outage.

- Only five reflected signals can be recorded if two fuses are blown in a substation or pillar. For this case if the Red and Blue fuses are blown, then RN, BN, RB, and BY reflected signals can be recorded without any further customer power outage.
- All six (the maximum number of reflected signals that can be recorded in a 3-phase ULVDN) reflected signals (RN, BN, YN, RB, YB) can be recorded if all three phases are blown in a substation or pillar and if the pillar is open ended.

**ADAPTIVE FILTERING**

The adaptive filtering technique forms the backbone of the intelligent processing applied. Adaptive filters have been successfully used in applications such as echo cancellation, speech modelling, multipath compensation, and radar signal processing [6, 7, 8]. A basic FIR (Finite Impulse Response) adaptive filter consists of an input signal \( x_k \), desired signal (reference) \( d_k \), an output filter signal \( y_k \), and an error signal \( e_k \) that are related as follows:

\[
e_k = d_k - y_k
\]

(1)

The output of the filter \( y_k \) is expressed as:

\[
y_k = \sum_{i=0}^{N-1} w_i x_{k-i}
\]

(2)

where \( w_i \) represents the adaptive weights (filter coefficients), and \( N \) is the number of weights.

The adaptive filter attempts to exploit the correlation that is assumed to exist between \( x_k \) and \( d_k \). The characteristics of the filter are changed in such a way that the output from the filter is made to approximate the correlated component of the desired signal [6, 8]. In this way, differences between the measured signals due to cable attenuation and phase characterisations are minimised.

**NEW TDR-BASED FAULT LOCATION METHOD**

The new method uses the existing TDR signals together with advanced signal processing techniques. This increases the accuracy and automation of the fault location process.

The flowchart for the new TDR based fault location system is shown in Fig. 4. After recording, the signals are pre-processed to detect any single-phase tees and also to locate 3-phase open and short circuit faults in the ULVDN. The pre-processing procedure is as follows: Firstly the reflected signals are thresholded (the reflected signal’s values below the pre-set threshold value are set to zero and values above are left as they are) to extract high amplitude reflections. Following thresholding, the signals are characterised as follows:

1. If only one phase reflected signal has a positive reflection at a cable position, then that phase may have an open circuit fault at that location.
2. If only one phase reflected signal has a negative reflection at a cable position, then that phase may have a single-phase tee or short circuit at that location.
3. If all the phases’ reflected signals have a negative reflection at a position and that is the first occurrence, then there is a 3-phase tee joint or perhaps a short circuit fault. If this occurrence is not the first, then it is classified as secondary reflection of the fault. The 3-phase tee and short circuit faults are differentiated by the magnitude of their reflections. The 3-phase tee will have one third of the amplitude reflection of the short circuit fault.
4. If all the reflected signals have a positive reflection at a position then there is a possible open circuit fault at that location. If this occurrence is not the first, then it is classified as a secondary reflection of the fault.
5. All other peak locations are classified as either an open or short circuit fault.

If any single-phase tees are detected, these locations are stored for later use. If a 3-phase open or short circuit fault is detected then the routine calculates the fault distance without further intelligent processing.

Following the pre-processing process, adaptive filtering is carried out on all reflected signals in pairs and all possible combinations. As mentioned, one reflected signal is fed as input and another is fed as reference to the adaptive filter. The adaptive filter output (error signal) will give the difference of the departures between the pair of reflected signals and not the amplitude difference. The resulting error signals from the adaptive filter are thresholded to localise the significant key departures. If a departure is detected, then that location is compared with the stored cable characterisation information. If that location is related to a single-phase tee, then that departure is ignored and the fault location process is continued until a fault is found. If that location is not related to a single-phase tee, then that location is identified as a fault location. The fault distance may then be calculated using the error signal by finding the position where signal departure commenced.
The new method addresses the single-phase tee problem. It does not require an experienced engineer to interpret the results and the instrument can be used on live line.

RESULTS

Consider the training network as shown in figure 5. There are 2 Tee joints in the network. The first Tee joint is labeled S/S3 and the second Tee joint is labeled S/S4. Each Tee-joint is approximately 40m from each other. When the cable is pulsed from S/S1 towards S/S3, the TDR signals are as shown below.

Figure 5 Schematic of the training network

When a short circuit was created between the blue and yellow phase at the end of the cable leading from S/S4 to S/S1, as shown in figure 8, the resulting TDR signals are as shown in figure 9.

Figure 6 TDR signals recorded on real non faulted cable

When these TDR signals are adaptively processed, the resulting error signal is as shown below.

Figure 7 Adaptive results after thresholding

While there are minor amplitude differences caused by the effect of Tee joints, the adaptive filter reduces these effects and prevents the error signal to cross the threshold, and hence a decision of no fault found.
CURRENT DEVELOPMENT

The prototype TDR instrument, IFL 1000, is being duplicated and these beta units would be used in field trials by different companies.

CONCLUSIONS

The novel approach to ULVDN fault location, as first described in CIRED 2003, was implemented on firmware and hardware to produce a prototype instrument capable of automatic fault location for low voltage underground cable network with multiple tee-joints.

The instrument is easy to use and does not require an experienced user to interpret the captured waveforms.

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REFERENCES


