An Industry Practice Guide for Underground Cable Fault-Finding in the Low Voltage Distribution Network

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This work was co-funded by Energy Transfer Partnership (ETP-Scotland) and Scottish Power Energy Networks (SPEN). SPEN also provided us with site visits and data for the case studies. The Authors also thank Mr. Patrick McKenna, Mr. Andrew McDiarmid and Prof. James Yu from SPEN for providing consultation on the industrial fault-finding practices.

ABSTRACT

This paper aims to critically analyze the IEEE std 1234-19 and other power cable fault-finding technical guides produced by leading industries to assess their applicability in practice to the underground low voltage distribution network (LVDN). The analysis reveals that there is no clear distinction between the fault-finding techniques and procedures of LV and MV/HV systems. Innumerable branching to residential loads in the underground LVDN makes them unsuitable to the application of most of the fault-finding techniques mentioned in the IEEE Std 1234-19 that are effective for MV/HV networks. Moreover, state-of-the-art techniques which are used as part of common industrial practice for LV fault-finding are not mentioned in the standard, nor collectively in any technical industry guide, which gives the impression that the content applicable to LV fault-finding is insufficient and lost amongst content only applicable to MV/HV fault-finding. In this paper, further contribution is provided; by means of presenting a recommended guide to fault-finding in the underground LVDN that will comprehensively fill in the knowledge gaps from the IEEE Std 1234-19 and other technical guides. The recommended guide presented in this paper is formed from practices reported in literature in addition to in-field case studies from one of UK’s largest energy providers; Scottish Power Energy Networks (SPEN) - part of Iberdrola. The paper presents and discusses these literature-based and practical-based fault-finding practices, and uses them to construct the proposed guide which is presented in the form of a detailed flowchart procedure. This procedure is put forward to industry practitioners to be used in conjunction with existing technical standards and industry guides.

INDEX TERMS Cable faults, fault-finding, low voltage distribution network (LVDN), underground power cables.

I. INTRODUCTION

Fault-finding in underground power cables can be long, challenging, and costly due to the inaccessibility of the cables, especially LV distribution networks in congested urban areas which have no option of implementing overhead lines [1]. DNV GL (Energy), a Dutch company that specializes in quality assurance and risk management, surveyed around 170 failures that took place with underground power cables between 1994 and 2014. According to the survey, there was a 37% failure rate of joints, a 32% failure rate of terminations, and a 31% failure rate from the actual cables. An interesting finding in the results is that they indicate that 69% of faults are caused by the cable accessories rather than the cables themselves. Additionally, the survey showed that 52% of faults with cables themselves were determined to be caused by cable production and installation errors, i.e., manufacturing defects and poor workmanship. By contrast, 17% of faults were attributed to external causes (damage inflicted by third parties) and 9% to ageing cables themselves. Similarly, 57% of cable accessory faults were related to installation mistakes [2].

There are 3 different types of faults; a series fault is created when there is a break in the conductor core, thereby partially or completely inhibiting the current flow, this is also known as an open fault [3-5]. A shunt fault occurs...
when two or more conductors form a connection with each other, or at least one conductor forms a connection with the earth. When these shunt faults occur, they can change the electrical circuit by forming a physical contact between the conductor(s) and/or sheath/ground. However, most shunt faults occur due to insulation degradation where there is no physical change in electrical circuit. i.e., there is no physical contact formed between the conductor(s) and the ground, rather, the dielectric material deteriorates and results in excess leakage current from lowered resistance. Insulation degrades due to several aging mechanisms applying stresses on different causes such as voids and defects, these causes are created by manufacturing or installation errors. Further degradation results in voids and defects expanding to trees and cracks which make the cable prone to failure [3-5]. A sheath fault usually occurs when an external mechanical force damages both the (non-metallic) over-sheath and the inner metallic sheath, thereby causing contact of the metallic sheath to ground, or when damage to the over-sheath exposes the metallic sheath to water ingress, thus creating a fault by eventual corrosion [3].

Field staff at Scottish Power Energy Networks (SPEN) revealed that the main practise relied upon for underground LVDN fault-finding during the second half of the 1990’s was Time Domain Reflectometry (TDR) [3,5-10]. A report published in 1977 [11] shows that many of the same techniques/technologies that are still used as common industrial practise today have been around for many decades. The report categorises the techniques as either ‘tracing’ or ‘terminal’, which indicates that although the concept of obtaining pre-location fault estimations and finding precise pinpoint fault locations already existed, the two procedures were not used in conjunction as part of a methodical process.

The report [11] shows that at least from 1977, techniques such as the TDR, Bridge techniques [3,5,6], Voltage Gradient method [6,9,10], Acoustic and Electromagnetic pinpointing techniques using the Thumper [3,5,6], were in practise for fault-finding in underground power cables, just as they are at present. The report mentions techniques collectively for fault-finding in underground power cables as a general practise and does not distinguish the applicability of techniques specifically for different voltage levels and network arrangements. The resonance technique mentioned has been ceased in modern practise because it was essentially the same as the TDR method but inferior in its success because the TDR is easier to interpret. The Tone Tracing method was similar in principle to the Twist method [12], with the difference being that it was applied to a line-to-ground fault instead of a line-to-line fault, however, because the Voltage Gradient method is more precise, its preference phased out this method altogether. The Tracing Current method specifically measured the current profiles of the faulted cable between manholes.

Although this technique is still applicable today, the distance between two manholes is not an acceptable length to consider achieving the fault location and a pinpointing technique will still need to be considered [11]. HV Radar methods [3,5-10] were not mentioned in the report as they had not been developed at that time. The Bridge techniques are still used in industrial practise, but due to multiple branching of networks, they aren’t suitable for the application to networks and are limited to only single/stand-alone cables [6]. The TDR has inherited a more dominant role in modern fault-finding. Its ability to determine the fault type as well as its improved ability to detect intermittent faults has made it a fundamental appliance to every field staff’s inventory. Fault-finding techniques used for the LV distribution network are discussed in detail in Section III.

Although faults occurring on MV/HV networks have a greater detrimental impact compared to LV networks, there are ten times more cables in the LV distribution network [13] and Con Edison Inc. (a USA network operator) reports about experiencing a thousand LV cable faults every year [14]. LV cable faults are quite serious as they are a direct cause of loss of supply to customers, which is not only disadvantageous to the end user but also comprises lost revenue and additional costs to the network operators. This loss of supply is measured using two parameters; number of customer interruptions (CI’s); and customer minutes lost (CML’s) [14]. Figures from the UK energy regulator, Ofgem [15], show that in year 2017/18, the distribution network operators (DNOs) reported between 30 to 50 percent of total customers experiencing electrical interruptions with CML’s averaging between 30 to 40 minutes for most DNO’s - it’s important to note that the number of CML’s only indicates the average time taken for customers to be restored a power supply and not the time taken to find the fault, repair it and reconnect the customers back to the grid. Nonetheless, UK Power Networks was reported to pay more than £1.8 million in penalty fees and fines in 2016/17 [13].

There are existing efforts for technical standardization of fault-finding in underground LVDNs. These include the IEEE std 1234-2019 [6] (updated from IEEE std 1234-2007 [16]) for hardware methods and C37.114-2014 [17] for computational methods. The 1977 report [11] shows, there has not been much advancement in the hardware fault-finding concept of underground power cables. The HV Radar techniques have similar operating principles as the TDR except they use a thumper to create measurable reflective discharges. The advancements in the fault-finding concept are focused on the MV/HV networks because advancements are based on automated data processing procedures which require continuous condition monitoring (smart sensors), something that is widely available in MV/HV networks. This is addressed in detail in Section II.
The contributions of this paper are:

1. A critical analysis on the IEEE std 1234-19 for its insufficiency of addressing LV fault-finding can be found in Section II.

2. Detail on state-of-the-art LV fault-finding technologies which are currently used as common industrial practice, yet not mentioned in the IEEE std 1234-19, can be found in Section III.

3. A recommended comprehensive guide to LV fault-finding that has filled in the knowledge gaps from existing literature such as the IEEE std 1234-19 is presented in Section VI. The guide has been produced in accordance with all sections, including the fault-finding procedure discussed in Section IV and fault-finding case studies provided by SPEN in Section V.

4. Lastly, a critical analysis of the underground LVDN and the current fault-finding practice is discussed in Section VII.

The rest of the paper is organized as follows; Section II presents the critical analysis on the IEEE std 1234-19 and other technical guides; Section III details the state-of-the-art LV technologies/techniques that are commonly used in industry; Section IV presents the LV fault-finding process; Section V reports LV fault-finding case studies as provided by SPEN; Section VI introduces the proposed LV fault-finding guide; Section VII consists of a critical discussion on the overall fault-finding condition for the underground LVDN; followed by the conclusion.

II. CRITICAL ANALYSIS ON THE IEEE STD 1234-19 AND OTHER TECHNICAL GUIDES

The IEEE std 1234-19 [6] aims to provide practitioners with detailed knowledge of the overall fault-finding procedures and available techniques and technologies indiscriminately to all voltage levels. It also addresses application criteria and safety considerations. Technical brochures from industrial manufacturers also use the opportunity to advertise their fault-finding equipment. This section presents critical analysis of the IEEE std 1234-19 and other technical guides from leading practitioners [3,5,12,18] in order to provide the reader with an understanding on the shortfalls of these documents.

A. CRITICAL ANALYSIS OF IEEE STD 1234-19

A standard was produced by the IEEE in 2007 which provided a guide to fault finding in shielded cables, (IEEE Std 1234™-2007) [16]. The standard was only aimed to guide practitioners fault-finding in MV cables, but in 2019 the standard was updated with significantly more detail and aimed to guide practitioners fault-finding in cables of all voltage levels, (IEEE Std 1234™-2019) [6].

Although the updated standard is very thorough with elaboration on every aspect of conventional fault-finding techniques, it doesn’t acknowledge that nearly all the mentioned techniques are not practiced on LV distribution networks. The reason is because techniques such as Surge Arc Reflection/Single/Multiple Impulse Method (SIM/MIM), Impulse Current method, Burn Arc Reflection method and Decay Voltage method i.e., HV radar methods, as well as pinpointing techniques which involve acoustic and electromagnetic transducers are not applicable as they utilize a process called ‘thumping’ [6]. Thumping involves using HV with a certain threshold of energy to break down the fault resistance through arcing. The arcing causes measurable reflecting pulses as well as detectable signals in the form of a ‘thump’ sound and an electromagnetic impulse. The reflected pulses which travel back and forth in the cable from the fault point can be measured for distance in respect to time of received pulses at the cable terminal. The ‘thump’ sound can be further used for quick and high precision pinpointing using acoustic and electromagnetic transducers. However, the HV used for thumping can be detrimental to the domestic loads connected on the LV network, therefore every residential connection branched on to the faulted cable needs to be disconnected first. Yet, the issue arises that access to disconnect every resident from the mains is not always practical and can be time consuming. Hence, practitioners do not consider techniques that use ‘thumping’ to be applicable on the LV distribution network.

Furthermore, there are a few important technologies that are commonly used by practitioners on the underground LVDN that aren’t addressed in the standard, namely, (1) the sniffer method for permanent fault pinpointing, (2) smart fuse application for pre-locating intermittent faults, and (3) smart Time Domain Reflectometry (TDR) devices that filter T-joint reflections which cause interferences with the signal. This gives an impression of neglect on the LV network’s practical considerations.

B. CRITICAL ANALYSIS OF TECHNICAL FAULT-FINDING GUIDES FROM LEADING INDUSTRIAL PRACTITIONERS

Although there’s plenty of literature aside from the IEEE standard that also discuss the effectiveness of available fault-finding techniques/technologies in underground power cables [7-10], they generally also fall short in a similar manner to the standard. In fact, many well-established organizations such as Megger [5] and Cigre [3] have published brochures and structured guides on fault-finding procedures, but either the brochures are mainly aimed at MV/HV cables or most of the techniques, especially the most effective, are not applicable to LV fault-finding because they utilize the thumping procedure. An example can be given by looking at a fault-finding procedural flowchart provided by Megger in [18]. The flowchart shows only one technique applicable for pre-locating a fault in the
LV network. Although a small part of the Arc Reflection method icon overlaps into the LV section, this is just to resemble the potential of applicability with the criteria that every residential premise branched onto the faulty cable be removed, or if the technique is applied for a fault occurring on the ‘in-comer’ cable which is connected only to the substation. Additionally, the pinpointing procedure itself is presented as a general step instead of specifying applicable techniques, this may be to avoid the case of not having a procedure to mention for the LV network.

Although there are numerous other examples to consider, some examples such as Baur [12] do produce guides that do indeed distinguish fault finding techniques by voltage levels. However, the guides still fall short in addressing techniques used for high resistance and intermittent faults in the underground LVDN – which are the most common types of faults [19]. Other equipment manufacturers such as Omicron only make equipment for MV/HV cables [20]. Hence, the underground LVDN is limited to only one conventional pre-location technologies/techniques for permanent faults, which is the TDR. Failure of the TDR usually resorts to the cut & test method [3, 5-10]. There are three conventional pinpointing techniques applicable for locating permanent faults; the Sniffer method [21]; the Twist method and the Voltage Gradient method. The Bridge techniques are not suitable to apply to the underground LVDN because the process requires the faulted cable to be connected to at least one other cable with matching length and impedance, however, due to several residential branches, the length and impedance profiles cannot be matched [7].

There is also comparatively less amount of literature on LV fault-finding than there is for MV/HV [22]. The reason may be because the LV distribution network doesn’t have an integrated monitoring system such as Supervisory Control and Data Acquisition (SCADA) or Phasor Measurement Units (PMU). Therefore, not only are occurring faults acknowledged almost exclusively by trouble calls from customers, but as modern innovations in fault-finding techniques are based on computational algorithms which require data acquisition from smart monitoring systems, they can only be studied on MV/HV networks that are equipped with the likes of such systems. These shortcomings have resulted in the practice of LV fault-finding to be missing a modern methodical approach, rather, it has become based on accumulated personal experience of senior engineers and passing the knowledge on.

III. LV FAULT-FINDING TECHNOLOGIES/TECHNIQUES

A fault occurring on the LV distribution network has 4 main stages; transitory; intermittent; persistent; and permanent [23]. A transitory fault causes a slight voltage drop for an insignificant period of time, such that the fault current is insufficient to melt the fuse. An intermittent fault is a temporary fault that causes a large enough fault current to melt the fuse, but the fault is not permanent so the fuse can be replaced and the cable continued in operation. A persistent fault is an intermittent fault but in a worse condition, such that it persistently melts fuses after many replacements. A permanent fault is the final stage of a fault process where a fault becomes established and the cable is no longer in operational condition. Not all faults initiate from the transitory stage, they can be immediately permanent, however, if an intermittent fault is not treated and repaired then it will eventually become a permanent fault [23].

A. TRANSITORY FAULT-FINDING TECHNOLOGIES/TECHNIQUES

The aim behind treating transitory faults is to catch the fault at its earliest stage so to prevent those CI’s and CML’s that would occur if the fault were to be left to progress into the intermittent or permanent stage. Transitory faults are often referred to as ‘high impedance faults’ (HIF) and the main concept behind this type of fault-finding is to measure the phase voltages across feeders and substations to localize the faulted area. Measuring the phase voltage is preferred over the fault current because the fault currents in HIFs are insignificantly small and difficult to detect [24, 25]. However, these techniques require the network to be under continuous, wide area monitored with sensors attached to every feeder and/or substation, using a PMU system, so that when phase voltages of any area reach a faulted level then the associated sensors will alarm the DNO. In [26, 27] the same principle of analyzing voltage measurements and harmonic content is used, but they base the monitoring device requirements on smart meters instead of a PMU system. As of 31st March 2020, 31% of the UK have installed smart meters onto their properties, therefore, locating transitory faults will likely be practiced in the near future [28].

B. INTERMITTENT FAULT-FINDING TECHNOLOGIES/TECHNIQUES

The principle behind intermittent fault-finding is to catch the fault at an early stage where the cable is still operational so the electrical profile of the cable can be used for fault localization via impedance measurements. The main instrument used for this is an auto-recloser fuse, also known as a smart fuse device, that replaces a melted fuse caused by an intermittent fault. Once a fault has occurred, if the fuse is able to be replaced and holds intact then the fault is intermittent or persistent and not permanent, henceforth, the
melted fuse is replaced by an auto-recloser that re-fuses the same line in wait for the fault to re-occur. Upon the re-occurrence of the fault, the auto-recloser records and sends the electrical profile (fault current and voltage measurements) before tripping then automatically reclosing the fuse again. The electrical profile is used to provide an estimated location of the fault in terms of distance from fuse point [29].

The two more industrially renown smart fuses are the REZAP Fault Master and Bidoyng, which can be bought from Kelvatek (part of the Camlin group) [30]. In [29], details are given of a study conducted with energy network operator, Alliander, by implanting the REZAP on part of their network. They record key benefits of implementing the auto-recloser in having reduced the number of intermittent faults from 35 to 11 per year, thereby reducing the CIs and CMLs as the reduced number of faults meant less CIs, and the auto-reclosing reducing the CMLs. Although the study mentions that Alliander considered it important to “attack the fault” in its intermittent stage rather than wait for it to become permanent, the study doesn’t mention data on reduced number of permanent faults from intercepting intermittent faults. The difference between the REZAP and the Bidoyng is that the REZAP is a multi-shot recloser and the Bidoyng is a single shot recloser, which means that the REZAP will continue to reclose after multiple faults have tripped it, whereas the Bidoyng will only reclose once, so should there be second fault it will not reclose after tripping. Nonetheless, the Bidoyng is a formal winner of the Queen’s Award for Enterprise and is employed by Scottish and Southern Energy Networks (SSE) [13].

Another technology which has been a valuable contribution to the LV fault-finding procedure is the automated time domain reflectometer (TDR) which was proposed by [31] in 2001 in a project funded by Scottish Power Plc and supported by Hathaway Instruments Ltd. The automated TDR is pre-processed to filter the trace from interfering reflections caused by T-joints/service breeches, which are innumerable in LV distribution networks as they’re used for branching the supply off to domestic loads (households). Additionally, Kelvatek [30] have developed an automated TDR called Transflekt which can be used for locating intermittent faults. The Tranflekt can be used in conjunction to smart fuses for confirmation or as an alternative for the same purpose of obtaining a pre-location on the location of intermittent faults. The TDR is discussed in greater detail in Section III-D.

C. COMPUTATIONAL FAULT-FINDING TECHNIQUES

The main focus of literature for fault-finding in underground power cables of all voltage levels has been diverted to computational techniques which implement algorithms using various measurements and data for estimated fault locations, thereby, automating the fault detection and location process with minimal human interference [22]. These techniques categorize into 5 main methods; impedance-based; travelling wave-based; knowledge based; sparse measurements; and hybrid [32]. Impedance-based methods consist of taking voltage and current measurements as well as line and load data to determine the distance of faults from the point of measurements [22,32,33]. Travelling wave-based methods can be highly accurate but expensive because they require very high frequency sampling and signal processing such as wavelet transforms to analyze voltage and current travelling waves which are generated at a wide frequency spectrum by a fault and propagate throughout the cable [18,34-36]. Knowledge based methods consist of training artificial neural networks (ANN), fuzzy logic, expert systems (ES) etc. with large amounts of simulated or real data so that it can recognize faults and provide highly accurate fault location estimations [35-38]. Sparse measurement methods are used for locating HIF/transitory faults, as previously discussed, and hybrid methods are the combination of any two or more methods mentioned.

Although, the impedance-based method is most popular, both it and the travelling-wave method have been thoroughly analyzed by IEEE standard C37.114-2014 [17]. Computational techniques offer high accuracy and efficiency, but they rely on measurements and data obtained from online continual monitoring systems such as SCADA implemented networks or smart meters [33]. As previously mentioned in Section III-A, only 31% of UK have implemented smart meters, and faults on the LV distribution network (not only in UK) are acknowledged by customer trouble calls i.e., when customers lose power supply and phone up their electricity supplier [22,37]. Hence, until the majority of the UK’s LV distribution networks implement SCADA or smart meters, these techniques will not be applicable.

D. PERMANENT FAULT-FINDING TECHNOLOGIES/TECHNIQUES

Although permanent faults on LV/MV distribution networks account for only 10 – 25 % of total faults to occur [39], many intermittent faults which don’t get repaired will inevitably become permanent. Permanent faults are much more challenging because the faulted cable becomes un-operational and the delay in repair-work due to fault-finding complexities can bring greater expenses from longer loss of supply. Furthermore, in contrary to fault-finding on the MV/HV network, there is a very limited number of options available for fault-finding on the LV distribution network because the majority of effective MV/HV techniques are not applicable as they employ ‘thumping’ which utilizes HV to break the fault resistance to create arcing. The arcing can then be honed by acoustic or electromagnetic transducers. However, the HV used for
arcing is detrimental to LV domestic loads, and although fuses can be removed and the cables grounded, access to every fuse service box is not always given, nor is access always given to ground every cable, particularly the cables branching to households [40]. None the less, there is only one conventional pre-location technology/technique and three conventional pinpointing technologies/techniques that can be used by utilities for finding faults in this type of network: TDR, Sniffer, Twist method, and Voltage Gradient method. Unsuccessful outcomes resulting from the application of these technologies/techniques will resort to the cut & test method as the only remaining option.

1) Time Domain Reflectometer (TDR)

Time domain reflectometry, also known as pulse echo method, involves sending low energy (around 50 V) pulses into the faulty cable in aim to receive reflections of some energy from the signals when they encounter a point of change of impedance within the cable. Thereby, making a map (trace) by calculating the distances of reflections from the time of the received reflected signals with the propagation velocity of the sent signals.

Due to its quick, easy, non-destructive application and relatively high success rate when operated on optimal fault conditions, they’re often the first choice (if not the only choice) to obtain or confirm a fault pre-location in distribution power cables of every voltage level. They are portable handheld devices as shown in Figure 1 and work best with two particular fault conditions; the first being a short circuit fault with a resistance of less than a hundred ohms; and the second being an open circuit fault, because these conditions result in sufficient reflections for the TDR to recognize [3,5]. As mentioned in Section III-B, the underground LVDN network has innumerable T-joints/service breeches that can interfere with the trace and create difficulty with interpretation, hence, it is standard practice to use an automated TDR such as a Reflekt (from Kelvatek [30]) which is pre-processed to filter such interferences from the trace.

2) The Sniffer Method

The cable sniffer is a device that senses and analyses gases which are emitted from a cable fault due to breakdown of insulation. The sniffer is a fault pinpointing technique and is much more preferred method than resorting to the cut and test method which faces additional costs of almost 50%. During the pinpointing process, small 8mm holes are first bored into the surface of the ground before the sniffer nozzle is inserted into a hole to detect and analyze the presence of any gases [21], this is shown in Figure 2. The concentration of detected gas spikes as is gets closer to the point of fault, thereby, pinpointing its location.

The sniffer is not always successful because it has limitations; at times, the gas produced from the fault dissipates into the air before an approximated fault location gets determined; other times, the cable may be ducted or the makeup of the ground may not allow gas to disperse to the surface; and sometimes, sufficient gas is not released by the cable fault because the insulation doesn’t break down enough [21].
3) The Twist Method

This pinpointing technique is patented by Baur [12] and is used to find fault locations in multi-cored cables that have twisted cores. The technique finds the location of faults between cable cores by sending a high frequency audio signal continuously through one of the faulted cores, which is then returned through the other faulted core by passing through the mutually connected faulted area. The twisted cores result in a rotating magnetic field along the cable length up to the fault point. A transducer above ground will perceive the rotating field as maxima and minima signals and upon passing the fault point the signals will cease, therefore highlighting the fault location, refer to Figure 3. The most effective condition for the application of this technique is when the fault resistance is less than 2 ohms. In the case of a fault occurring between a cable’s core and sheath, the sheath will need to be separated from ground for this technique to work. This technique is only suitable for low resistance faults because high resistance faults would require a very powerful audio frequency generator [12].

4) The Voltage Gradient Method

For completely burned-out faults where the surrounding soil forms contact with the faulted section of the sheath, the voltage gradient method can be an effective pinpointing technique. The technique is based on connecting one lead of a generator to the faulted sheath and the other lead to a grounding point connected to the earth. A current is supplied to the sheath that flows along the cable length and disperses through the soil at fault point and flows towards the grounded lead of the supply generator. The resistance in the soil develops a potential difference for the current flowing along the surface. An A-frame style of transducer with two measuring probes separated by the distance of approximately an arm’s length is used to measure the potential difference. When an AC generator is used to supply the sheath current, the A-frame voltage measurements will increase as the A-frame moves closer to the fault point. The measurements will become zero when placed directly above the fault with one probe at each side of the fault. Immediately passing the fault, will increase the voltage measurements again, as shown in Figure 4. With a DC generator supplying the sheath current, pulses of several seconds are measured using an A-frame with a zero-center meter. The meter will point in one direction for every measured pulse on one side of the fault and point towards the opposite direction when the measurements pass to the opposite side of the fault. Similar to the AC generator case, the measurement will be zero when directly above the fault with one probe on each side of the fault. The limitation of this technique as previously mentioned, is the need for surrounding soil to be in contact with the faulted area of the sheath so that current can flow therefrom. As there is no test to determine that soil has made contact with the fault, the only way to confirm if this technique is applicable is to actually set up the system and obtain a measurement from the A-frame. If the cable is ducted in plastic casing, then this will also restrict the applicability of the method [3, 5, 6].

5) CAT and Genny

C.A.T is an abbreviation for cable avoidance tool and Genny is short for generator. The CAT and Genny are not specifically used to locate faults, rather, they’re used for tracing cable routes in fault-finding practices. They are well known in the construction industry as they have the important function of finding any underground cable or pipes before starting excavations. The CAT operates by electromagnetically coupling with the electric field(s) of any live cable(s), and the Genny is used to supply current to offline cables or pipes, either directly or by induction, as to create an electromagnetic field to couple with the CAT [9, 41], as illustrated in Figure 5.
The cut and test method is exactly as the name suggests. It is highly destructive as it compromises cable integrity by cutting healthy cable to conduct testing. As proven by case study A in Section IV-A, the cut and test process can quadruple the fault repair time, making the total process in excess of a day. In financial terms, exploratory excavations from this technique can add over £1000 to the fault repair process (depending on the number of excavations) [21]. Hence, this technique is undoubtedly considered outdated and a last resort option when other techniques are unsuccessful. The testing part of this method involves taking TDR traces and/or impedance measurements. This method is used in one of two conditions:

1. If a positive pre-location is obtained with the use of a TDR and the cable sniffer is attempted to pinpoint the fault but is unsuccessful, then a cut and test would be required to confirm the TDR estimation and hone into the fault (see Figure. 6 (a)).
2. If no positive pre-location is obtained by the TDR, then the only option left to determine the fault location would be to section the cable down with this method, starting from the cable half-way point, until the location of the fault is found [5] (see Figure. 6 (b)).
A. FAULT ACKNOWLEDGEMENT

As continuous online monitoring such as SCADA is not installed onto most of the UK’s LV distribution network, the occurrence of a fault on the network can only be acknowledged by trouble calls received from customers who experience a loss of supply and [22] informs that the UK is not the only country that is challenged with the dependency of trouble calls for fault acknowledgement. Nonetheless, a sufficient number of trouble calls can help approximate an affected area. However, reliance on trouble calls as a fault indicator presents many issues; there is normally a delay in customer’s information about the outage; critical information can be false; faults occurring during sleeping hours also won’t be reported until early morning hours.

B. FAULTED CABLE/SECTION IDENTIFICATION

The operators use maps and schematics of feeder configurations, positions of protective devices that may have been operated, in conjunction with critical information such as the route of supply for the troubled customers to narrow down the possible location of the faulted area. The faulted cable/section is confirmed once the engineers inspect the fuses of the suspected area. If the faulted area/section is not accurately determined due to insufficient information, then finding the faulted cable can be a tedious task. In these cases, the task becomes heavily dependent on the engineers having sufficient experience on the network as well as having a good knowledge and understanding of the area and in possession of adequate cable records. This method, albeit outdated, is still the main process adopted by SPEN for identifying a faulty cable/section.

C. STAGE AND TYPE OF FAULT

The stage of the fault can be determined by replacing the fuse(s); if the fuse(s) remains intact and the power is restored then the fault can be classified to be intermittent; if the fuses remain intact but the power is not restored after replacing the fuse(s) then this indicates the presence of a permanent open circuit fault; if the fuse(s) doesn’t hold, and the power is not restored then this indicates a permanent short circuit fault. Testing lamps and ohm meters are most commonly used on site to confirm what type of fault has occurred on the network (be it an open or a type of short circuit fault), although, using a TDR for the pre-location stage can also reveal the fault type. Testing lamps can be used online to identify melted fuses or dead cores, whereas continuity and insulation resistance testing can only be done on cables which are offline.

D. PRE-LOCATION

The step to pre-locate the fault is crucial to reduce the time spent for pinpointing it. Cable fault location techniques are generally categorized into two sections, pre-location and pinpointing. Pre-location is based on testing cables at their terminal ends to determine the distance to fault. TDR is the main technique used for LV network faults, but sometimes short circuit faults need to be conditioned if the fault resistance is too high because the TDR is limited to only recognizing short circuit faults under 100 ohms. Conditioning occurs in the form of ‘burning’ the fault, this involves in passing large voltages and currents down the cable to break down the fault resistance. A good pre-location can estimate a cable fault position within a small percentage of cable, but the estimated fault location can be considerably off in some larger underground cable sections. This may be due to incorrect cable mappings or if a cable section is made up of a variety of different cable types.

E. CABLE TRACING

The lay route of the faulted cable must be identified to allow for an accurate fault location. Cable records are used with the aid of tracing equipment to identify their routes. As the records tend to lack accuracy they’re only used as an approximation guide for tracing equipment to reveal the precise cable route. A successful pre-location and identified cable route will substantially increase the chances of pinpointing the fault. The CAT and Genny are the typical cable tracing equipment used for LV networks but they’re also subject to interference of other underground utilities such as different live cables and ground make-ups, which can affect the performance of the cable detection tool. This equipment is only used as a way of indicating a cable route and not as a way of identifying a cable amongst other infrastructure.

F. PINPOINTING

The purpose of pinpointing is to get a precise location of a cable fault after a successful pre-location is obtained. The pinpointing techniques used for LV fault finding are; the sniffer method; the voltage gradient method; and the twist method.
G. CABLE IDENTIFICATION

Cable identification measures are essential to ensure only the correct cable gets repaired. When the faulted cable is amongst several others in congested areas, then additional precaution and certainty must be advised to maintain safe working conditions and prevent fatalities or unplanned outages of other circuits. Hence, it’s essential that field staff and engineers are competently experienced with cable identification procedures. The process for identifying LV cables consists of initially consulting the appropriate cable records to indicate the position of the relevant cable(s) in respect to all other cables, pipes or ducts at the point of work. There can be several indicators to distinguish a specific cable or cable set from others such as past or present practices in respect to; cable types; armoring; jointing; and depth of laying. The distinguished cable(s) are then stripped from their outer layers including the sheath to expose the live cores. The cores are then tested live with appropriate testing equipment for confirmation.

H. REPAIR

Depending on the amount of damage caused by the fault, the cable and/or joint can either be repaired or if the damage is too significant then the damaged section of the cable and/or joint will need to be replaced. After all appropriate testing and repairs have been carried out to ensure the cable is still fit for service, the cable will be re-connected to the supply network.

V. LV FAULT-FINDING CASE STUDIES FROM SCOTTISH POWER ENERGY NETWORKS (SPEN)

There are two case studies provided by SPEN that are documented in this paper to provide insight into the field experience of the fault-finding procedure which will be used in the section to follow as basis for deriving the LV fault-finding flowchart. One of the case studies involves the occurrence of a three-phase LV underground cable fault which developed in the Newmains area of Wishaw, Scotland and will be referred to as case study A (CSA). The other case study involves a joint fault which occurred at a service breech in Hamilton, Scotland and will be referred to as case study B (CSB). The case studies are contrary to each other in the sense that in some of the main processes, one case study had success whereas the other required an attempt to restore power; however, they could not remain intact and this distinguished the fault to be permanent. Moreover, the melting of all three fuses had distinguished the fault to be a three-phase short circuit fault on the LV cable. Referring to Figure. 8 (b), a field engineer went to pillar 18 to carry out the confirmation testing and close the normally open point (NOP). The fuses remained intact which indicated that there was also a three-phase open circuit fault at the same fault point. Hence, from the fault point, the side going towards pillar 18 sat healthy but open and the side going towards Newmains Cross S/S sat short circuited, as shown in Figure. 9.

1) Fault acknowledgement

The faults of both case studies were acknowledged by troubled calls from customers, the first call for CSA came at 04:48am, then a further six calls came between 06:03 to 06:55 am with sixteen calls in total received throughout the day.

2) Faulted cable/section identification

The addresses of the calls were traced and linked to the assumed faulty LV mains cable using SPEN’s utility map viewer (UMV) shown in Figure. 8 (a). The diagram of Figure. 8 (b) shows the LV mains cable that fed out from Newmains Cross Substation (S/S) (underlined blue) and ran on both Manse Road and Westwood Road, thereby, potentially affecting approximately 72 customers. After several trouble call confirmations, the response team headed straight to Newmains Cross S/S rightfully expecting that the LV fuse(s) supplying the cable had melted. Fortunately, the engineers were able to narrow down the fault to a cable section which ran between 2 Manse Road and 57 Westwood Road. Number 57 was the last property along the cable route before the cable terminated into the number 18 LV link pillar (circled red in Figure. 8 (b)). This is another indication which informed that the residences after 57 Westwood Road were most likely still on supply and fed from a different source which could be used as a back-feed. In this case, the trouble call method and knowledge of network connections was very sufficient at narrowing down the faulted section of the faulted cable. However, it took nearly 2 hours to have a sufficient number of trouble calls to confirm a LV mains fault had occurred on the network, which is considered to be too long of waiting time before the response team could be deployed and too long for customers to have time off supply.

3) Stage and type of fault

To identify the stage and type of fault for CSA, engineers used LV test lamps to reveal that all three fuses supplying the cable had melted. The melted LV fuses were replaced in an attempt to restore power; however, they could not remain intact and this distinguished the fault to be permanent. Moreover, the melting of all three fuses had distinguished the fault to be a three-phase short circuit fault on the LV cable. Referring to Figure. 8 (b), a field engineer went to pillar 18 to carry out the confirmation testing and close the normally open point (NOP). The fuses remained intact which indicated that there was also a three-phase open circuit fault at the same fault point. Hence, from the fault point, the side going towards pillar 18 sat healthy but open and the side going towards Newmains Cross S/S sat short circuited, as shown in Figure. 9.
A back-feed restored the power to customers between pillar 18 and the point of fault, the remaining customers who were off supply were supplied with small generators. The field engineer had confirmed the fault conditions within 23 minutes of being onsite, but he did not arrive onsite until 06:49am due to the delay in trouble calls received because the fault had occurred during the night. This further delayed the time for the back-feed to be inserted as well as the time it took to get a pre-location.

4) Pre-location and cable-tracing

A semi-pre-location was already established by estimating the point of fault from the number of customers whose power had been restored from the back-feed. As power was restored between 24 Manse Road to 57 Westwood Road, this indicated the fault to be approximately outside 24 Manse Road. A TDR was then used successfully to pre-locate the estimated fault location and referring to Figure. 10 (a) and (b), the TDR indicated a short circuit fault at 51.1m from Newmains Cross S/S. The distance was measured out on UMV drawings to determine the position geographically. It was estimated that the point of fault was situated at the coordinates; X:282304, Y:656030, as shown in Figure. 10 (a). The OS coordinates indicated the fault to be outside of 28 Manse Road. The cable was then traced with the use of a CAT and Genny in conjunction with UMV maps.
The fault could not be pinpointed with the use of the cable sniffer method because the makeup of the ground did not allow gas to disperse to the surface. Therefore, the field staff resorted to the cut and test method to determine the direction of the fault. First the estimated fault location was excavated and the cable was identified through the use of UMV drawings and cable make-up. Then the cut and test was carried out on the LV cable at the first joint hole to establish the direction of the fault, as shown in Figure. 11.

The test indicated that the fault was back towards Newmains Cross S/S so a secondary TDR trace was carried out at the first joint hole position which indicated the fault to be in the middle of the road. As it’s not practical to excavate on the road unless necessary, a second joint hole was excavated at the other side of the road to allow for a second cut and test. This cut and test confirmed that the fault was between the position of joint hole 1 and 2. As the fault was cut off from the network now, the LV fuses could be replaced at Newmains Cross S/S, thereby, restoring power to all customers, as shown in Figure. 6 (a). This fault was not repaired until the following day because of the time it took field engineers to conduct the cut and test procedure. As field staff had positively identified the fault to be between joint hole 1 and 2, a track was excavated between the holes to determine the exact location of the fault. The faulty cable section was not large enough to require another cut and test so a new section of LV cable was just pieced in instead. The cable was then jointed live and the back-feed was removed from pillar 18 to prevent further disruptions and restore everyone back on to the main supply, as shown in Figure. 12.

This case concludes that even though all previous steps had relatively high success; there were sufficient number of trouble calls; there were no obstacles complicating the process, in fact there was sufficient information to narrow down the faulted area of the cable even before a successful pre-location was obtained from a TDR; yet, failure from employing the sniffer resulted in the field staff turning to the cut and test method from the pre-location estimated distance. An important point to note is that the underground LVDN is not continually monitored, so sheath faults go undetected until they deteriorate to form faults with the cable conductors. Since the voltage gradient method is conventionally known to be used for pinpointing sheath faults [3,6], field staff are not commonly aware that the voltage gradient method can also be used to find conductor faults which have affected the sheath and also made contact with the surrounding soil. Thus, the voltage gradient method is not commonly considered for faults in underground LVDN. The twist method is also not heard of in common industrial practice, mainstream literature such as the IEEE std 1234-19, Cigre and megger [3,5,6] don’t give any information about the procedure. Consequently, there has become a lack of awareness for available solutions, which is why the field staff in this case study resorted for the cut and test method before ruling out the possible application of the voltage gradient and twist methods beforehand.

The total time to repair the fault (from the time of receiving the first trouble call to the time the customers were restored to the main supply) was around 26 hours. Considering that an average fault repair process that doesn’t encounter any difficulties (such as unsuccessful pinpointing with the sniffer method) will take up to 6 hours, this fault repair case shows that the time delay caused by excess excavations from the cut and test method can delay the total fault repair time by 4 times as much.
B. CASE STUDY B (CSB)

1) Fault acknowledgement

The first trouble call from Hillside Crescent was received at 14:51. After the first call, a further 11 calls were received within 15 minutes. SPEN engineers were dispatched and were informed to attend a LV distribution fault in conformance to receiving a concentration of calls from the same street.

2) Faulted cable/section identification

The calls were traced to the area with distribution from Bent S/S, and upon arrival to Bent S/S, the SPEN engineers confirmed that all 6 ways on the LV board feeding out of the S/S were all in healthy conditions (no熔断的熔丝). Onsite the SPEN engineers cross examined their drawings with the customer call list and concluded the fault to be beyond pillar 153, as shown in Figure 13, circled red.

The troubled calls received revealed the fault to be within the highlighted yellow section. SPEN engineers went to the first pillar out from Bent S/S (Pillar 153 – a 6-way pillar) to investigate the fault further. Engineers used test lamps within the pillar to determine that way-1 within pillar 153 was the in-comer cable (the cable that fed from Bent S/S into pillar 153) and had a melted fuse on the red phase. In this case the in-comer fuse had melted first instead of the out-going feeder fuse on the faulty red phase of the cable because all fuses were rated at 400 A without any discrimination, therefore, the more heavily loaded in-comer red phase fuse melted when a passage of fault current was detected, as it was the weaker fuse.

The engineers established that the fault must be down either of the ways-2, 3, 4, 5 or 6 and the 400 A in these feeders didn’t melt as quick as the in-comer cable. Engineers then determined that the best port of call to establish what cable was faulty was to use a Fusemate [30]. The Fusemate is a circuit reconnector you can operate at the fuse point using a remote control from a 32m distance in-case there is dangers of a high fault current. Applying the Fusemate to each of the out-going feeders and replacing the melted fuse from the in-coming cable of way-1 determined that the fault was located on the cable of way-4 because all other out-going feeders kept the fusemate holding whereas way-4 didn’t. Hence, the fault was concluded to lie between pillars 153 and 156 as shown in Figure 14. The fuses of all remaining ways were replaced to restore power to the remaining customers who were off supply. CSB gives an example that although trouble calls were received in a shorter period than CSA, determining the faulted cable was a longer process and sufficient information was not available to narrow down the faulted section of the cable.

3) Stage and type of fault

Since the applied Fusemate circuit reconnector didn’t hold on way-4, this indicated the fault to be at a permanent stage and the fault type to be a three-phase short circuit fault. If the fuse had held and the power supply was not restored then the fault would’ve been concluded to be an open circuit fault.
4) Pre-location and cable tracing

Engineers attempted a pre-location of the LV fault which lied between pillar 153 and pillar 156. A TDR reading was taken of the cable but was unsuccessful in this case as no clear fault was seen. Engineers then fitted a REZAP (re-closer fuse) and done multiple re-closing because the fuse wouldn’t hold. This was done to ‘burn’ the fault with supply current and reduce its fault resistance so the TDR could acknowledge it. ‘Burning’ the fault successfully changed its conditions allowing the TDR to reveal a suspected three-phase short circuit fault. A second TDR reading gave an estimated fault location of 34m from pillar 153 and pointed towards the nearest service breech (a T-joint that connects a main service cable to domestic loads). Similar to the type of fault in CSA the other side of the short circuit fault was a three-phase open circuit between the fault and remainder of the cable to pillar 156, hence the same procedure had back-feeds installed at pillar 156 to restore power to all the customers up to the fault point. Beyond the point of fault, the customers who fed off the service breech were connected to generators until the fault was located and repaired.

5) Pinpointing/ Cable Identification/ Repair

Engineers used the sniffer at the pre-located fault point, approx. 34m from pillar 156, and obtained successful pinpointing of the fault, as shown in the UMV diagram of Figure. 15. The fault was then excavated to reveal that a three-phase short circuit at a service breech joint had occurred (service breeches and joints holes are shown as black dots in UMV diagrams). The service breech was repaired, the back feed was removed from pillar 156 and the mains supply was restored.

VI. PROPOSED LV FAULT-FINDING GUIDE

The proposed LV fault-finding guide is presented in the form of a conditional flowchart as shown in Figure. 16 and encompasses the range of fault-finding technologies/techniques, processes and fault scenarios detailed in sections III and IV. The information was derived from literature review and consultations with SPEN’s field staff in conjunction with several visits to faults sites and review of case studies provided in Section V. Unlike MV and HV networks, LV distribution networks lack integrated continual monitoring systems. This means that the acknowledgement of a fault can only be established by receiving troubled calls from customers and the faulted cable can only be determined by examination at fault site instead of by automated means such as through SCADA and PMU detection systems. To know whether a fault is intermittent or permanent is determined with the reclosing of the fuse – if the fuse recloses but the power is not restored to customers, this is also an easy indication on the occurrence of a permanent open circuit fault. As mentioned in Section III, there are four main stages of a fault – transitory, intermittent, persistent, and permanent. The transitory stage of faults doesn’t trip the fuse so it’s likely to occur unnoticed unless the network is integrated with computational fault-finding techniques. Persistent faults are considered as just a severer form of intermittent faults and permanent faults are faults at their final stage, hence, this paper only addresses intermittent and permanent type faults.

For intermittent faults, the first fault-finding protocol is to replace the melted fuse with a smart fuse. The smart fuse will record the voltage and current profiles before being tripped by the same fault. The recorded profile is used to track down the fault location. The fault location estimation (pre-location) from the smart fuse can then be used in conjunction with an automated TDR which is capable of obtaining intermittent fault location estimations. Since there
are no pinpointing techniques applicable to the LV distribution network for intermittent stage faults, the fault location estimations obtained from the smart fuse and automated TDR need to be within proximity before proceeding to the excavation process. If either measurement is not obtained or closely matching, then the chances of error in fault location are too high to engage. Hence, measurement attempts can be made every time the smart fuse trips at the re-occurring fault, especially if the intermittent fault degrades into the persistent stage. If matching measurements are still not obtained after repeated attempts, then the remaining option will be to wait until the fault becomes permanent. If near matching estimations are obtained, then the final steps are to trace the cable route using a CAT and Genny device before identifying the faulted cable and repairing the fault.

Notice also, that the intermittent branch doesn’t have a pinpointing element, this is because there is no pinpointing technology available for intermittent faults. The intermittent TDR has to be used in conjunction with the measurements obtained with the smart fuse and the fault can only be intercepted if both measurements are obtained and matching in close proximity. If either measurement is not obtained or not matching closely then the chances of error in fault location are too high to engage. Hence, measurement attempts can be made every time the smart fuse trips at the re-occurring fault, especially if the intermittent fault degrades into the persistent stage, but if matching measurements are still not obtained then the only option will have to be to wait until the fault becomes permanent. Furthermore, the TDR of the intermittent branch is not the same TDR used for permanent faults, rather this is an intermittent TDR as the likes of Transflekt mentioned in Section III-B. Although both types of TDRs are automated versions, the intermittent TDR can recognise intermittent faults whereas the TDR used for permanent faults can’t.

For permanent faults: testing lamps, ohm meters and even TDR’s can be used to determine if a fault is an open or a type of short circuit fault. Since HV radar techniques and bridge techniques can’t be applied to the underground LVDN, conventionally, the only technique known by field staff to be applicable for pre-location is the automated TDR. However, the twist method can be applied without the need for a pre-location estimation. The twist method is rightly specified as a pinpointing technique in the IEEE std (1234-19) [6] but figure 6 of the standard clearly illustrates that a pre-location is required before the application of the twist method. However, the twist method can actually be used as a pinpointing method without the need of a pre-location, and in fact, can be used if the TDR is unsuccessful. The application would be similar to that of cable route tracing as the process would require the engineer to walk up the cable length to the fault point. Understandably, the TDR remains as a primary option because it is able to pre-locate all fault types (not just faults between conductor cores) and is quicker than walking up several hundreds to a kilo meter, however, it is important to know that the twist method is an alternative in the event of an unsuccessful pre-location attempt. The voltage gradient method can’t be applied without a pre-location estimation because the supplied current that flows out from the faulted section of sheath and disperses into the ground will not likely reach more than 100 meters from the fault point. The sniffer method would also be impractical without a pre-location estimation as it consists of drilling 8mm holes a few centimeters apart in order to analyze and compare the level of gasses given off from the deteriorated cable dielectric. If the TDR is unsuccessful due to high fault resistance, then the ‘burning’ technique can be applied to reduce the resistance. As the TDR and twist method are only applicable for low resistance faults, it’s likely that if the TDR fails to identify a short circuit fault due to high resistance, then the twist method is also likely to fail. Although the IEEE std 1234-19 [6] advises precaution from excess burning and recommends avoiding the conditioning technique altogether, lack of alternatives make the process necessary as it is less destructive, less expensive and more efficient than the cut and test method.

If a successful pre-location is obtained using a TDR, the cable route is then traced using a CAT and Genny device before the fault is pinpointed. For sheath faults and faults where there is contact between the cable conductor and/or sheath to ground, the voltage gradient method can be used. For short circuit faults between cable conductor cores, the twist method can be applied. The sniffer is used for any fault where there is insulation breakdown i.e., line to line, line to ground etc. As the sniffer can be applied to a wider range of faults, it can be used as a back up to the twist and voltage method, should they produce unsuccessful results. If the pinpointing is unsuccessful, then the last resort will be to conduct the ‘cut and test’ method from the pre-location estimated area to find the exact fault location before repairing it. The flowchart in Figure. 16 is designed to summarize fault-finding procedure in a structured form, which is believed to provide a more complete picture for fault-finding and fills gaps in pre-existing literature, such as the IEEE std 1234-19 [6]. The gaps filled by the proposed flowchart are as the following:

- **Permane**
Fault is confirmed on LV network (Trouble call method)

Determine faulted cable/section

Is the fault intermittent or permanent?

Permanent

Fault identification (Testing Lamps)

Pre-locate fault (TDR)

Burn the fault and retry TDR

Was pre-location successful?

Yes

No

Trace cable route (CAT & Genny)

Pre-location obtained?

Yes

No

Is the fault L-L or L-L-L?

Yes

No

Pinpoint fault (Twist Method)

Is fault located?

Yes

No

Cut & test method from half-way point of circuit

Is fault located?

Yes

No

Pinpoint fault (Sniffer)

Is fault located?

Yes

No

Pinpoint fault (Voltage Gradient Method)

Is fault located?

Yes

No

Trace cable route (CAT & Genny)

Excavate and identify faulted cable

Repair fault

Reconnect cable and restore supply

Apply smart fuse and wait for fault to re-occur

After fault re-occurrence, use TDR* to confirm smart fuse fault location estimation

Does the smart fuse match the TDR location estimation?

No

Yes

Wait for fault to re-occur until the smart fuse and TDR* have near matching measurements

Is the fault intermittent or permanent?

Intermittent

Is the fault L-L or L-L-L?

Yes

No

Is the sheath damaged?

Yes

No

Pinpoint fault (Twist Method)

Is fault located?

Yes

No

Pinpoint fault (Sniffer)

Is fault located?

Yes

No

Cut & test method from pre-located area

FIGURE 16. FLOWCHART OF THE PROPOSED LV FAULT-FINDING PROCEDURE
The gaps filled by the proposed flowchart are as the following:

1. The HV Radar methods are unapplicable to underground LVDN due to practicality issues involving the access to disconnect every domestic load connected to the faulted cable section.
2. State-of-the-art technologies that are used as part of common industrial practice have been highlighted, though they were not mentioned in the IEEE std 1234-19. The technologies are:
   - For intermittent fault finding in underground LVDN:
     - Smart fuse
     - Intermittent automated TDR
   - For pre-locating permanent faults:
     - The automated TDR, which filters T-joints.
   - For pinpointing permanent faults:
     - The Sniffer method.
3. Permanent fault pinpointing techniques applicable to the underground LVDN have been distinguished:
   - The Twist method
   - The Voltage Gradient method
4. Acknowledgement is given that the twist method can be used without a pre-location estimation and as an alternative to the TDR if it’s unsuccessful.
5. Information has been presented about the Twist method.

There is no designated LV fault-finding process in SPEN that’s based on a methodical approach. Training in this field is based on gaining valuable experience and knowledge which is handed down from engineers who have become experts in their professions. Yet, limited documentation within SPEN can make it difficult for apprentices and trainee engineers to grasp a deeper understanding. Hence, this comprehensive guide was developed for the purpose of creating a more methodical structured approach to fault-finding that can be implemented during the course of a fault occurrence, or even after, to further enhance the learning experience from the processes and methods used.

VII. DISCUSSION

Research has shown there to be a limited number of available technologies/techniques for implementing on the LV distribution network. This is due to the network having connections to domestic loads which limit applicability of employing some of the same techniques that suffice for MV/HV fault-finding. The most effective techniques utilized for MV/HV fault-finding involve a process called ‘thumping’, which is a similar process to ‘burning’, as it involves using high voltage to break down the fault resistance through arcing. The arcing causes measurable reflecting pulses as well as a detectable signal in the form of a ‘thump’ sound and an electromagnetic impulse. The thump sound can be used for quick and high precision pinpointing using acoustic and electromagnetic transducers. However, because the high voltage used for thumping can be detrimental to the domestic loads connected on the LV network, the thumping technique is not applicable for LV fault-finding unless every residential premise branched on to the faulty cable is disconnected, which is not considered practical by practitioners. This limits the available options and narrows the rate of quick and efficient fault-finding in the underground LVDN.

As shown in CSA, the sniffer is not always successful and in an unsuccessful event, other options such as the voltage gradient or twist method should be considered before resorting to the cut and test method. However, due to the knowledge gaps in the IEEE std 1234-19 as well as insufficient content from other mainstream technical guides in general, e.g. [3,5,7-10,12,18], field staff are not aware of the alternative solutions and resort to cut and test too soon. The cut and test method is an outdated and primitive procedure that is too often relied on even though it is very time consuming, costly due to excess excavations, and detrimental to cable design life. Research shows that most cable failures occur due to poor workmanship [42], therefore it’s inevitable that cutting and repairing several sections of the cable will compromise the cable’s integrity and make it susceptible to faults occurring in future. Moreover, CSA in Section V-A, records that the cut and test procedure caused the total fault repair time to quadruple, thereby causing it to exceed 24 hours. The fault confirming process of using the trouble call method is highly inefficient because it relies totally on external sources (the customers) to supply critical information that is necessary for the response team to acknowledge the potential fault location. Indeed, CSA showed this method to be quite effective as it provided enough information to narrow down the faulted area to be between a few residences, but the dependency of external sources meant that as the fault occurred during the night, the fault could not be acknowledged by troubled calls until morning hours when the affected customers had woken up. Furthermore, the troubled calls in CSB were not sufficient to inform the field staff on the faulted cable, hence there were considerable delays in both case studies and these limitations deem the method to require updating. The MV/HV networks in most countries benefit from SCADA or PMU systems which continually monitor the networks in real-time operation. The systems allow for real-time data to be instantly processed back to the control room, so in the event of a fault or network irregularity, the engineers can be informed on a more localized fault area as well as the type of fault. The fact that the MV/HV networks have adopted a superior technological approach is evidence that technology is available to apply on to the LV network as well. Although in comparison, due to the innumerable branching to significantly more customers, the LV distribution network may not be feasible to implement SCADA or PMU systems.

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systems. Regardless, the trouble call method should be updated to a more technological approach for sufficient, fast and reliable data acquisition.

Technically, the most optimal approach would be to practice the detecting and locating of transitory faults using automated computational algorithms as this would be a pre-emptive approach to dealing with a fault before it causes an interruption in supply. However, this ideal concept requires the network to be updated with a smart grid operation using a more advanced PMU system setup which includes innumerable sensors at every node of the network. Furthermore, although automated algorithms can minimize human involvement, thereby minimizing the time delay caused by travelling, apparatus set up etc., the computational methods will require the algorithm to have a proven ability to provide high accuracy in fault location because there is no pinpointing technique available to confirm transitory (nor intermittent) faults. Nonetheless, this concept has great potential but will require a feasibility study to determine its applicability.

CONCLUSION

This paper developed a practice guide from research of industrial practices in underground fault-finding as well as field analysis conducted on cable fault-sites in collaboration with Scottish Power Energy Networks. The paper reviewed state-of-the-art LV fault-finding technologies and case studies provided from SPEN to produce an eight-step procedure as well as a detailed flowchart for LV fault-finding to be used in general industrial practice. Prior to this paper, there was a lack of a methodical approach to fault-finding in the underground LV distribution network. The reason could be because literature tends to give more focus on MV/HV fault finding as well as there being a lack of sufficient technologies/techniques since the majority of them which suffice for MV/HV fault-finding cannot be applied to LV cables as they are connected to LV loads.

This has placed more emphasis on field staff depending on their accumulated experience and time spent on fault cases rather than on a methodical approach.

The eight main steps in the LV fault-finding procedure are 1. Fault acknowledgement, 2. Faulted cable/section identification, 3. Stage and type of fault, 4. Pre-location, 5. Trace cable, 6. Pinpointing, 7. Cable identification and 8. Fault repair. From these steps, the following areas require improvement. Firstly, the research concluded that the fault acknowledgement process via trouble call method is outdated and a feasibility study should be conducted to determine viability of integrating smart systems such as SCADA or PMU onto the LV distribution network so that faults can be identified and reported in real-time to the DNO control rooms, thereby drastically reducing the time customers spend offline. Moreover, it will also be worthwhile to conduct a feasibility study into implementing a PMU system in conjunction with smart sensors into the network so that computational methods can be practiced for more efficient and accurate fault-finding as well as increasing capability to practice locating transitory faults. Undoubtedly, an investment is required to develop new technologies for underground LV distribution network, especially for the pinpointing process as currently the only non-destructive pinpointing technology for this sector is the sniffer method. Perhaps the implementation of computational methods will suffice with high accuracy algorithms, but if the algorithms themselves can only provide pre-location scale measurements, then DNO’s will still be subject to the same shortfalls.

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