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Review of Cable Fault Locating Methods and Usage of VLF for Real Cases of High Resistance Fault Location First

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Abstract

We are in the cable age, and cable circuits are the primary carriers for electrical transmission and distribution networks. Cable and its associated accessories faults are always predictable and quite common. Failure of cable circuits can occur at the commissioning stage or while they are in service. Utilities and service providers consider such failures unacceptable as they impact their reliability and business continuity, necessitating the implementation of specific measures to mitigate them. This paper examines the history of cable fault-finding methods and the most effective techniques for locating high-voltage cable and accessory faults. It identifies the most effective methods based on their ease of use, speed, accuracy, and minimal impact on the cable circuit's life cycle. It also talks about how useful it was to use the very low-frequency (VLF) method to convert high-resistance faults into low-resistance. It also talks about the real failure scenarios for high-resistance faults in high-voltage cable circuits at the commissioning stage.

Keywords: Cable Circuits; Cable faults; High resistance; Low resistance History; Type of cable faults; VLF.

1. Introduction

In today's modern world, electricity is an essential part of everyday human life. A blackout occurs when part or ALL the transmission or distribution system is out of service, potentially affecting a greater number of human activities. A variety of factors, including cable circuit failure, can potentially cause a blackout. The entire system of cables and accessories is prone to failure. These failures can be the primary cause of extensive outages or even blackouts, affecting both the transmission and distribution systems, as in [1,2].

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Utilities and service providers consider such failures unacceptable as they impact their reliability and business continuity, necessitating the implementation of specific measures to mitigate them. One of the measures involves securing their transmission and distribution network using the contingency N-k criteria, which usually has a minimum contingency of N-1. If one feeder fails, the second standby feeder can restore the power supply without any interruption. A complete blackout, like the one that happened in Turkey in 2015 as in [1,2], cannot fulfill this contingency plan. If a contingency plan is available or if one of the feeders is out of service, a cable failure due to overloading, external damage, or an unexpected fault can cause a portion of a blackout. This happened in the UK in 2022, as in [3], when a huge area of northern London faced a blackout due to a fault in an underground cable. There was a complete power outage in Zanzibar, Tanzania, due to cable failure, as in [4], from 21 May to 18 June 2008. Manufacturer errors and deficiencies caused multiple cable and accessory failures in the Netherlands between 1997 and 2014, as stated in [4]. There is a potential risk to the normal operation of the power grid in China due to some cables reaching 40 years old, as in [5]. The prolonged design life of cables has resulted in multiple failures in developed nations, such as the UK, as noted in [6].

Similarly, faults during a new cable installation project can result in significant delays and higher costs, as well as greater transmission or distribution network risk, due to commissioning delays. As a result, cable circuit faults are always predictable and require rapid localization with appropriate procedures.

There are two main categories of faults in underground cables and accessories: defects and damage. Electrical, mechanical, THERMAL, and environmental factors, as well as poor workmanship during installation, particularly in cable accessories, can lead to defects. The cable route corridor may sustain damage from installation or third-party labour, as in [4] [7]. The ideal solution accurately locates cable faults in the least amount of time and with the least amount of insulation vulnerability. Most publications primarily focus on open-circuit and low-resistance faults, with comparatively less attention given to high-resistance faults, which could be considered a gap in the fault-locating approach, as in [8].

High-resistance faults: The cable's fault point has a higher DC resistance than the typical cable surge impedance, and the failure only impacts the insulation.

This paper talks about the use of very low frequency (VLF) to deal with high-resistance faults, as well as the results of case-based fault-locating methods.

2. Cable Fault Locating Method

Thomas Edison invented the first power cable over a century ago, and New York City was the first to install it. Nowadays, power cables are essential elements for the transmission and distribution of electricity. Hence, the emphasis on locating faults in cables keeps growing, as shown in Fig1.

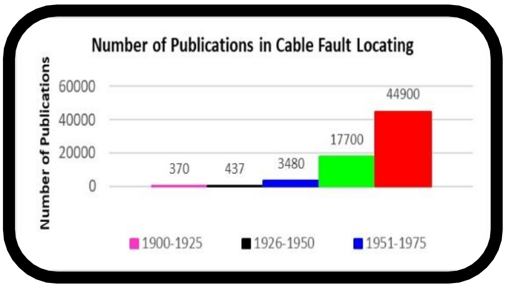

Figure 1: Number of publications

There are two methods for locating faults in underground cables: offline and online. As in [9] [10] [11], offline fault-locating methods fall into two categories – terminal and tracer types. THE TERMINAL (OR PRE-LOCATING) TYPE MEASURES FAULT DISTANCE BY COMPARING THE ELECTRICAL CHARACTERISTICS OF FAULT CONDUCTORS WITH NORMAL CONDUCTORS. The tracer, also known as the pinpointing type, injects a signal into the cable for detection along its length, and when the detector response changes, it indicates the fault location. The process involves "walking along a cable route" to locate an audible or electromagnetic signal. The online fault-locating method provides fault distance, as well as the recorded measured values of fault current and voltage. Nowadays, the preference is for online fault-locating methods. The fault in the underground cable and accessories can be due to manufacturer defects, damage or poor workmanship, as in [12] [13]. Regardless of the cause, the fault classes can be open-circuit, low-resistance or high-resistance, as in [14] [15] . High-resistance faults are further divided into three subcategories: reducible, bumper, and water faults, as mentioned in [16], as shown in Fig2.

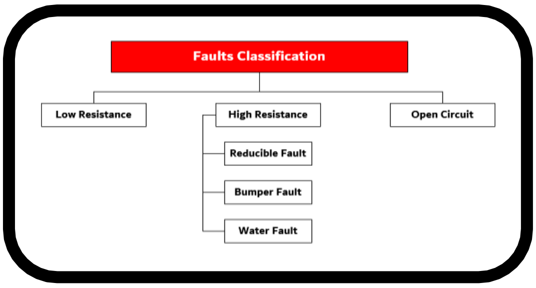

Figure 2: Fault Classification

A high-resistance fault exhibits non-linear characteristics; therefore, it is necessary to either burn or lower the breakdown voltage to a specific limit to facilitate fault location. Applying a high voltage causes a type 1 reducible fault, which transforms a high-resistance fault into a low-resistance fault. A type 2 bumper fault occurs when we periodically lower a high-voltage fault resistance, which triggers a flash. We cannot lower water fault resistance in all cases, as in [16].

We conducted an extensive literature review on fault-locating methods for the different fault classes listed in Table 1. Depending on fault characteristics, we choose the best methods and voltages to apply. Therefore, continuity tests or insulation resistance measurement tests can identify whether the fault is low or high-resistive. Table 1 demonstrates that there are comparatively more publications on low-resistance fault identification, such as bridges and TDR, with acceptable accuracy. FOR HIGH-RESISTANCE FAULTS (≤GΩ), LOWER THE FAULT

RESISTANCE BY BURNING IT WITH HIGH-VOLTAGE DC USING METHODS LIKE IMPULSE OR ACOUSTIC. DC VOLTAGES ARE USED TO DETERMINE CABLE BREAKDOWN VOLTAGES. However, there is a limit on DC-applied voltages that cable manufacturers have concerns about and can allow (e.g., <30kV for a 145kV rated cable), as DC voltage can build up space charges in insulation. The space charges weaken the insulation breakdown strength and can lead to premature failure, as in [17] [18]. Testing voltage at a higher frequency (e.g., 50/60 Hz) takes a longer time to locate the fault and increases the defect size, whereas at VLF (e.g., <1 Hz), the defect size does not increase, as in [19].

Table 1: Timeline Survey on cable fault-locating method publications

Method		Ref (s)	Years	Description
Tracer	Terminal (pre-locating)			
Cut and try	-	[20]	1901	The cable undergoes multiple cuts to identify the location of the issue. An expensive and unscientific method.
Smoke method	-			Injecting current causes the fault to burn, generating smoke. The location of the smoke shows the fault. However, this method accelerates the ageing of the cable and accessories.
Compass / induced	-			Inject a current that changes its polarity every 10 seconds and use a compass needle to measure the changing polarity. If the needle stays stationary, it shows a fault.
-	Bridge Method	[21]	1911	Shares experience of cable fault-locating and suggests using Murray Loop.
		[22]	1931	Used for locating resistance faults on cables and focuses on Varley Loop. For low resistance faults, it can provide an exact location, but for high resistance, it is less accurate.
		[23]	1991	Presents classic techniques of fault locating and suggests using the Murray Loop for low resistance fault and Capacitance Bridge for an open circuit fault.
		[8]	2008	Improve the Bridge Method that can pre-locate fault to a range of tens of MΩ instead of tens of kΩ.
		[15]	2012	Explains the principle of Murray Loop and Glaser Loop. The Murray loop method can be inaccurate if the cable ends at gas-insulated switchgear (GIS).
		[24]	2020	Proposes a digitalised Wheatstone bridge to improve pre-location accuracy.
		[25]	2020	Optimization method for accurate fault-locating by automating Murray and Varley Loop test using MATLAB.
Acoustic Method	-	[21]	1912	The voltage keeps increasing until the breakdown. The fault is located by sound.
		[26]	1932	Locates high resistance faults by using a constant current transformer to reduce the high initial resistance and to prevent its increase by connecting to a short-circuiting switch. This generates signals for locating the fault by sound.
-	VLF	[19]	1989	The high resistance faults are NODUS, which requires, in most cases, burning the fault to lower resistance for a locating method. In the late 1970s, research revealed that employing higher DC testing voltages could reduce the lifespan of cables due to the presence of defects. On the

				other hand, cables not exposed to high DC voltages lasted longer. The DC voltages build up a space charge around defects in insulation [33]. VLF test recognises existing defects and faults without jeopardising cables.
		[28]	2016	Uses VLF to assess cable condition by measuring tan delta (TD) or partial discharge (PD)
		[29]	2014	The assessment of hydropower cable insulation is conducted by studying the resistance, tan delta, and partial discharge using the VLF method. The system gives a series of guidelines to enhance the quality of testing.
		[30]	2022	Real-time evaluation of cable insulation uses VLF to improve tan delta measurements.
-	TDR	[19]	1989	The limitation of the time domain reflectometer (TDR), also known as the pulse-echo/radar method, is its inability to distinguish small fault reflections from reflections of naturally occurring irregularities in cable faults between the conductor and shield with resistance values greater (x10) than characteristic cable impedance (Zo). Impulse and TDR allow for the location of any type of fault.
		[23]	1991	Reflection method
		[31]	1993	The cable dimensions and the fault conditions can find the pulse-echo.
		[32]	2017	Uses TDR to pre-locate faults in submarine cables.
		[33]	2019	Tests TDR and can reach 100km of cable.
	Impulse Method	[23]	1991	The impulse method (also called the capacitor discharge or thumper method) is the most practical for pinpointing all types of faults. An adjustable spark gap figures out the level of charging of a capacitor, which receives a DC. We connect the defective cable in series with the gap to allow the capacitor to discharge into the cable.
		[18]	2020	Locates high-resistance faults by using the impulse method and reflection wave form.

Use VLF to reduce high-resistance faults. While most of the publications we reviewed – such as in , [35] [29] [36] [37] – used VLF to assess cable condition by measuring tan delta (TD) or partial discharge (PD), very few publications used it for cable fault-locating. Therefore, this paper reports on real failure scenarios in cable and accessories using VLF for locating high-resistance faults (≤G). Fig. 3 and Table 2 demonstrate the use of fault-locating test kits.

Figure 3: Fault Locating Test kits

Table 2: Kits Details used for High Resistance faults Identification

	MIT 1025	HVA120	Shirla	Teleflex SX-1	SWT 32
Input Voltage	90-264 V 47-63 Hz	210-240V 50/60 Hz	240V 50/60Hz	240V 50/60Hz	240V 50Hz
Output Voltage	100-10kV	0-120kV peak (sine)	10kV max	50V (pulse 20ns -10us)	8-32kV
Max Output Current	3mA DC	56mA AC	10mA 5kV 50mA (bridge) 700mA (pinpointin g)	-	-
Frequency	-	0.01 - 0.1Hz	-	-	-
Accuracy	Resistance $\mp 5\%$	(voltage) $\mp 1\%$	$\mp 10\mu A$	0.1%	-
Load Range	10nF- 25 μF 10k-20TΩ	Thirty μ F max	-	10-149 m/us	-

Test Results

We have identified three circuits with faults. Circuit A consists of six sections, five joint bays and two sets of terminations with a total route length of 3,905 metres; Circuit-B consists of three sections, two joint bays and two sets of terminations with a total route length of 1,494 metres, and Circuit-C consists of nine sections, eight joint bays and two sets of terminations with a total route length of 5,779 metres. All cables and accessories have passed routine tests in the factory. The cable's diameter is 90mm, and the XLPE insulation thickness is 16mm. The cable circuit's design is for 132 kV, with a rated voltage of 145 kV. According to IEC 60840, cable circuits must withstand an HVAC test for one hour after the completion of installation-related works before commissioning, as shown in Fig4.

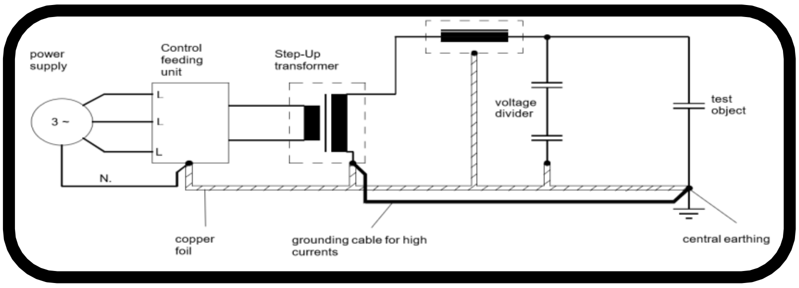

Figure 4: Resonance 132 kV HVAC test set-up

The HVAC tests tripled to 76.1 kV for Circuit A, 50 kV for Circuit B and 113 kV for Circuit C due to a fault in one of the cables or its accessories. HVAC tests identified faults in each cable phase, causing Circuit A to trip at 22 kV, Circuit B at 20 kV, and Circuit C at 36 kV. The fault rectification process follows as shown in Fig. 5.

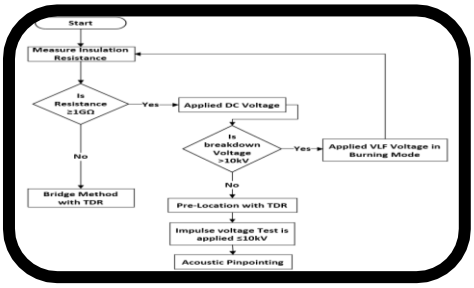

Figure 5: Fault Location Process

A one-minute insulation resistance test at 5 kV on the XLPE cable using the MIT 1025 kit showed these results: 128 GΩ for Circuit A, 4.8 GΩ for Circuit B, and 5 GΩ for Circuit C before the VLF test. It was a high-resistance fault. The DC breakdown voltage for all circuits surpasses 10kV and requires reduction with Very Low Frequency (VLF).

Therefore, it has been determined to reduce the resistance fault in the three specified circuits by adhering to the procedure outlined in the figure. Using VLF and the test set-up shown in Figs. 6 and 7.

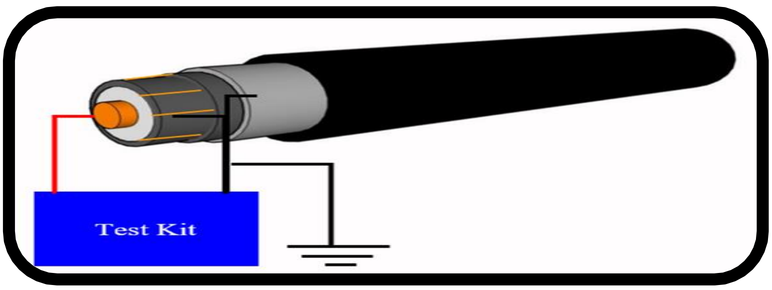

Figure 6: test kit Connection

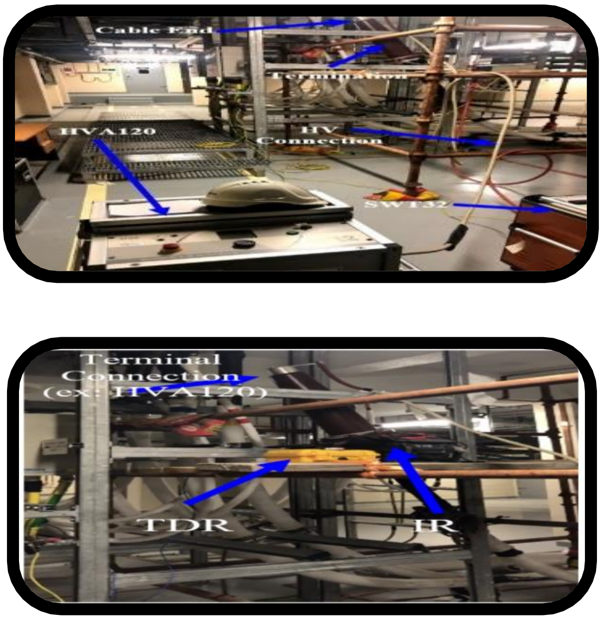

Figure 7: Actual Set Up & Connection

Circuit A

The VLF testing equipment was set to burning mode with the kit at 30 kV for two to three cycles. During this process, the breakdown voltage decreased to 9 kV, while the insulation resistance remained in the GΩ range.

we applied a 10 kV DC voltage pulse to the core of the faulty cable at five-second intervals. This allowed us to pinpoint the fault using the acoustic method. Using the headphones and receiver, we were able to detect a thumping sound at the faulty joint location as shown in Figs 8 and 9

Figure 8: Sound amplifier at fault location

Figure 9: Impulse method with acoustic pinpointing

CIRCUIT B

Using the same method, Circuit B's breakdown voltage was about 1 kV and its insulation resistance was in kilohms. bridge method with TDR is employed to pinpoint the fault at the joint location.

CIRCUIT C

Circuit C's breakdown voltage was about 8 kV, with insulation resistance just under 1 GΩ. Using the surge generator, we applied a 10 kV DC voltage pulse to the core of the faulty cable at five-second intervals. This allowed us to pinpoint the fault using the acoustic method. Using the headphones and receiver, we were able to detect a thumping sound at the faulty joint location.

3. Discussion

An approved manufacturer jointer completed the jointing work in Circuits A, B and C, and the initial dismantling findings show that the fittings and materials used adhered to the manufacturer's instructions. They investigated the failed joints and found less burning, making it easier to track the cause of failure, as shown in Figs. 10 and 11. After the dismantling failure, we discovered almost identical locations for all three joints; we can share brief details in future publications.

Figure 10: Dismantling of joints

Figure 11: Faulty Joint in two cut view

4. Conclusion

We developed a method to reduce the breakdown voltage within the OEM-recommended acceptable range of DC applied voltages or to convert high-resistance faults into low resistance. Presently, VLF testing is a competitive and highly effective tool for MV cables. We adopted VLF testing for identifying high-resistance faults in HV cable circuits.

In three cases involving high-resistance faults, we applied the VLF methodology and determined that it is both cost-effective and time-efficient. This approach also minimizes damage to insulation when addressing complex cable circuit faults. By applying this methodology, we have successfully identified five high-resistance faults in cable joints and one in a cable, along with a comprehensive analysis of three incidents. Early results from disassembling failed joints and looking at them show clear electrical traces that point to the cause of failure.

The publication also briefly covered a joint failure analysis. Other works can explore this topic in greater detail.

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