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Identification and Location of PD Defects in Medium voltage Underground Power Cables Using High Frequency Current Transformer

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ABSTRACT Fault location is an important diagnostic task in condition monitoring of underground medium voltage cables. Available solutions are well capable of determining the location of a single partial discharge (PD) defect on a cable section. In case several PD defects are active simultaneously along a cable section, the interpretation of the measured data becomes complex to identify the presence of more than one PD sources. In this paper, experimental investigation of two PD defects/sources at different locations on a medium voltage (MV) cable section is presented. A high frequency current transformer is used for single end PD measurements. Time domain reflectometry-based in-depth study of the reflected pulses provides the most valuable information to identify the presence of PD sources which further leads to the location of the individual PD sources. In this paper, the proposed solution is presented for two PD sources, however, the same methodology can be extended to locate multiple PD sources on the cable.

INDEX TERMS Cable insulation, power distribution lines, partial discharges, time domain analysis, sensors, condition monitoring.

I. INTRODUCTION

Overhead power lines are highly vulnerable to various external and climatic factors, such as faults initiated by accidents, adverse weather conditions and natural disasters. Unfortunately, extreme weather events, including hurricanes, storms, snow, and floods usually cause significant damage every year. The operation of overhead power lines is severely affected by this. To minimize the occurrence of faults in the future, several initiatives have been made around the world to replace overhead lines with underground power cables. For example, studies made by Consolidated Edison, Inc. and Florida Public Service Commission have suggested converting the overhead lines to underground cables and provided estimated costs in the range of billions of dollars to accomplish this conversion for New York and Florida [1]. Similarly, in Europe, underground cabling has been adopted as a preferred solution for a reliable and secure means of power distribution [2]. In Finland, the replacement of underground cable installations in distribution network is in progress; reaching an estimated 70% installation in 2023; the target is to complete the replacement by 2028 [3].

This trend is likely to continue, as the security of supply is a top priority for grid utilities and underground installations will significantly reduce the frequency of power outages compared to overhead lines in a vast majority of operating conditions. However the aging, operational stresses, and abnormal situations in the installed underground distribution cables is a looming issue. Therefore, upgrades in the condition monitoring of power cables are needed to pre-emptively avoid fault occurrences in expensive cable installations and the associated critical infrastructure.

Dielectric insulation is one of the most critical components in power equipment, ranging from low voltage to high voltage applications. In all the major network components such as power transformers, cables, switchgear, machines, etc. the purpose of the insulation materials (which can be in either solid, liquid or gaseous state), is to electrically separate the

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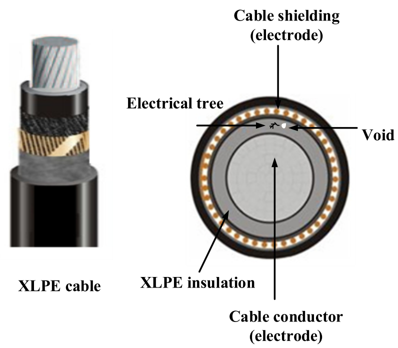

FIGURE 1. Insulation defects depicted in the MV cable insulation.

energized conductors of different phases from each other and from earth. However, when the insulation material has some defects (cracks, voids, or cavities) as depicted in Fig. 1, the dielectric strength of the defective part decreases, which causes the occurrence of partial discharges (PD). PD activity within solid insulation is initiated in the defective locations under suitably high electric field stress. PD activity progresses in time and may lead to the development of carbonized paths inside the insulation, so-called 'electric trees', which tend to expand and after a certain amount of time lead to insulation failure if not attended to in a timely manner.

Although PD activity is a gradual process of degradation and it may follow a certain pattern to failure, however an event of elevated stress may lead to an accelerated rate of degradation and cause sudden failure [4]. To prevent the unexpected outages, PD-based online condition monitoring is an effective tool to observe the PD profile of the most failure-prone grid components. Cables are of particular interest in this regard as the most vulnerable components of the electric grid regarding insulation faults [5], [6]. Cable repairs are time-consuming and accurate fault location is not always straightforward.

PD is accompanied by electromagnetic activity, which can be used to identify its occurrence. In case of cables, the PD pulse emitted from the defect site propagates along the cable line and can be monitored using appropriate sensors and suitable techniques. Over the past few decades, there has been increasing interest in improving the available monitoring and diagnostic solutions. A lot of work has been done in order to improve the detection and location of the PD defects. However, most of the efforts are aimed at detecting and locating the presence of a single PD defect on the section of a cable.

An ample amount of research has been conducted on the investigation of multiple PD faults initiated by different types of PD sources [7]–[10] in different power components. The developed techniques are used to detect and identify the presence of multiple PD sources which may present as corona, discharges in dielectric liquids, surface discharges or internal discharges using phase-resolved PD (PRPD) patterns. These types of discharges can be identified based on PRPD analysis because each type of PD activity appears during certain phase angles of the voltage cycle. However, when two PD sources of same type are active simultaneously, they will appear at the same phase location and identification of these sources is generally not possible by PRPD analysis. It is important to investigate the individual PD signals to analyze the presence of single or multiple PD-causing defects of the same type.

Antenna and acoustic sensor based techniques have been used for the location of multiple PDs of the same type using PD pulse analysis in the substation equipment such as power transformers, switchgear, and similar types of enclosed system components. These techniques are often, however, not effective when investigating cables. The fact that the cable may span over several kilometers renders the methods based on measurements using multiple antenna and acoustic sensors unfavorable [11]–[13]. A detailed explanation of the capabilities of sensors specific to the type of power equipment has been discussed in detail in [14].

The location of single PD faults in power cables has been traditionally accomplished using the time domain reflectometry (TDR) method [15]. However, its application to multiple PD sources in a single cable has rarely been considered thus far. The TDR technique is usually implemented using one-end measurements (single sensor) or two-ends measurements (two sensors). Both of these methodologies are based on observing the time of arrival (ToA) of the original PD pulse arriving at the sensors, its subsequent reflected pulses arriving at the sensors, the wave propagation speed, and the total length of the cable. However, when two or more PD sources are active simultaneously on a cable section, the sensor(s) at the end(s) of the cable record the emitted (original) PD signals indiscriminately together with the reflected pulses propagating along the line. This makes the implementation of location techniques a complex task. These recorded signals have to be separated from one another in order to correctly recognize each PD source.

Recently, the work presented in [16] describes how to detect the presence of multiple PD sources along the cable section using power spectral separation. The use of this technique can provide adequate results. However, its implementation needs high expertise in signal processing techniques and prior knowledge and assumptions regarding the number of PD sources to aid the experts in making the correct evaluation. Therefore, there is need to keep developing the conventional and speedy techniques.

This paper proposes a simple approach based on time domain analysis for identification and separation of PD pulses from different sources, configuring the number of PD sources, and the location of the PD sources in power cables. The work is based on experimental investigations carried out in a laboratory environment using a high frequency current transformer (HFCT) sensor and single-end measurement. TDR based analysis is used to localize the PD signals.

II. TIME DOMAIN REFLECTOMETRY (TDR) BASED FAULT LOCATION

When PD activity is initiated, PD occurs at particular phase angles over the power frequency voltage cycles.

The amplitude and polarity of these PD pulses depend on characteristics of the PD source, the instantaneous value of the applied voltage, and its polarity. PD presents at a certain repetition rate. The PD initiates an electric pulse, which propagates towards both ends of the cable. The signals are reflected from one end of the cable and propagate towards the other end. When using single end measurement, the signal which first reaches the measurement sensor (HFCT in this case) is designated as the original pulse and the signal reaching the sensor after reflection from the far end is designated as the reflected pulse. The time difference between the original and the reflected pulse can be used to determine the location of the PD source using TDR.

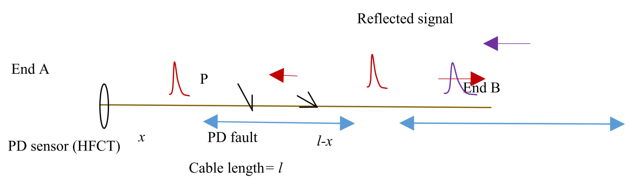

FIGURE 2. PD pulses and their reflections propagating in the cable.

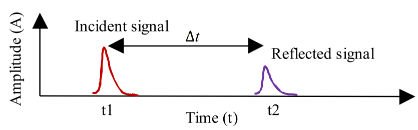

FIGURE 3. Output of PD sensor illustrating time difference of arrival between incident (original) and reflected PD pulse.

As illustrated in Fig. 2, the PD pulse generated from P starts to travel towards End 1 of the cable with length l and is recorded with the HFCT (installed at End 1) at a distance x from point P at time t_1. Simultaneously, the other PD pulse from P starts to travel towards End 2 of the cable by first covering the distance *l-x*. It is reflected from End 2 and reaches End 1 after also covering the distance l and is eventually recorded by the same HFCT sensor at time t_2 as shown in Fig. 3. Considering the wave propagation speed in the cable v, the time t_1 at which the first PD pulse reaches the HFCT can be expressed as:

$$t_1 = \frac{x}{v} \tag{1}$$

Covering the direct distance (*l-x*) towards End 2 and 'reflected distance' l, the time t_2 can be expressed as:

$$t_2 = \frac{l + (l - x)}{v} \tag{2}$$

The time difference of arrival Δt between the pulses is determined as:

$$\Delta t = t_2 - t_1 \tag{3}$$

$$\Delta t = \frac{l + (l - x)}{v} - \frac{x}{v} \tag{4}$$

The distance x of PD source at point P from End 1 can be calculated as:

$$x = l - \frac{\Delta t v}{2} \tag{5}$$

III. PRACTICAL CONSIDERATIONS REGARDING REFLECTION OF PD SIGNALS ON A CABLE

While using TDR based fault location methods, it is important to consider the measurement arrangements, i.e. the length of the cable being tested, the response of the measurement sensors, data acquisition system (DAS) and apply this knowledge when interpreting the data. In this section, practical issues regarding cable length and the capabilities of the measuring sensor are discussed briefly while DAS and data interpretation will be discussed in the following sections.

A. CABLE LENGTH

A PD signal has a certain pulse width P_w, which ranges from a few nanoseconds to microseconds. Based on the wave propagation velocity and the length of the cable, the reflected pulse arrives at the sensor after a certain time difference and is captured by the sensor. It is very important to capture the complete reflected PD pulse, particularly the first part of the pulse. The first peak of the pulse can be considered more reliable for determining the time difference of arrival between the pulses. If the cable length is not sufficient to cause a suitably long time delay between the original and reflected pulse, the reflected pulse will arrive at the measuring sensor during the time interval when the original pulse is being captured. This will cause superposition of the reflected pulse and the original pulse, which causes ambiguity and in many cases it is impossible to reliably distinguish or separate the two pulses in the obtained signals.

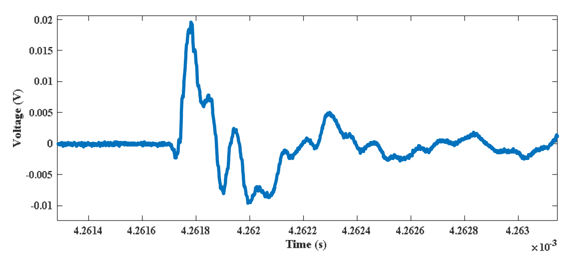

FIGURE 4. Experimentally measured PD signal (pulse).

In Fig. 4, a PD pulse measured on a medium voltage (MV) cable of 10 m length is presented, in which the wave propagation velocity has been measured at 1.54×10^8 m/s. Performing TDR on such a short length of cable may not be useful, because the PD pulse width is approximately 0.142 μs (see Fig. 3), while the reflection appears after a short time, 0.064 μs. The pulses have been superimposed and the reflected pulse cannot be distinguished from the original pulse as illustrated in Fig. 4. The PD pulses undergo multiple reflections, but due to attenuation, the subsequent reflections may not have a high enough amplitude to be measured. In Fig. 5, no reflections can be identified even until 20 μs

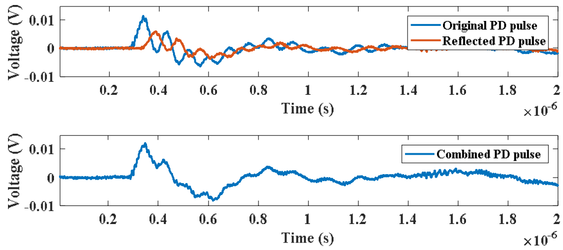

FIGURE 5. PD signal superposition due to short cable length; top- individual waveforms of original and reflected pulse, bottom- the resultant waveform of original and reflected pulse.

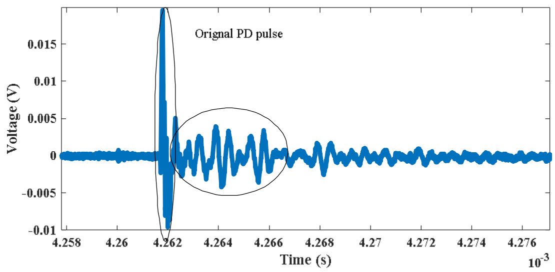

FIGURE 6. Experimentally measured PD signal with post-pulse oscillations.

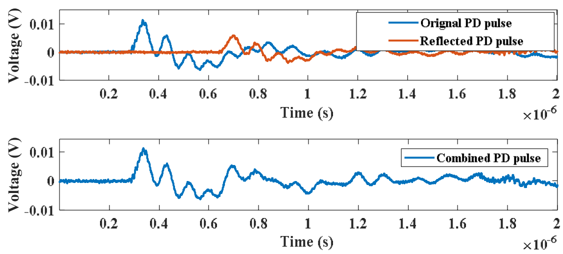

FIGURE 7. Effect of the longer oscillation due to sensor's response; top-individual wave shape of original and reflected signal, bottom- the resultant waveform of original and reflected pulse.

has passed, while a measurement done on a longer cable of 200 m in length would present the first reflection after approximately 2 μs.

For the sake of argument, it can be stated that for a reliable location diagnostic the minimum cable length should be approximately 25 m or more. However, even cables in this length category can experience problems with PD source location diagnostics. This is caused by problems associated with the response characteristics of the measurement sensor.

B. MEASUREMENT SENSOR

A sensor with suitable sensitivity and bandwidth is important for measurement of PD that leads to a reliable location diagnostic in MV cables. Based on their geometrical design and materials used, the cable and HFCT sensor possess intrinsic RLC parameters (resistance, inductance, and capacitance) [14], [17], [18], which affect the waveform of the measured signals.

Oscillations may appear in the sensor output following the PD pulse and are damped after a certain period of time as shown in Fig. 6. It can be seen that the oscillations remain quite significant until the time interval of 12 μs after the appearance of the first PD pulse. Therefore, ideally the study of reflected PD pulses will be reliable if they appear after the oscillatory part. If the sensors have better sensitivity, the amplitude of the measured reflected wave is high enough that the pulse can be identified even if it appears during the oscillatory part. However, a sensor with higher bandwidth has reduced oscillatory time that leads to better measuring performance.

IV. EXPERIMENTAL SETUP FOR FAULT LOCATION ON MV CABLES

Considering the real cases in the MV network, the usual length of cables is in the range of hundreds of meters up to some kilometers. This is sufficiently long for reflections to be easily seen during real world diagnostic measurements. In this study, an experimental investigation is performed at High Voltage laboratory in Tallinn University of Technology. A 20 kV single phase MV cable, type HXCMK with a conductor cross-section of 35 mm^2 and 199.3 m in length, is used for the investigation. The investigation is performed in two stages.

1) Determining the wave propagation velocity of the cable,
2) PD measurement at AC voltage (50 Hz).

A. WAVE PROPAGATION VELOCITY OF THE CABLE

Under fault conditions, cable maintenance is time consuming and expensive due to digging, repairing, and refilling the site while on the other hand inconvenience to the general public is an added burden. Therefore, accuracy of the location of the fault site is imperative. While performing TDR based location diagnostics, accurate information of the propagation velocity is important so that time and velocity based calculations can provide accurate distance and location.

The velocity of wave propagation for a transmission line having air as insulation between its conductors can be calculated as:

$$v_a = \frac{1}{\sqrt{\varepsilon_o \mu_o}} = 3 \times 10^8 \frac{\text{m}}{\text{s}} \approx c \tag{6}$$

which is approximately the velocity of light in vacuum. However, when the insulation is not air or another low-pressure gaseous medium, the velocity is reduced by the velocity factor (VF) which is determined as:

$$VF = \frac{1}{\sqrt{\varepsilon_r \mu_r}} \approx \frac{1}{\sqrt{\varepsilon_r}} \tag{7}$$

The relative permeability $\mu_r \approx 1$ for dielectric materials due to their non-ferrous properties, so the VF primarily depends on the relative permittivity of the dielectric ε_r. VF is defined as the ratio of the propagation speed of light or electromagnetic waves in a medium to the speed in vacuum. Therefore, the calculated wave propagation speed of a cable $v_{c,c}$ can be expressed as:

$$v_{c,c} = c \times VF \tag{8}$$

The diameter of the cable used in the study is 26 mm, cross-linked polyethylene (XLPE) is the main insulation while a semiconducting compound material is used in conductor and insulation screens. The data sheet does not provide any information on the wave propagation speed for this cable. Considering the $\varepsilon_r = 2.2 \ldots 2.4$ for XLPE, the $v_{c,c}$ is in the range of $2.02\times10^8 \ldots 1.93\times10^8$ m/s. However, in order to verify the propagation speed, it is necessary to determine the pulse velocity experimentally as well.

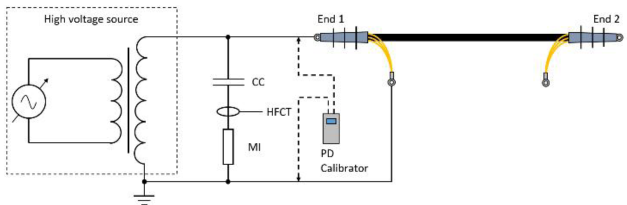

FIGURE 8. Laboratory test setup for online measurement of PDs in the MV cable (electrical layout); CC- coupling capacitor; MI- measuring impedance of commercial system.

The propagation velocity can be measured using a PD calibration device, which is connected in parallel to the tested cable, as illustrated in Fig. 8. The PD calibrator is connected to End 1 and the HFCT used to detect PD signals is installed in series with the coupling capacitor (CC) and the measuring impedance of the commercial PD measurement system. The original (the PD pulse injected into End 1) and the reflected signal (from End 2) are captured by the HFCT (see Fig. 9), the time difference of arrival (TDoA) is determined, and considering the distance the pulse travels is twice the length of the cable, the experimental propagation velocity $v_{c,m}$ is determined as:

$$v_{c,m} = \frac{2l_c}{t_d} = \frac{2 \times 199.3}{2.285 \times 10^{-6}} = 1.745\times10^8 \frac{\mathrm{m}}{\mathrm{s}} \tag{9}$$

The difference between the calculated and measured speed is 9%. The difference can be mainly attributed to the presence of semiconducting screens on the conductor and insulation. The aging of XLPE insulation has also been shown to have an effect on the wave propagation speed, although the cable used in this investigation is manufactured in 2016 and has not experienced aging in field service. The effect of the semiconducting screens and aging has been investigated in [19], [20]. In further analysis, the experimentally acquired value will be used, as it takes into account all the possible effects influencing propagation speed and provides the most accurate information of pulse velocity.

B. EXPERIMENTAL SETUP FOR PD INVESTIGATIONS ON MV CABLES

The test setup used for measuring PDs is depicted in Fig. 10 (physical layout) while the principle electric schematic is shown in Fig. 8. For measurement of wave propagation velocity, the PD calibrator was used as shown with dotted line connection. For PD measurements, the PD calibrator was

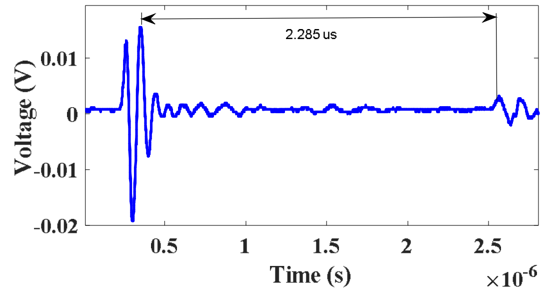

FIGURE 9. Original and reflected pulses injected with PD calibrator in the tested cable.

FIGURE 10. Laboratory test setup for online measurement of PDs in the MV cable (physical layout).

replaced by the high voltage source as shown in Fig. 8. The source has a variable power supply and at the voltage level 13.5 kV the PD started to emerge. In order to have a better signal-to-noise ratio, the applied voltage was raised to 20 kV. The cable terminations are designated as End 1 and End 2 of the cables. A coupling capacitor (1 nF) was connected at End 1 of the cable while the cable is open ended at End 2.

The HFCT has a 15-mm round primary window, the HFCT parameters are:

- Transfer ratio 1:10;
- Bandwidth 0.5 to 80 MHz (-3 dB).

The HFCT output was connected to a digital storage oscilloscope (DSO) with sampling frequency 2 GS/s.

In addition to the equipment used for recording the waveforms of PD pulses, a commercial PD measuring system was used for simultaneously monitoring other parameters, such as PD apparent charge magnitude, repetition rate etc. The commercial system included a coupling capacitor (CC) which was connected in series with the measuring impedance (MI). The impedance and CC in combination work effectively as a voltage divider and the signal acquired from the measuring impedance was used to record the applied voltage waveform using above mentioned high frequency DSO.

In this work, single end measurements are used and the captured data is shown in Fig. 11. The data is recorded

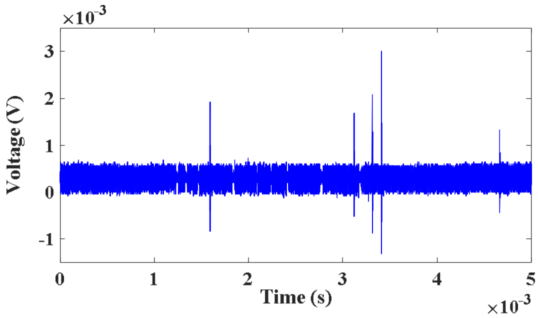

FIGURE 11. PD data of the MV cable measured with HFCT at 20 kV over one voltage quarter-cycle.

with a sampling period of 5×10^{-9} s and is stored in comma-separated values (CSV) format that can easily be imported to Matlab for further analysis on a personal computer.

V. DETECTION AND LOCATION OF THE PD SOURCES

Several measurements have been taken in order to analyze the PD activity. The measurements are recorded subject to the limitation of the number of points (1,000,000 samples) that the DSO can store for a single measurement and a suitable sampling frequency (0.2 GHz) is used to capture the PD signals reliably.

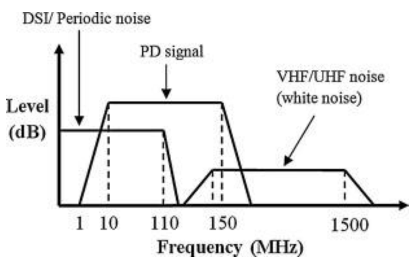

FIGURE 12. Spectra of noise and PD signal [21].

Presence of noise is a critical issue during field measurements and extracting useful signals having lower amplitude is a major challenge. The common sources of noise are: discrete spectral interference (DSI), periodical pulses, random pulses, white noise, and reflections. Figure 12 describes the presence of the noise and PD signals based on their frequency ranges and dB levels [21]. A variety of methods have been reported based on digital signal processing (DSP) techniques denoising such as finite impulse response (FIR) filters, infinite impulse response (IIR) filters, fast Fourier transform (FFT) [21]–[23]. In this work, discrete wavelet transform (DWT) technique presented in [21] has been used. The denoised signal, which presented a better signal-to-noise ratio, is shown in Fig. 13.

For analyzing the individual PD pulses in the time domain, two PD signals have been chosen as shown circled in Fig. 13. These PD signals have been identified based on the post-first pulse behavior that mainly includes reflections and the distances at which they occur. Figure 14 presents PD type 1 having two reflections at certain intervals following the first (original) PD pulse while in case of the PD type 2 shown in Fig. 15, three pulses are observed following the original PD pulse. Considering the apparent behavior, further investigation is made based on TDR principles. The analysis can be proceeded further with two basic findings. Firstly, PD activity is present on the cable line, which means there is at least one insulation defect. Secondly, two types of reflection behaviors indicate the presence of two PD sources at different locations. However, further investigation will explore the PD happening along the line in more detail.

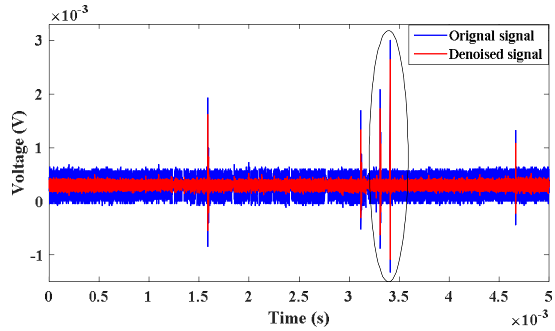

FIGURE 13. Denoising of the measured PD data.

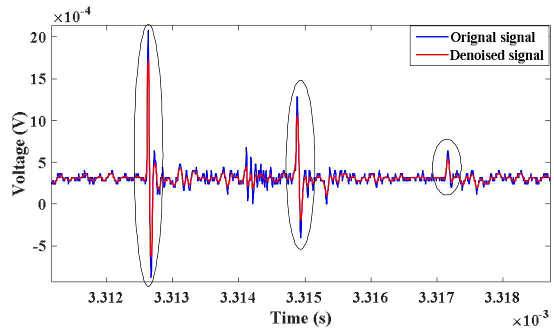

FIGURE 14. PD type 1, PD data identified as potential PDs from a PD source.

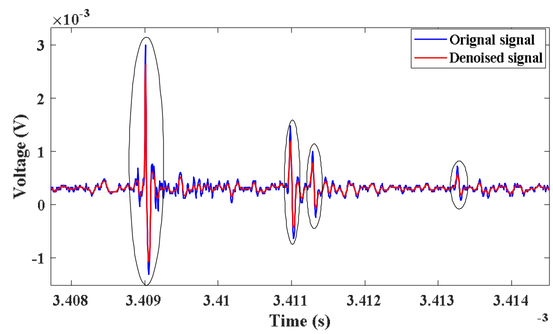

FIGURE 15. PD type 2, PD data identified as potential PDs from a PD source.

A. PD TYPE 1

Figure 16 is re-plotted starting with time zero for better understanding of the TDR analysis. It is observed that Pulse 1 or the

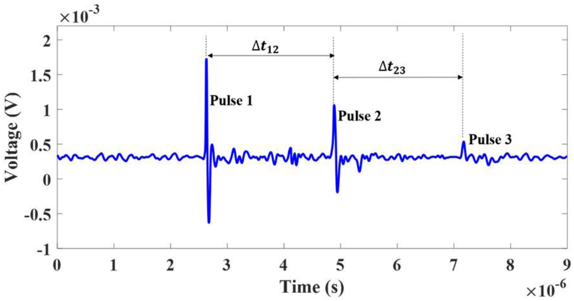

FIGURE 16. TDR based analysis of PD type 1.

original pulse appears at $t = 2.63$ μs, Pulse 2 appears at $t = 4.88$ μs while Pulse 3 appears at $t = 7.17$ μs. Considering the length of the cable (two way length) is 398.6 m and the propagation velocity is 1.745×10^8 m/s, it can be assumed that any pulse appearing within the time frame 2.284 μs, which is the time it takes for the pulse to travel twice the length of the cable, after Pulse 1 will be the 1st reflection of Pulse 1. The time difference between Pulse 1 and Pulse 2 is $\Delta t_{12} = 2.25$ μs. Recalling equation (5), the fault location can be determined as:

$$x_1 = l - \frac{\Delta t_{12} v_p}{2} = 2.56 \text{ m} \tag{10}$$

where x_1 is the distance of the PD fault from the cable End 1, at which the HFCT is connected for PD measurements. It can be seen that Pulse 3 appears at a time difference $\Delta t_{23} = 2.285$ μs after the second pulse. The lattice diagram presented in Fig. 17 for the located PD defect can be used to further explore the observed propagation behavior.

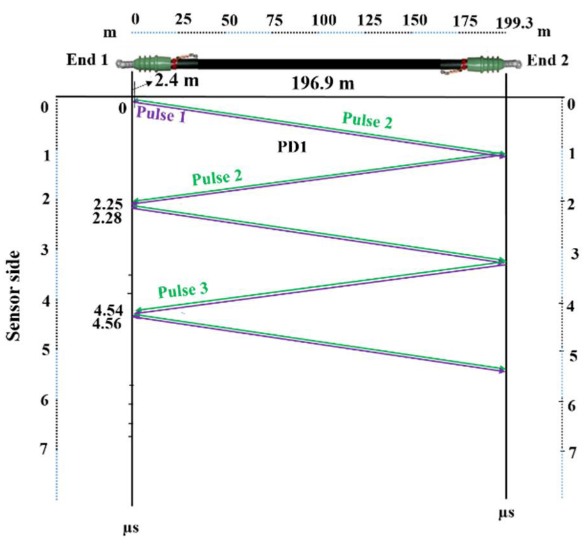

FIGURE 17. Lattice diagram to study the propagation behavior of PD type 1 along the cable.

Considering the PD defect is located at a distance of 2.56 m from End 1, the PD pulse is incepted at the defect site and starts to propagate towards both ends of the cable. Assigning a reference time, the pulse covering the distance of 2.56 m reaches the HFCT at $t_1 = 0$ s as Pulse 1 while towards the other end of the cable, the pulse is reflected from End 2, continues its propagation towards End 1, is measured by the HFCT as Pulse 2 at a time of $t_2 = 2.255$ μs. The time 2.255 μs corresponds to a distance of 2.255 μs $\times$ 1.745 $\times$ 10^8 m/s = = 393.5 m. After having been recorded and the reflection from End 1, it travels towards End 2 and reaches End 1 (as Pulse 3) again.

On the other hand, when Pulse 1 is measured by HFCT at instant $t_1 = 0$ s, it also reflects from End 1 and travels towards End 2. Having reflected from End 2, it also travels towards End 1. This is a time when both the pulses are moving towards End 1 with Pulse 1 following the Pulse 2 at a distance of 5.12 m and reaches End 1 at a time of 2.28 μs. The difference of the ToA is 0.029 μs between Pulse 2 and Pulse 1, which is so small that the two pulses cannot be distinguished during the whole measurement time frame. In addition, comparing the amplitude of the PD pulses after each reflection, significant attenuation can be observed and after Pulse 3, the PD pulse amplitude is so small that it is merged into the noise and cannot be observed any further.

This propagation continues under the effect of two critical characteristic factors of the cable: attenuation and dispersion. These two factors affect the PD pulses in two ways respectively: the decrease in amplitude of the pulse and the increase of the pulse width [24], [25]. After a certain amount of distance travelled along the cable, the pulses ‘disappear’ due to decreased amplitude. The number of reflections after which the pulses disappear also depends on the length of the cable. In other words, the attenuation and dispersion depend on the distance that the pulses travel along the cable.

B. PD TYPE 2

The second type of PD signals are shown in Fig. 18. Considering the zero reference point in the plot, the first (original) PD signal Pulse 1 is measured at 2.61 μs and its first reflection Pulse 2 is captured at 4.585 μs. Similarly, the further reflections Pulse 3 and Pulse 4 are measured at times 4.895 μs and 6.87 μs, respectively. As analyzed above for PD type 1, the first pulse and its first reflection are used to determine the location of the PD fault, while the rest of the reflections are

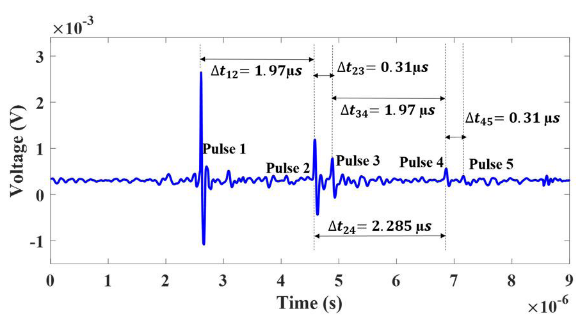

FIGURE 18. TDR based analysis of PD type 2.

important to confirm the determined location and to further study the propagation behavior of these PD pulses between the cable ends. The TDoA between Pulse 1 and Pulse 2 is $\Delta t_{12} = 1.97\ \mu$s. Due to differences in ToA as compared to PD type 1, the location of the corresponding PD fault from End 1 (measuring point) x_2 is calculated using (5) as:

$$x_2 = l - \frac{\Delta t_{12} v_p}{2} = 27.42 \text{ m}$$

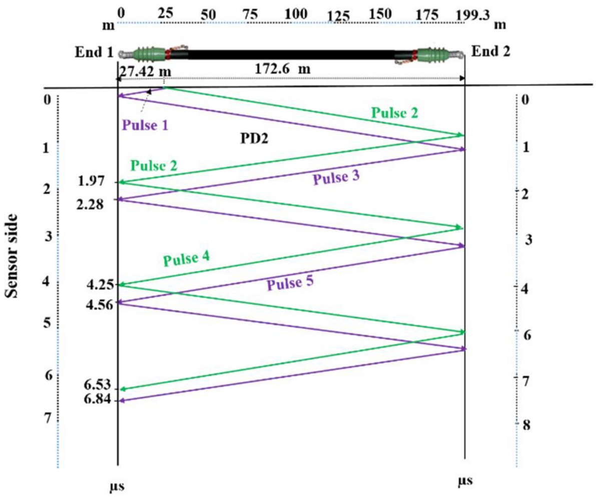

FIGURE 19. Lattice diagram to study the propagation behavior of PD type 2 along the cable.

The lattice diagram for PD type 2 is shown in Fig. 19 and because of the relatively greater distance from the measuring end as compared to PD type 1, the reflected pulses can be distinguished visually. Incepted at the defect site (27.42 m from End 1), Pulse 1 reaches the measuring point at $t = 0$ and at the same time Pulse 2 was travelling towards End 2. In the meanwhile, Pulse 1 is reflected from End 1 and starts to propagate towards End 2 following the Pulse 2 at a distance of 54.84 (2×27.42 m). After being reflected, Pulse 2 and Pulse 3 reach End 1 and are captured at times 1.97 μs and 2.28 μs, respectively. Similarly, continuing after their reflections from End 1 and returning after reflections from End 2, the pulses are captured as Pulse 4 and Pulse 5 at times 6.53 μs and 6.84 μs. The lattice diagram explains the propagation behavior of PD type 2 and confirms the location of the PD fault at 27.42 m from cable End 1.

In summary, PD emission is a continuous activity that emits numerous PD pulses during each voltage cycle. This is obvious and it has been analyzed that the time delay between all the pulses and their respective reflected pulses is the same for the same PD source. In case there are two or more PD sources located at different locations, there should be two or more sets of PD pulses and the time differences of the respective PD pulses should be the same. A study encompassing more reflections provides further insight about the PD sources. In this paper, the experimental investigation is presented that encompasses a cable having two PD sources at different locations. Analysis is made to differentiate the PD signals coming from different PD sources and a location diagnostic is performed.

VI. FAULT LOCATION ACCURACY AND DISCUSSION

The location of both PD defects has been determined and they appear to be at a distance of 24.86 m from each other (x_2 - x_1), based on investigation of their individual pulses. Comparing both signals of PD type 1 and PD type 2 in a time reference where the original (first) pulses are simultaneous, it can be seen that the time difference of the reflected pulses ($\Delta\ t = 0.286\ \mu$s) confirms the distance between both faults on the cable as shown in Fig. 20. Having dual confirmation of the location of the PD defects, the experimental findings have to be compared with the real location of the defects which caused the PD.

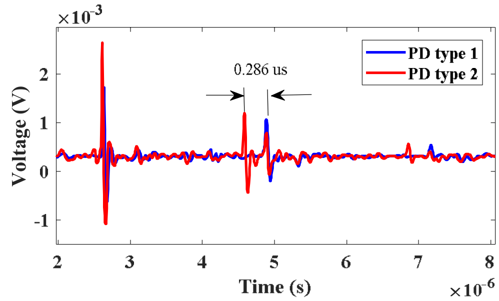

FIGURE 20. Comparison of PD type 1 and PD type 2 signals for location validation.

The MV cable used in this experimental investigation has two defects. The locations of both defects have been manually measured at $x_{1m} = 2.4$ m and $x_{2m} = 27.8$ m while the experimentally inferred distances are $x_1 = 2.56$ m and $x_2 = 27.42$ m. The comparison of the manually measured and located using TDR distances shows an error of $\Delta x_1 = 0.16$ m and $\Delta x_2 = 0.38$ m. This still indicates a good match of the real and determined location of the PD faults.

The slight mismatch in defect locations can be due to effective length of the cable, taking into account the termination part and the end of the cable shielding; the finite signal sampling rate as well. Although the distance of the defect points from the cable end was measured diligently, it is still subjected to various measurement errors. The manually measured distances were determined using the sequential numeric meter markings inscribed on the cable sheath during manufacturing and a tape measure to determine the distance of the cable lugs and the defective spots from the nearest meter marker. The cable ends were unrolled from a drum, therefore some residual bending is also a possible source of measurement errors. To account for these factors, the manually measured distances are presented with a conservative accuracy of 0.1 m.

Apart from the aforementioned sources of error, the sampling period can also cause minor errors in a systemic manner. In this work, the measurements have been recorded with a sampling period of 5×10^{-9} s. This means the measurements are recorded with a spatial resolution of 0.872 m. Therefore, there is always a possibility of an error of 0.872 m in terms of distance inherent to the measured waveforms. The issue of the sampling period can also affect the location diagnostics in another way. Assuming that two or more PD sources are at a very small distance from each other on the cable, for example at a distance of less than a meter. Because of the limitation of the sampling period, most likely they will be identified as the same PD source. Considering the particle aspects, such PD sources should be considered as the 'parts' of the same defect site while digging or repair is being made and visual analyses will be important for further confirmation.

The individual PD pulse analysis presented in this work describes the basic idea and methodology of the proposed technique of PD source detection and their location. The analyses are made for several data frames of half power cycles spanning 10 ms. Regarding continuous PD monitoring, one might raise concerns about the feasibility of the proposed technique regarding processing of such a huge amount of data having a high number of PD pulses. When it comes to continuous online condition monitoring of the cables, a comprehensive approach can be developed based on the measurement/data acquisition system and algorithm based processing for automated detection of the PD signals, identification of the number of PD sources, and their location.

While using DSO, a trigger can be adjusted at a certain threshold level to capture the data when a PD pulse appears. The length of the data (of PD signals) to be captured can be selected considering the length of the cable and the sampling period. The length of the data segment should be long enough to accommodate the reflections of the pulses, considering attenuation in the cable. The algorithm can be developed to mark the time of peaks appearing for incident and reflected pulses. The TDoA of the first two pulses (original and the reflected) determines the location of the defects. The data frames, presenting the same TDoA, will belong to the same PD source. Similarly, analysis encompassing all of the incoming data frames will continuously determine if there is a single PD fault or more and where they are located.

In this work, single cable/phase is used to implement the proposed location technique. In case of three phase cable installations which is the usual case in the real networks, the presented technique can be extended accordingly. At the joints and terminations, the shielding of each of the cable/phase is separated and three HFCT sensors should be installed i.e., one sensor for each shielding. During faulty conditions, the emerged PD signals from defective cable/phase will be measured by the corresponding sensor and the fault location can be determined by using TDR techniques as presented above. It should be noted that in this case, the corresponding sensor (installed around the shielding of defective cable) will measure the strongest amplitude of the PD signal, while the other two sensors may measure a weak PD signal induced due to capacitive /inductive coupling between the three phases.

VII. CONCLUSIONS

Due to aging and operational stresses insulation defects develop in cable insulation which cause PD. PD location in underground cable networks is of critical importance. Accuracy of fault location can improve the efficiency of the maintenance system for underground cable assets significantly, especially considering the factors such as repair time, cost, and discomfort to the general public due to power interruptions and on-site repairs. A cable section or branch can be long up to 500-1000 m and can have multiple defects, which can cause PDs simultaneously. When the PD measurements are made, it contain all the information of the ongoing PD activity along the affected cable. If multiple PD sources are active, analysis of the PD signals is quite complex. Reflections of the PD signals plays important role for separation of the PD sources while performing TDR based analysis.

In this work, experimental investigation was made on a 200 m long MV power cable that has two PD sources at different locations. It is proposed that the wave propagation velocity of the cable should be determined experimentally which will enable to locate the PD faults with increase accuracy. TDR based measurement methodology has been adopted by using single end measurements using HFCT sensor installed at one end of the cable. The presented study describes the methodology for two PD sources. However, in case several PD sources are present at several locations, a brief discussion is presented for implementation of an 'automated' monitoring system based on principles of the proposed technique.

Although XLPE has emerged as a robust dielectric insulation that makes the insulation of a cable sections quite reliable. However, joints and terminations are always needed and are the most vulnerable components of an MV cable. When the PD measurements are performed at a certain part of the cable feeder having number of joints/terminations, there is a possibility that more than one locations are suffering with the PD defects simultaneously. In this case, the presented methodology will be useful to identify and locate the PD sources efficiently. This scenario is more likely in the paper insulated cable that are installed decades ago and have increased number of joints due to number of repairs during operation.

As the networks are reaching to their capacity limits, high temperature superconducting (HTS) cables are introduced as a potential solution for carrying significantly higher voltage and currents along with much lower losses as compared to conventional power cables. The presence of liquid nitrogen based cooling in the HTS cable is an added capability that reduces the thermal stresses significantly to avoid the defects in dielectric insulation layers. Similarly, the dielectric insulation is mechanically more protected because of inner and outer cryostat. Such features can improve the issues of dielectric deterioration in these cables to a great extent. However, the cable joints and terminations are still the threat of the PD inception. Being new installations, it is proposed to 'embed' the PD sensors at the suitable locations along the cable feeder during HTS cable installation that will improve the reliability of the network by early detection and location of the possible PD defects using proposed location technique.

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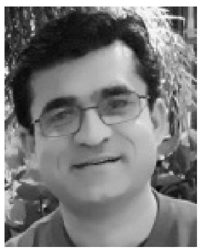

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