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RESEARCH ARTICLE

**An ethical committee approval and/or legal/special permission has not been required within the scope of this study.*

EFFECT OF THE CABLE CROSS-SECTION FOR LOCATING PARTIAL DISCHARGES IN UNDERGROUND XLPE CABLES

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ABSTRACT

Partial discharge (PD) frequently occurs in underground cables. Gradually, these discharges can lead to permanent and hazardous faults, causing severe damage to the cable insulation and distribution in the service quality. Therefore, it is crucial to accurately locate PD sources and intervene before they evolve into irreversible failures. PD location can be determined using fundamental traveling wave equations. Therefore, cable cross-section significantly affects the cable parameters and eventually performance of PD localization method is hindered. In this study, it was observed that identical PD sources yielded different location estimates when cable cross-sections are varied. These results were demonstrated through a comprehensive simulation model of a cable feeder developed in EMTP-ATP Draw program using actual field data.

Keywords: *Partial discharge, Location, Cable modelling.*

YERALTI XLPE KABLOLARINDA KISMİ DEŞARJLARIN KONUMLANDIRILMASINDA KABLO KESIT ALANININ ETKİSİ

ÖZ

Yer altı kablolarında sık sık Kısmi Deşarj (KD) olayı yaşanmaktadır. Zamanla bu KD'ler kalıcı ve tehlikeli arızalara neden olarak kablolarda geri döndürülemez hasarlara ve dolayısıyla arz güvenliğinde azalmaya neden olabilir. Bu nedenle KD'lerin yerlerinin tespit edilmesi ve kalıcı arızaya dönmeden müdahale edilmesi gerekmektedir. KD konumu temel yürüyen dalga denklemleri ile tespit edilebilmektedir. Bu nedenle kablo kesitinin KD konumuna etkisi kaçınılmazdır. Bu çalışmada farklı kablo kesitlerinde aynı KD konumu içi farklı mesafeler bulunduğu tespit edilmiştir. Sonuçlar bir kablo fiderinin EMTP-ATP Draw'da kapsamlı simülasyon modeli üzerinde gösterilmiştir. Simülasyon verileri gerçek arazi ile uyumludur.

Anahtar Kelimeler: *Kısmi deşarj, Konum tespiti, Kablo modelleme.*

1. INTRODUCTION

Increasing demand for uninterrupted power leads to changes in traditional distribution systems. In the past two decades, the deployment of underground cables has substantially increased. This trend is primarily driven by their advantages in terms of supply reliability, enhanced current-carrying capacity, improved physical safety, and aesthetic benefits. However, underground cables have a finite physical service life (Zhou et al., 2017).

During normal operations, underground cables are exposed to environmental stresses such as elevated temperature, excess humidity, and dust. In addition to these, underground cables are subjected to electrical stresses including over voltages and overloading. Over time, these factors contribute to the degradation of the cable's insulation health. Ultimately, this degradation leads to the occurrence of partial discharge (PD) events.

It is known that the severity of PD is typically low at the beginning. However, their persistent nature results in cumulative degradation of insulation materials. Gradually, this progression may culminate in either short-term or prolonged power

outages, in addition to incurring substantial economic losses. Therefore, the location of PD along the underground cable feeder must be determined with the highest possible accuracy.

To detect the location of the PD signals, traveling-wave-based methods are commonly employed in the literature and commercial field applications used by the distribution system operators. These methods include TDR (Time Domain Reflectometry) and ATA (Arrival Time Analysis). In the TDR method, measurements are obtained from the beginning of the cable feeder. The PD location is then determined from the time difference between the incident and the reflected PD signals. The TDR method is generally applied offline. Therefore, cable feeders are de-energized. In practice, most of the commercially available field instruments used for locating PD signals in underground cables are based on the TDR technique. However, due to the attenuation and propagation of the PD signals toward the end of the cable, the TDR technique generally does not provide effective results for cables longer than four kilometers (Morales & Ardila-Rey, 2023).

Numerous studies have been conducted in literature to determine the PD location. These studies can be divided into three groups. The first group is the onsite PD location studies. In onsite applications, the location of PD can be determined either online or offline. Online measurements are generally performed under normal operating voltage conditions, whereas in offline measurements, a test voltage higher than the operating voltage is applied to the cable's insulation. This situation leads to deterioration of the cable's insulation integrity.

Some important research about onsite PD location is given as follows. Using the Customized Envelope Detection, the PD location is determined in (Atsever et al., 2025). The onsite implementation of the proposed method has been carried out, and it was applied to a medium-voltage cross linked polyethylene (XLPE) cable feeder with a length of approximately three kilometers. In (Atsever et al., 2025) one type of PD detection sensor, namely, High Frequency Current Transformer (HFCT's) are mounted in cables' sheats to capture the PD signals rather than the cables'

cores. However, hybrid sensors have been used in (Yan et al., 2023). Hybrid sensors consist of PD detectors and internal signal injectors. By generating pulse signals, online detection of PD location can be enabled. The effectiveness of the proposed method was demonstrated on a 485-meter XLPE cable feeder.

The second group is the laboratory-based PD location studies. In these studies, test voltage is generally applied on the cable's insulation. However, the effect of noise is often neglected. Many studies have been conducted on the location of the PD in the laboratory environment. For example, Mycielski algorithm is proposed to find the location of the PDs in (Serttaş & Hocaoglu, 2025). Seven meters XLPE cable is used for the laboratory test set up. PD is generated by damaging cable's insulation using needle tips.damage. Envelope detection is used in (Granado et al., 2015). The effectiveness of the proposed approach is demonstrated on the 340 meters XLPE cable feeder. Cable is damaged by the artificially generated PD signals in laboratory test set up.

Although field- or laboratory-based studies generally provide more accurate results in terms of PD signal generation, detection and localizing such facilities are not always available. At this point, simulation-based studies can be conducted with the aid of mathematical models of PD signals, PD sensors, and underground cables. Transfer function of the cable is employed to determine the PD location in (Shamsoddini et al., 2025). Measurements are performed from one side of the cable. TDR method is used to calculate location. For the cable feeder, XLPE cable is modelled. Simulations were conducted on the PSCAD. By using phase difference between reflected and incident signal PD location detection method proposed in (Mardiana & Su, 2010). The validity of the proposed approach was verified through simulations conducted on an EMTP model of a 1000-meter XLPE cable, thereby demonstrating its effectiveness. In (Atsever et al, 2024), partial discharge (PD) signals recorded in the field were compared with those obtained from simulations using the EMTP-ATP Draw program. The PD location was determined with an error rate of about 1%, thereby validating the accuracy of the simulation. This result has further encouraged the use of EMTP-ATP Draw as a reliable tool in PD localizing research.

In recent years, numerous review studies have been published on PD location. A study published in 2021 provided a comprehensive examination of PD detection and localization methods in power cables (Zhang et al., 2021). In a study conducted in 2023, PD detection and localization methods were classified, and the research trends in the field were identified (Morales & Ardila-Rey, 2023). The most recent review study was published in 2025. This work focused on practical approaches and circuit-based modeling techniques for PD analysis. (Alqtish et al., 2025).

Moreover, shipboard or offshore power systems need to be long length ground cables. Thus, the generated energy can be transmitted to the mainland via high-voltage submarine cables. Therefore, it is critical to monitor and locate the PD activities for naval engineering.

Above mentioned studies and conventional/commercial PD measurement reports indicates that the effect of cable cross-section is neglected regardless of whether the cable is installed underground or subsea. However, it should be recognized that variations in cable cross-section change the capacitance, thereby modifying the characteristics of the traveling wave of cables. Ultimately, this leads to changes in the PD location accuracy. Therefore, the influence of cable cross-section on PD localization should be thoroughly investigated. Accordingly, this study investigates the effect of the cable-cross section on the PD localization efficiency. Comprehensive parametric analysis is carried out. Simulations are conducted on the EMTP-ATP Draw program. Results clearly indicate that the cross-section of the underground cable affects location of the PDs.

2. PARTIAL DISCHARGE LOCATION

The determination of PD location is based on well-known traveling-wave equations. The PD location is calculated using two different equations depending on whether a single-sided or double-sided measurement setup is applied. If the measurement is single-sided, the PD location is calculated using Equation (1). Here, L_{PD} represents the distance to the PD in meters, L_{Cable} denotes the total length of the cable in meters, Δt corresponds to the time difference between the incident and reflected PD signals, and v indicates the propagation velocity.

$$L_{PD} = L_{Cable} - \frac{\Delta t.v}{2} \quad (1)$$

The propagation velocity is influenced by the dielectric properties of the cable insulation materials. Table 1 summarizes the propagation velocity values corresponding to different cable insulation. As a result, a change in propagation velocity also leads to a change in the calculated PD location. In medium-voltage networks, XLPE insulation is widely used across Continental Europe. Field measurements indicate that, for XLPE insulation, the propagation velocity typically falls within the range of 166–172 m/µs.

Table 1. *Propagation velocity of different cable insulation (El Bahı Azzag & Touaibia, 2019).*

Cable insulation	**v (m/µs)**
Impregnated paper	140-155
Polyethylene	*170*
Ethylene propylene	*136-166*
Polyvinly chloride	*155*

In the test configuration employing double-ended setup, the PD location is determined by evaluating the time difference between the PD signals arriving at the sensors mounted at both cable ends. The corresponding formulation of the PD location is given in Equation (2).

$$L_{PD} = \frac{L_{Cable} - (t_2 - t_1).v}{2} \quad (2)$$

Here, t_2 and t_1 represent the arrival times of the PD signal at the second and first sensors, respectively. Figure 1 shows the classification of PD location studies in open literature.

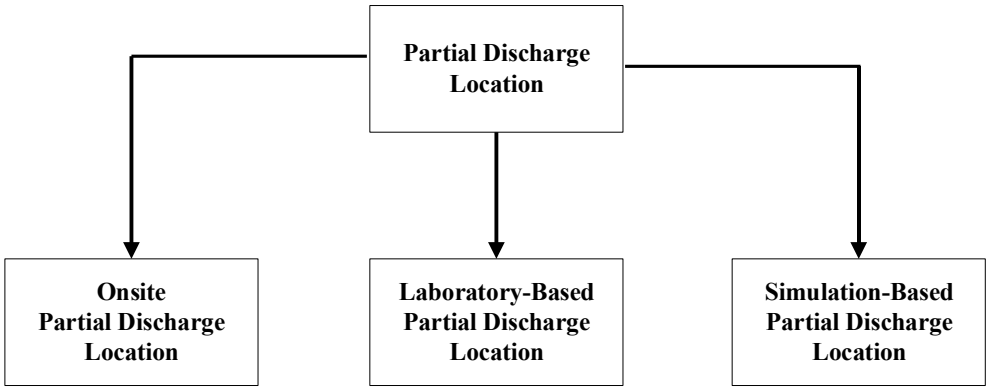


Figure 1. *Classification of the partial discharge location studies in open literature*.

Onsite PD location studies inherently provide a more rigorous validation environment for the proposed algorithms, enabling them to be tested with higher accuracy. This is because the raw data collected from the field inherently contains disturbing effects such as noise, switching transients, and other real-world interferences. However, conducting a wide range of parametric analyses is often not feasible under such field conditions. Furthermore, conducting onsite partial discharge measurements involves the use of expensive and specialized test equipment diagnostic vehicles, which are generally owned and operated by electricity distribution utilities, thereby limiting accessibility for external researchers and engineers.

In laboratory-based PD localization studies, the raw PD signal is typically clean and free from noise. Noise and other interference sources caused by the grid are usually generated artificially in laboratory. Moreover, the location of the PD is known in advance. Due to the dispersion and attenuation, length of the cable is the critical parameter for the location of the PDs. However, due to the physical limitations of laboratory setups, performing partial discharge localization experiments on long-length cables is often impractical or unachievable. Likewise,

conducting detailed parametric analyses under these conditions proves to be both technically challenging and economically demanding.

Simulation-based PD localization studies have gained prominence due to several advantages, such as enabling extensive parametric analyses, requiring virtually no cost for test setup, and eliminating the need to apply high voltage to the cable to generate PD signals. Furthermore, simulation platforms enable controlled variation of cable parameters—such as cross-section, length, dielectric materials and topology—which would otherwise be difficult or impractical to explore in laboratory or onsite conditions. Therefore, simulation-based PD location studies serve as a complementary method, offering flexibility and scalability while supporting the development and preliminary validation of advanced PD localization algorithms.

This study investigates the effect of underground XLPE cable's cross-sectional areas on the accuracy of PD localization. For this purpose, a representative single cable feeder has been modeled in EMPT-ATP Draw program. The developed simulation framework incorporates the modeling of the PD source, cable parameters, and HFCT for raw PD signal detection.

2.1. PD Source Modelling

PD events are extremely fast discharges that occur within microseconds and are typically characterized by magnitudes in the range of several thousand picocoulombs. A review of the literature shows that the EMTP-ATP Draw simulation environment is frequently used to model PD signals (Sukardi et al., 2018). The mathematical representation of a typical PD pulse is commonly formulated using double exponential function that incorporates parameters such as rise time, fall time, and peak value. This is expressed in Equation (3) (Shafiq et al., 2015).

$$i_{PD}(t) = A(e^{a_1 t} - e^{a_2 t}) \tag{3}$$

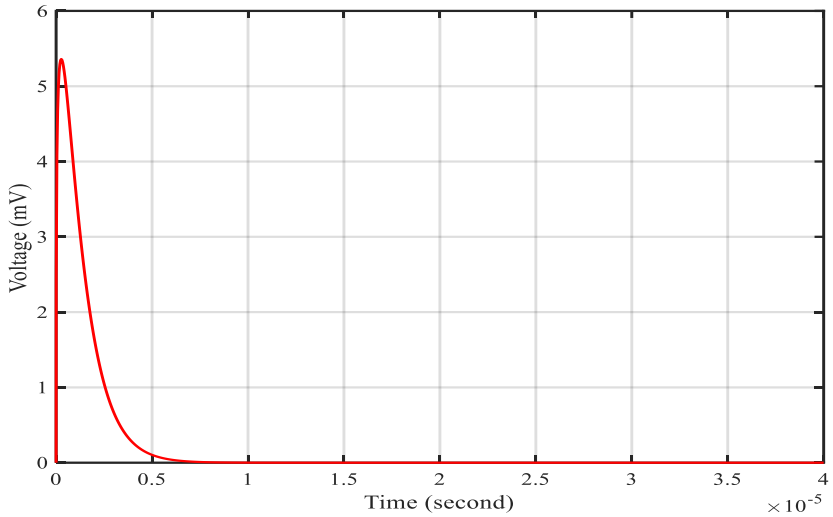


Figure 2. *A sample PD signal generated by the simulation.*

Using Equation (3), a sample PD signal was generated in the EMTP-ATP Draw environment. The generated PD pulse is illustrated in Figure 2. As seen in Figure 2, the peak value of the signal is approximately 5 mV. In all simulations conducted throughout this study, PD pulse injected to the phase of the cable. Then after, raw PD signal is obtained from the HFCT's.

2.2. Underground XLPE Cable Modelling

Underground cables are the vital equipment for distribution systems for ensuring uninterrupted power delivery. However, during the operation the insulation of the cables may deteriorate in time. Such deterioration may happen due to aging, moisture, third party physical damage or faults. Since cables are typically buried underground, it is quite challenging for maintenance crews to access and replace them during any faults or insulation-based failures. Therefore, it is necessary to continuously monitor the underground power cables for PD activity and to determine the PD location within the cable with a high degree of accuracy. Hence, underground XLPE cable modelling for PD analysis is quite important. EMTP-

ATP Draw is highly capable software for underground cable modeling. It enables both steady-state and transient analyses. The program contains various cable models such as Bergeron, PI, J-Marti, Noda, and Semlyen (Høidalen & Soloott, 2010). Therefore, choosing the proper cable model is critical.

Since the PD is a rapidly developing insulation defect, the J-Marti model is chosen among the available options for its suitability in capturing fast transient signals. Main research objective of this study is to investigate the effect of different underground cable types on PD localization. For this purpose, cables with different cross-sectional areas have been modeled extensively. These are copper-conductor cables with XLPE insulation and cross-sections of 70 mm², 95 mm², 150 mm², and 240 mm². When modeling the underground cables in EMTP-ATP Draw, it is essential to accurately calculate and input the physical radius of the cable into the program. The typical radial dimensions of an XLPE cable, from the inner-radius to the outer-radius layer, are illustrated in Figure 3. Here, R_1 represents the radius of the hollowed area used to model the DC resistance of the cable. R_2 denotes the conductor radius of the cable. R_3 refers to the inner radius of the sheath conductor, while R_4 represents its outer radius. Finally, R_5 corresponds to the overall radius of the cable.

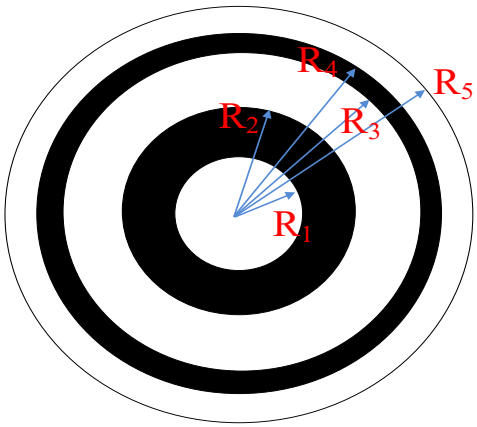


Figure 3. *Dimension of the underground cables for the PD modelling.*

Variations in cable cross-section lead to changes in the radial dimensions of all cable components. At this point, the critical issue is the accurate calculation of these radii and their incorporation into the EMTP-ATP Draw model. The radial dimensions corresponding to the cable cross-sections analyzed in this study are presented in Table 2.

Table 2. *Dimensions of the different underground cables.*

Dimension / Cable Cross Section	**R_1 (m)**	**R_2 (m)**	**R_3 (m)**	**R_4 (m)**	**R_5 (m)**
70 mm^2	0.0019	0.00495	0.017059	0.017192	0.0195
95 mm^2	0.00223	0.0058	0.0179621	0.0180879	0.0205
120 mm^2	0.00255	0.0065	0.0184638	0.0185862	0.021
150 mm^2	0.00280	0.0072	0.0193374	0.0195126	0.022
185 mm^2	0.00294	0.008	0.0203417	0.0205083	0.023
240 mm^2	0.00358	0.00925	0.021747	0.022903	0.0245

As shown in Table 2, each cable cross-section exhibits distinct radial dimensions. An increase in the overall cross-sectional area results in a proportional increase in the radii of all cable components, including the conductor, insulation, and outer semiconductive layers. This geometric expansion directly affects the cable's electrical parameters, particularly its capacitance and surge impedance. Therefore, it is expected to the effect the location of the PD signals. It is also important to emphasize that the burial geometry of underground cables significantly influences their impedance characteristics. Parameters such as cable spacing, depth, and soil resistivity can alter the propagation velocity and signal attenuation, thereby impacting the accuracy of PD localization. To ensure that the parametric comparisons conducted in this study are comparable and consistent, a key

modelling assumption has been adopted: All cables are assumed to be buried under identical geometrical conditions throughout the simulation. This assumption isolates the effect of cable cross-section variations from other potential sources of error, allowing a focused analysis on how geometric and electrical changes induced by different cable sizes influence PD signal propagation characteristic and localization. The buried geometry of the cables is illustrated in Figure 4. The cables are buried at a depth of one meter, and the distance between adjacent cables is 70 mm.

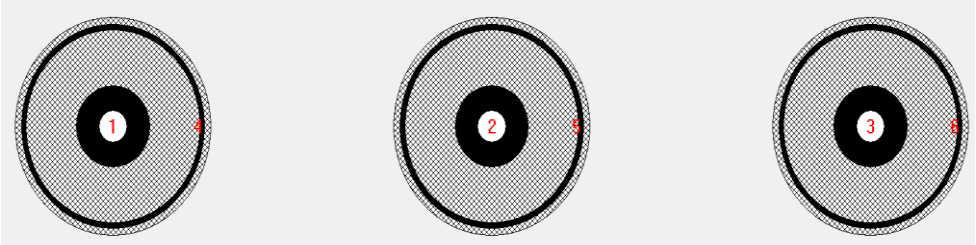


Figure 4. *Buried geometry of the underground cables.*

2.3. HFCT Modelling

Raw PD data obtained from the sensors. Different sensors can be used to capture raw PD data. These sensors can be listed as follows: Rogowski Coil (RG), Ultra High Frequency Coupling Capacitor, Ultra High Frequency Antenna (UHF), Acoustic PD sensors, Optical PD sensor, HFCT. These sensors are mounted on the phases or sheats of the underground cables. RG and HFCT are the most common sensors in field applications and open literature. Therefore, in this study, detailed model of the HFCT is presented. Transfer function of the HFCT is expressed in Equation (4) ((Robles et al., 2008).

$$V_{out}(s) = \frac{\frac{1}{L_c C}}{s^2 + \frac{1}{L_c C}\left(\frac{L_c}{R_t} + R_C C\right)s + \frac{1}{L_c C}\left(\frac{R_c}{R_t} + 1\right)} M_C s I_{in}(s) \quad (4)$$

Where; V_{out} is the output voltage, I_{in} input current of the current transformer, L_c is the coil inductance, C is the capacitance, R_t is the terminating resistance, R_C is the coil resistance, M_C is the mutual inductance. In measurement and field studies reported in the literature, the use of different types of sensors has resulted in variations in their parameters. The parameters of sensors employed in different studies are summarized in Table 3.

Table 3. *Comparison table of the HFCT parameters.*

Parameters	**Value (Shafiq et al., 2013)**	**Value (Rohani et al., 2016)**	**Value (*Robles et al. ,2019*)**
Coil Resistance (R_C)	0.71 Ω	0.19 Ω	0.1 Ω
Coil Inductance (L_c)	1.19 µH	2.5 µH	1.2 µH
Coil Capacitance (C)	16.46 pF	57.21 pF	5.7 pF
Mutual Inductance (M_C)	125.4 nH	4.68 µH	9.51 µH
Terminating Resistance (R_t)	1 MΩ	2 kΩ	10 kΩ

By using the parameters given in Table 1, frequency response of each HFCT sensor is obtained. Figure 5 shows the frequency response of the three different HFCTs.

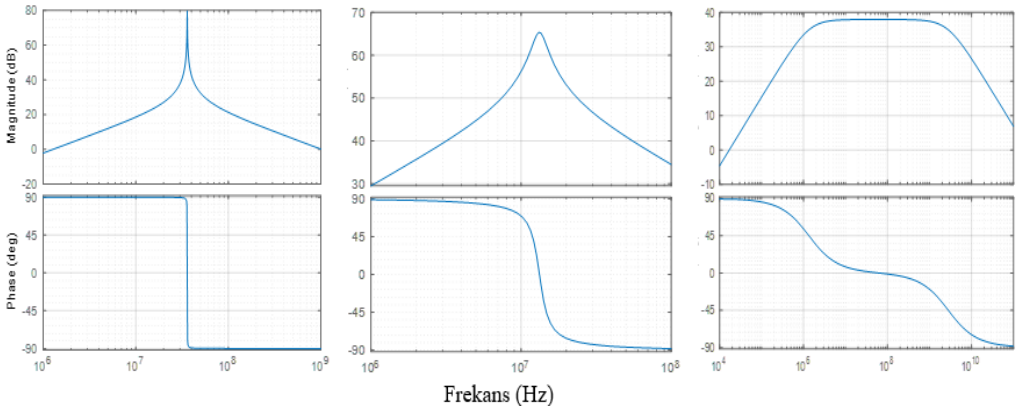


Figure 5. *Frequency response of the sensors given in Table 1.*

The HFCT sensors exhibit differences in bandwidth and resonance frequency, which should be considered when selecting the appropriate sensor for measurements. Due to the similarity between the simulation outcomes and onsite measurements, the HFCT parameters provided by Rohani et al. (2016) were adopted in the modeling process to ensure consistency and practical relevance.

3. TEST CASE

To investigate the effect of cable cross-section on PD localization, a test case consisting of a single XLPE cable feeder is established. Figure 6 shows the schematic presentation of the test case. The total length of the feeder is selected as 2000 meters. It was assumed that the 2000-meter XLPE cable is a single continuous segment. The sheaths were grounded at both ends, and no cross-bonding was considered. As shown in Figure 6, a PD signal is injected into the cable's core. Subsequently, PD signals are measured from HFCTs placed at both ends of the feeder as indicated in figure. Therefore, PD signals captured by the HFCT Left and HFTC Right. It is also mentioned that these PD signals are captured from the cable sheaths.

For each cable type, the simulations have been repeated. Since the 240 mm² cross-section cable is the most used cable type in medium-voltage distribution networks, it has been selected as the reference cable type. The results obtained with other cable types are then compared against this reference.

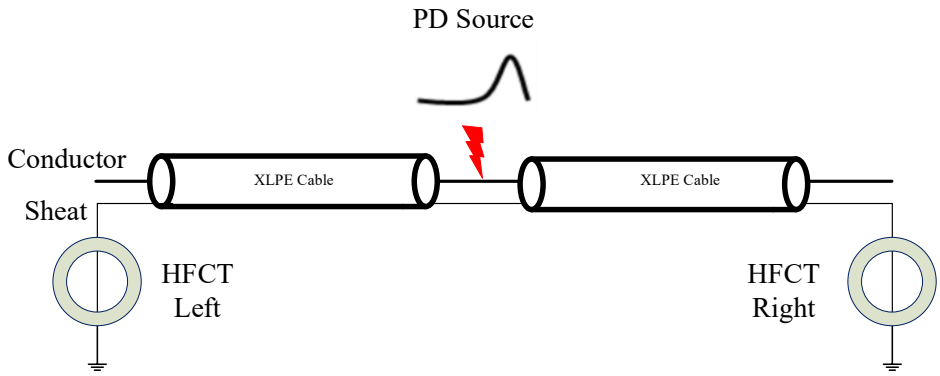


Figure 6. *Schematic presentation of the test case.*

Figure 7-Figure 12 presents a comparison between the other cables and the 240 mm² cross-section XLPE underground cable. For both cases, the PD signal was measured by the same HFCT-Left. Due to the PD signal injected to the same location for both cables, the expectation is that the time difference between the incident and the reflected signals will remain identical. However, since the cable cross-sections are different, the time difference between the incident and reflected signals is found to be distinct.

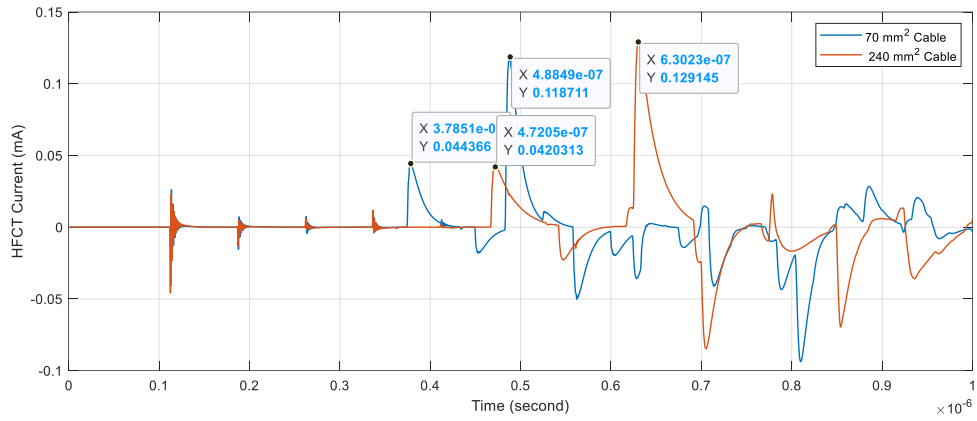


Figure 7. *PD signal measured from the HFCT Left for 70 mm² and 240 mm² XLPE cable.*

By using the TDR technique, PD location has been calculated for all cables. Then after, location differences are obtained for the 240 mm² XLPE cable. Time values are also marked in Figure 7. The simulation cases which consist of other cross sections are shown as a 3D plot in order to provide simplicity in Figure 8. In this figure, blue bolted signal represents the HFCT signals for the 240 mm² XLPE cable. Red dashed line represents the compared cross-section.

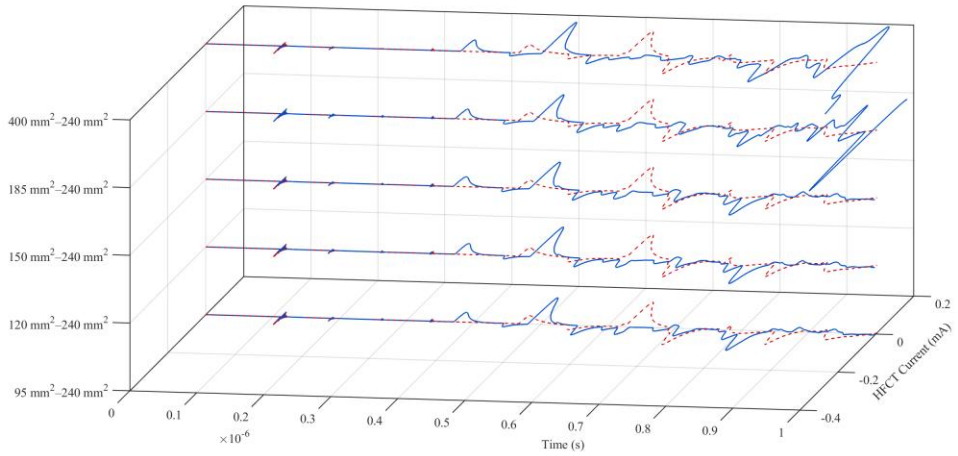


Figure 8. *HFCT signal comparison for different cross sections of the XLPE cable.*

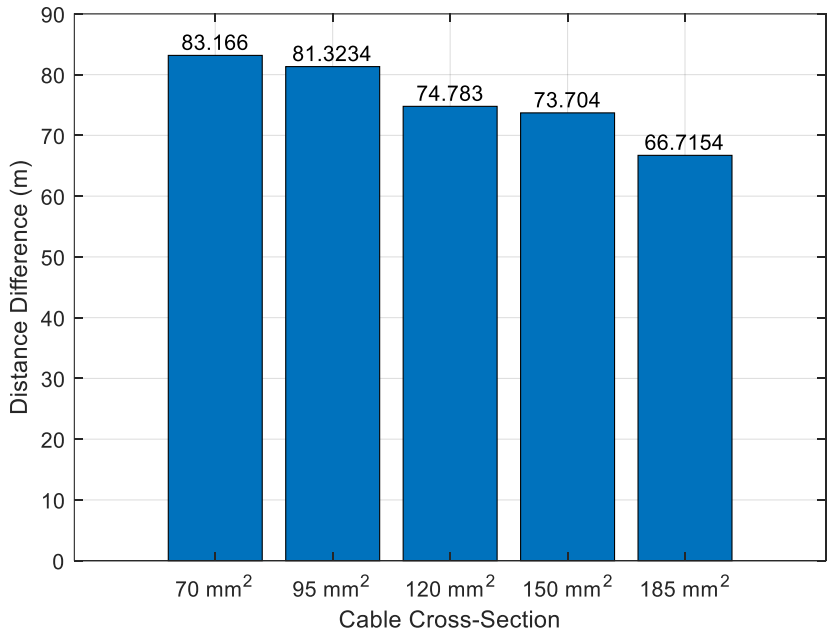


Figure 9. *PD location differences depending on the cable cross-section.*

Figure 9 shows the PD location differences depending on the cable cross-section. As shown in the figure, when a 70 mm² cable is used, the PD location can be estimated with an error of approximately 83.166 meters in 2000-meter cable feeder. The PD localization errors obtained for other cable cross-sections are also presented in the form of a bar chart. The most critical observation here is that the localization error decreases as the cable cross-section increases. In comparison with the reference 240 mm² cable, the closest result was obtained using the 185 mm² cable, whereas the largest deviation was observed with the 70 mm² cable. These findings clearly demonstrate the influence of cable cross-section on PD localization accuracy.

It is well kwon that the type of insulation material (XLPE, EPR; PILC) is directly affect the velocity of the PD signals. As the cable cross-section increases, the capacitance per unit length also increases, which in turn reduces the propagation velocity of the traveling wave. Since the TDR-based and ATA-Based PD localization relies on the time difference between the incident and reflected signals or arrival time differences, a lower propagation velocity leads to a larger estimation error in the calculated distance. Therefore, the increase in cable cross-section differences indirectly causes higher PD localization errors due to the variation in wave propagation characteristics.

4. CONCLUSION

Physically accessing underground cables by crews is often a challenging task and labor-intensive process. In cases where high-magnitude PD signals are detected, it may be necessary to excavate the relevant section of the underground cable and replace it entirely. Therefore, PD localization must be performed with the highest possible level of accuracy.

In the literature, existing studies on PD localization can be broadly categorized into three groups: onsite-based, laboratory-based, and simulation-based investigations. Among these, simulation-based studies offer a cost-effective and flexible approach,

allowing the continuous evaluation of multiple parameters without the logistical and financial constraints associated with field or laboratory testing.

The XLPE cable type is the most used cable in PD localization studies. However, a review of the literature reveals that the influence of cable cross-sectional area on PD localization has not been thoroughly investigated. Since traveling wave equations form the basis of PD localization algorithms, it is evident that cable cross-section plays a significant role in determining the accuracy of the estimated PD location.

In this study, comprehensive modeling and simulation efforts were carried out by using EMTP-ATP Draw program. For this purpose, a sample PD source, XLPE cables with different cross-sectional areas, and an HFCT sensor were modeled. It was observed that the PD signals exhibited different characteristics depending on the cable cross-sections. The PD locations were calculated by taking the 240 mm^2 cable as the reference. The results indicate that as the difference in cable cross-section increases, the error in PD localization also becomes more significant. In future work, these findings are intended to be validated through both laboratory experiments and field measurements.

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