Location Technique based on Multiple Partial Discharge Signal in 11kV Underground Power Cable using EMTP-ATP Software

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Abstract. Power cables are very critical in electrical power systems as power cables failure can interrupt the electrical flow due to unexpected power failure. There are a few sorts of partial discharge (PD) estimations gadgets in the market. For instance, PD can be distinguished by utilizing Rogowski coil (RC) sensors in the disconnected procedure. The current issue PD signal does not usually occur as a single source. Thus, the analysis of multiple PD sources is required to ensure that the cable insulation is in a healthy condition. PD location technique based on multiple signals in 11kV underground power cable was conducted in this research to estimate the accurate location of the PD signal. Modelling of single power cable in a distance of 10km with the RC sensor is installed at several distances to capture the PD signal that travels along the power cable. By selecting the distance between six RC sensors and synchronous multiple PD signal, the design of the power system has been constructed by using EMTP-ATP software. Multi-point technique based on time difference of arrival (TDOA) was performed in the single line power cable to obtain the PD location. The measurement using multi-point of RC sensor technique is preferred based on the conditions due to the value of velocity elimination. Based on the results, the accurate location of PD Source 1 is detected 501 m along RC sensor A1 to RC sensor A3. In contrast, PD source 2 has been detected 2800.15 m along RC sensor A4 to RC sensor A6 with the percentage error of 0.2% and 0.0053%, respectively. The findings show that the location of multiple PD signal that occurred along the line cable can be detected accurately by using the multi-point technique and TDOA. Hence, the performance of the power system has been improved.

1. Introduction

The power cable is the most significant in the electrical power network since the power cable is the only way for electricity to transfer to the other equipment via a distribution. The failure of insulation in the power cable may lead to a loss in the power system. According to IEC 60270, a limited electrical discharge that incompletely links the insulation between conductors might or might not happen to a
conductor [1]. Normally, PD occurs because of local electrical stress concentrations seeming in the cavity/voids, bubbles inside the insulation or on the surface of the insulation [2]. The PD phenomena in the medium voltage (MV) cable are categorized in the internal discharge, corona discharge, surface discharge, and discharge by electrical treeing, as shown in Figure 1 [3-8]. The internal discharge implies that PD occurs in voids or cavities inside solid or liquid dielectrics. For high-voltage (HV) power cables, PD also appears in the cavities or void between semi-conductive protection on the conductor and insulation or semi-conductive protection between insulation and exterior [9]. Typically, the internal discharge caused by the cavities in the insulator of power cables formed in the insulating material consists of gas or air (void). It is also capable of degrading the insulation material depending on the field strength and magnitude of discharges. In contrast, the corona discharge is obtained in gasses and liquids, where the sharp edge of discharge occurs to the earth potential. The surface discharge normally occurs outside or on the power equipment, such as bushing, underground cables, and overhead lines terminal. The discharge can also occur at any point of insulator between electrodes. Lastly, the electrical treeing channel is caused by the defect of insulation material.

![Figure 1](image-url)

**Figure 1**: Type of partial discharge, (a) internal discharge, (b) corona discharge, (c) surface discharge, and (d) discharge by electrical [10].

Early-stage detection of insulation degradation is essential before the interruption or fault happens. Typically, the PD happens in short duration, low amplitude, which lasts for a few nanoseconds [11-13]. Different PD may have different effects on the insulation performance of the power apparatus. Therefore, the identification of multiple PD sources is of great interest to both system utilities and equipment manufacturers [14]. These days, there are a few sorts of PD estimation gadgets in the market. For instance, PD can be distinguished by utilizing RC sensors in the disconnected procedure. The selection of air-cored RC sensor as a PD sensor is based on the characteristic of sensors, which are wide bandwidth, lightweight, linearity, fast response, no hysteresis losses, low cost, and easy to construct in the laboratory [15]. It is also easy to manage and safe to use during PD calculation, as it is not attached to the cable. The RC sensor was designed in 1912 by W. Rogowski, who is a Russian engineer [16]. A measuring circuit, an external power supply, as well as uncoupled and de-energized power link is required for disconnecting the estimation of PD. In the event that there is PD measured, which frame the potential hazard for cable, it is essential to know the position of PD in the cable. Thus, location technique should be applied when the area is known. The cable can then be excavated at the exact area. Hence, it can be directly repaired.
2. Methodology

The main parts of the configuration of the PD monitoring system model are PD source, three-phase 11 kV XLPE underground power cables with 240 mm² nominal area copper conductor cable, and RC sensor model. A single-end and double-end PD measurement technique are mostly used to detect the PD signal for different RC sensors [17]. In this research, EMTP-ATP software is used to simulate a system of the off-line PD monitoring system for multiple PD source in double-end of power cable. Single line double-end diagram and modelling using ATPDraw of 10 km of power cable for multiple PD signal with six RC sensors are presented in Figures 2 and 3, respectively. PD source 1 is placed in the middle between RC sensor A1 and RC sensor A2 with the actual distance between them is 0.5 km and 1.5 km, respectively. In contrast, PD source 2 is placed 0.8 km from RC sensor A5 dan 1.2 km from RC sensor A6. Both PD sources are injected from phase A. The PD pulse is split into two identical pulses that travel in the opposite direction detected using RC sensors between point A1 and A2 and between A5 and A6, where the RC sensor is located at 2 km and 4 km, respectively, from the PD source. The modelling of RC sensor is based on the lumped parameter, as shown in Figure 4. During each PD case, the induced charge is produced quickly, resulting in a high-frequency current pulse induced on the electrode [18-17]. The PD pulse occurs typically in a concise duration in rising time and nanosecond time of the fall time. The mathematical model of the PD current pulse is expressed in equation (1), where A is the peak of pulse value, $a^2t$ is the rate of the rising time, and $a^1t$ is the rate of the fall time [19].

$$t = A(e^{-a^2t} - e^{-a^1t})$$

(1)

Figure 2. Single line double-ends diagram of 10 km power cable with six RC sensors.

The modelling of PD simulation for double-end of three-phase 11 kV XLPE underground power cables is based on the actual scenario of PD occurring at a certain point. Resistor-inductor-capacitor (RLC) branch is added at both terminals of the line to connect the conductor-end directly to the ground, as shown in Figure 3. Figure 4 shows the RC lumped model, where the value of this RC sensor's lumped parameter is selected by the previous researcher [20]. The value of resistance, inductance, and capacitance are 0.110 $\Omega$, 0.60 $\mu$H, and 50.30 pF, respectively. In addition, the ability to design a three-phase line cable in PD detection analysis using J-Marti model is suitable for simulating the travelling wave phenomena in long transmission lines. The J-Marti model is frequency-dependent line model developed by J. R. Marti, which is useful in showing the correlations with actual line response. It is efficient and accurate for transient simulation cases as well [21]. One of the advantages of using J-Marti model line cable is its ability to distinguish the faulty phase based on the polarity of the signal that has been measured. The positive polarity means the PD phenomenon is occurred, while the negative polarity indicates no PD at that phase. This is due to the coupling capacitance effect between the neighbouring phases.
In this research, six RC sensors labelled with ABC are set up along the line cable with 2 km separation between each of the RC sensors, as expressed in Figure 5. Two sides of line cable have been separated based on Case 1 and Case 2. These cases were divided following the two conditions for the multiple PD sources that occurred synchronously on the power cable. For Case 1, the reading of time domain of PD signal is captured by RC sensor A1, RC sensor A2, and RC sensor A3, where the location of PD source is at PD source 1. For Case 2, the reading of the same sensor is captured at location PD source 2. The other three sensors, RC sensor A4, A5, and A6 also have the same reading as previous three sensors. The fastest time domain of PD signal of both cases is taken to calculate the location of the PD source. The detection of time-domain using the multi-point technique is performed for this research.
Figure 5. Multi-point location technique for (i) condition 1 case 1 (ii) condition 1 case 2 (iii) condition 2 case 1 (iv) condition 2 case 2.

The mathematical formula is applied to calculate the location of the PD source based on the TDOA obtained utilizing the EMTP-ATP software. The calculation for the time-domain for point \(ab\) and \(cb\) is shown in equation (2) and (3), respectively. \(X_1\) and \(X_2\) are the results obtained from the location of PD pulse from RC sensor for case 1 and case 2, as shown in equation (4) and (5), while \(L\) is the total length of power line cable in the range of these three RC sensors, which is 4 km. The calculation of percentage error is shown in equation (6).

\[
t_{ab} = t_a - t_b
\]  
(2)

\[
t_{cb} = t_c - t_b
\]  
(3)

Derivation for case 1: \(t_{ab} \leq t_{cb}\). Thus, \(X_1\) becomes

\[
X_1 = \frac{1}{4} L \left( \frac{t_{ab}}{t_{cb}} + 1 \right).
\]  
(4)

Derivation for case 2: \(t_{ab} > t_{cb}\). Thus, \(X_2\) becomes

\[
X_2 = \frac{1}{4} L \left( 3 - \frac{t_{cb}}{t_{ab}} \right).
\]  
(5)
Percentage error = \frac{\text{actual distance} - \text{calculated distance}}{\text{actual distance}} \times 100 \tag{6}

3. Results and Discussions
The results are discussed based on TDOA of PD signal on the 11 kV XLPE underground power cable. As shown in Figure 6, the voltage and time of PD signal detected by RC sensor A1 is 4.05 mV and 5.22 μs, while RC sensor A1 captured 3.431 MHz. The other PD source obtained a small value of time domain due to the range of RC sensor A1 and the PD source is too far.

![Figure 6](image)

Figure 6. Detection of PD signal from RC sensor A1, (a) Waveform of time-domain obtained from RC sensor A1 (b) Waveform of the highest frequency captured by RC sensor A1.

The next RC sensor, which is A2, is located 1.5 km from the PD source 1 and 6.8 km from PD source 2, as shown in Figure 7. The RC sensor A2 can detect PD source 1 because the distance of PD source 1 is closer to the RC sensor A2 compare to the distance between the RC sensor A2 and PD source 2. Figure 7 shows that the highest peak of the waveform is 3.433 mV and the time taken of the PD signal recorded is 15.28 μs with the frequency of PD pulse captured is 3.462 MHz.

![Figure 7](image)
Figure 7. Detection of PD signal from RC sensor A2, (a) Waveform of time-domain obtained from RC sensor A2 (b) Waveform of the highest frequency captured by RC sensor A2.

While for RC sensor A3, the highest peak value detected is from PD source 1 due to the distance between RC sensor A3 and PD source 1 is shorter compared to the PD source 2. RC sensor A3 is located at 3.5 km from PD source 1 and 4.8 km from PD source 2. The voltage of the PD signal is 2.506 mV, and the time taken for the highest peak of the PD signal is 35.44 μs with the frequency of PD signal is 3.423 MHz, as shown in Figure 8.

Figure 8. Detection of PD signal from RC sensor A3, (a) Waveform of time-domain obtained from RC sensor A3 (b) Waveform of the highest frequency captured by RC sensor A3.

Based on these three RC sensors, which are RC sensor A1, RC sensor A2, and RC sensor A3, the detection of the PD signal is from PD source 1. The PD source 1 and PD source 2 occurred synchronously on the power line cable. However, these three RC sensors obtained the fastest time domain of PD signal from PD source 1 due to the range that has been set up in the RC sensor. The RC sensor detected the PD signal within a range of 2 km from the PD source. Even though the distance between RC sensor A3 and PD source 2 is 4.8 km, the waveform formed is too small because the RC sensor cannot capture the signal since the RC sensor is able to detect within the range of 5 km, where 4.8 km is nearer to the 5 km. From the RC sensor A1 to RC sensor A3, the time domain of the PD signal is slightly increased. The fastest time domain obtained from RC sensor A1, RC sensor A2, and RC sensor A3 is used in equation (2), (3) and (4) to obtain the accurate location of PD on the power line cable. The results of the time-domain, which capture the highest amplitude in these three RC sensors is illustrated in Figure 9. Table 1 shows the calculated location of the PD signal from point A based on the measured signal captured by RC sensor A3 at point A1 and point A2 in phase A, as shown in Figure 8. Based on the multi-end technique, the calculated length of the PD location is 501 m, while the percentage error is 0.2%.
\[ \text{tab} = \text{ta} - \text{tb} = 5.22\mu s - 15.28\mu s = 10.04\mu s \]

\[ \text{tcb} = \text{tc} - \text{tb} = 35.443\mu s - 15.28\mu s = 20.16\mu s \]

**Case 1: tab} \leq \text{tcb},**

\[ X_1 = \frac{1}{4} L \left( \frac{\text{tab}}{\text{tcb}} + 1 \right) = \frac{1}{4} (4\text{km}) \left( \frac{10.04\mu s}{20.16\mu s} + 1 \right) = 0.501\text{km} \]

![Figure 9](image)

**Figure 9.** Single line diagram based on the results of time difference of arrival captured by RC sensor A1 to A3.

**Table 1.** PD data analysis measured by RC sensor A1.

| RC Sensor location | A1     | A2     | A3     |
|--------------------|--------|--------|--------|
| Amplitude (mV)     | 4.05   | 3.433  | 2.506  |
| Time of travelling wave (μs) | 5.22 | 15.28 | 35.44 |
| Actual length of PD location (m) | 500.0 | 0     | 0      |
| Calculated length of PD location (m) | 501.0 | 0     | 0      |
| Percentage error of PD location (%) | 0.2   | 0     | 0      |

Figure 10 shows the waveform of the PD signal captured by RC sensor A4 with the voltage of the PD signal captured is 2.797 mV and the time taken of the PD signal is 28.39 μs. The PD signal captured by RC sensor A4 is from PD source 2 as the distance between RC sensor A4 and PD source 2 is closer compared to PD source 1, which is 5.5 km from RC sensor A4. The RC sensor A4 sensed 3.419 MHz of frequency for the PD pulse along the 10 km of the line cable.
Figure 10. Detection of PD signal from RC sensor A4, (a) Waveform of time-domain obtained from RC sensor A4 (b) Waveform of the highest frequency captured by RC sensor A4.

The highest peak of the waveform of PD signal shown in Figure 11 is from PD source 2 as the distance of PD source 2 is closer to the RC sensor A5 compare to PD source 1, which is 7.5 km from RC sensor A5. The voltage captured is 0.003857 V in 8.219 μs, and the frequency of PD pulse from the multiple PD sources is 3.449 MHz.

Figure 11. Detection of PD signal from RC sensor A5, (a) Waveform of time-domain obtained from RC sensor A5 (b) Waveform of the highest frequency captured by RC sensor A5.

Figure 12 shows the waveform captured by RC sensor A6 with the voltage and time of the PD signal detected by RC sensor A6 are 3.597 mV and 12.25 μs, respectively. However, the PD source cannot be detected due to the range between PD source 1 and RC sensor A6 is too far. The RC sensor A6 is located 8.3 km from PD source 1 and 1.2 km from PD source 2. The frequency of PD pulse from the multiple PD sources sensed by RC sensor A6 is 3.456 MHz.
In conclusion, from these three RC sensors, which are RC sensor A4, A5 and A6, the detection of PD signal is from PD source 2 due to the range between these sensors and PD source 2 is closer compared to PD source 1. The results of the PD signal from PD source 1 is too small as the RC sensor was designed to capture the PD signal within a range of 5 km. The RC sensor A5 shows the fastest time reading for PD signal to be detected, which is 8.219 μs followed by RC sensor A6 and RC sensor A4, which are 12.25 μs and 28.39 μs, individually, due to the distance between each of the RC sensor and PD source 2. The time-domain of the PD signal is slightly increased as the distance between PD source 2 and RC sensors increases. The fastest time domain obtained from RC sensor A4, RC sensor A5, and RC sensor A6 is used in equations (2), (3) and (5) to obtain the accurate location of PD on the power line cable. The results of the time domain, which captured the highest amplitude in these three RC sensors is illustrated in Figure 13. Table 2 shows the calculated location of the PD signal from point A based on the measured signal captured by RC sensor A5 at point A and point B in phase A, as shown in Figure 11. Based on the multi-end technique, the calculated length of the PD location is 2800.15 m, while the percentage error is 0.0053 %.

\[
tab = ta-tb = 28.390\,\mu s - 8.219\,\mu s = 20.171\,\mu s.
\]

\[
tcb = tc-tb = 12.250\,\mu s - 8.219\,\mu s = 4.031\,\mu s.
\]

**Case 2: \( \text{tab} > \text{tcb} \)**
\[ X_2 = \frac{1}{4} L(3 - \frac{t_{ab}}{t_{ab}}) \]
\[ = \frac{1}{4} (4km)(3 - \frac{4.03 \mu s}{20.17 \mu s}) \]
\[ = 2800.15 \text{m}. \]

**Figure 13.** Single line diagram based on the results of time difference of arrival captured by RC sensor A4 to A6.

**TABLE 2.** PD data analysis measured by RC sensor A5.

| RC Sensor location | A4  | A5  | A6  |
|--------------------|-----|-----|-----|
| Amplitude (mV)     | 2.797 | 3.857 | 3.597 |
| Time of travelling wave (μs) | 28.39 | 8.219 | 12.250 |
| Actual length of PD location (m) | 2800.00 |
| Calculated length of PD location (m) | 2800.15 |
| Percentage error of PD location (%) | 0.0053 |

4. Conclusions
The investigation of the PD phenomenon in 11kV power cable is well fulfilled with the most suitable type for power cable is made up from cross-link polyethylene (XLPE). By using EMTP-ATP software, the real model of the power system can be simplified into a simple model with the PD source injected anywhere along the line cable. From the analysis result, for the three RC sensors, which are RC sensor A1, RC sensor A2, and RC sensor A3, the detection of the PD signal is from PD source 1. In contrast, for RC sensor A4, RC sensor A5, and RC sensor A6, the detection of PD signal is from PD source 2 due to the range between these sensors and PD sources is closer to each other. The time taken to capture the location of the PD signal is fastest with the voltage produced from them is higher when the nearest RC sensor detects it.

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