Abstract—Time domain reflectometry (TDR) applied to live cables is hampered by the absence of a clear reflection from the far end. Instead, location of partial discharge (PD) can be extracted from small structures in recorded patterns arising from any impedance variation along the signal propagation channel. This paper explores two approaches for a single-sided PD location system. The first method compares similar signal sequences occurring in PD pattern and pattern obtained from an injected signal. The second method exploits the change of impedance at a far end Ring Main Unit (RMU) by introducing ferrite material, whose effect can be switched on and off. Experiment on medium voltage (MV) cable with about 560m length shows that both methods can locate the PD within 2% uncertainty.

I. INTRODUCTION

Underground power cables are important components in the electrical transmission and distribution system. In the Netherlands, nearly 100% of the total low voltage (LV: ≤ 1 kV) and medium voltage (MV: 1 kV - 36 kV) grid consists of underground power cables. Utilities want to be informed on the condition of the cable system in order to plan the maintenance and to locate potential defects before failure. One effective way for condition monitoring is based on partial discharge (PD) measurement [1].

Live cables connected to the power grid often lack clear reflections from the far end as is the case for off-line TDR tests on disconnected cables. One option is to use double-sided measurement. The origin of the PD is determined by the difference in time-of-arrival $t_{oa}$ of the PD pulse at each end of the cable, as shown in Figure 1. The detection units at both ends require accurate synchronization. This can be realized by injection of synchronization pulses at one end and the detection of these pulses at the other end of the cable [2].

The need of two units is a major drawback. It complicates the system and makes it more expensive. Moreover, for some circuits it is not possible to install the units due to lack of space. It is a new idea to make use of the impedance variations along a cable to find the PD location based on TDR reflection. This system demands only one pulse injection unit and sensor instead of two. Impedance variations occur at cable joints, transfer between different type of cables, RMUs, etc.

\[ \Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \]  

(1)
where \( Z_L \) is the load impedance and \( Z_0 \) is the characteristic impedance of the cable. While the transmission coefficient is [4]:

\[
\tau = \frac{2Z_L}{Z_L + Z_0}
\]

(2)

![Diagram](image_url)

(a) Schematic of the system with single-sided sensor.

(b) Reference pattern: reflection pattern for injected pulse seen by the sensor.

(c) PD pattern: reflection pattern for PD occurring at joint b (aligned with injected pulse pattern). Dashed block part has the same locations as reference pattern.

Fig. 2: Principle of partial discharge location with single-sided sensor; signals are detected at RMU1, thus RMU1 does not appear in the pattern.

At the same end as the injection unit, the sensor will detect several reflection pulses from different impedance variations. These reflections, together with the injected pulse itself, form a pattern, which is referred to as “reference pattern”. Another pattern (“PD pattern”) arises at the same sensor if there is a PD occurring somewhere along the cable, because the PD signal will also travel along the cable in two directions and partly reflected when it encounters an impedance variation. As the impedance variation points are physically fixed, the reflection pulses from these points will have unique features in the detected pattern compared with the “reference pattern”. By comparing the reference and PD patterns, it is possible to locate the PD origin. The principle is shown in Figure 2, in which multiple reflections are omitted for simplicity. Injection unit and sensor are placed in RMU1. Figure 2a shows the circuit is terminated with characteristic impedance to avoid reflections from beyond joint c in the example of Figure 2a. Figure 2b shows the reference pattern recorded by the measurement unit upon the injected pulse from the pulse injection unit. It can be seen that the reflections from joint b (indicated as “b”), joint a (indicated as “a”), RMU 2 (indicated as “RMU 2”) and joint c (indicated as “c”) are arriving after the injected pulse in proportion to the pulse propagation distance from the injection point. The reflection pulse from the left of RMU 1 is depicted with negative polarity (“a”), whereas the reflection pulse from the right of RMU 1 is shown with positive polarity (“b”, “RMU 2” and “c”). The polarity indication here is only meant to simplify the explanation. Obviously reflection from either end may have positive and negative polarities. Figure 2c gives the “PD pattern”. A PD occurring at joint b will travel also in two directions. The PD itself and the reflections from the right of the PD origin (“RMU 2” and “c”) will be recorded in the measurement unit with the same time interval as between “b” and “RMU 2”, “c” in the “reference pattern”. After the PD pulse has arrived at RMU 1, it will split: one fraction travels to the left through RMU 1 and the other fraction reflects back to RMU 2. The transmitted PD pulse will reflect partly back at joint a which is labeled with “a” in Figure 2c. The reflected PD pulse will have a reflection at joint b, which is also shown in Figure 2c. By comparing Figure 2b and Figure 2c (the injected pulse and the PD pulse are aligned in time), it is clear that Figure 2b and 2c contains two common reflection pulses (b and a).

B. Directional sensing

A PD signal can come not only from the cable under test but also from other cables. In order to avoid the confusion from the PD signal arriving from other cables which are not under test, directional sensing can be applied. Directional sensing aims to distinguish whether the detected PD signal is from the cable under test or not. The idea is based on the topology shown in Figure 3 [5]. Figure 3a shows the detailed structure of a typical RMU. Figure 3b and 3c give the propagation directions for signals from two different cables, e.g. one XLPE and one PILC in this example. Two sensors are installed: one around the earth of transformer connecting cable (TCC) and the other around the earth of XLPE cable. Assuming the XLPE cable is the one under test, it can be seen that the two sensors give the same polarity when the signal comes from the cable under test (XLPE) while the polarities from the two sensors are opposite when the signal is from the other cable (PILC). Thus with the two combined sensors around TCC and XLPE cable, it is possible to distinguish the signal from cable under test and the signal that originated from other cable(s). If a PD signal is detected by the sensor and judged not to be from the cable under test, the PD signal will not be processed further. Only PD signals from the cable under test can trigger further analysis. It should be noted that it is user defined which cable is the one under test. The idea is based on the topology shown in Figure 3 as an example, for signals from XLPE cable as in Figure 3b, the
first transfer function is derived:

\[ H_1 = \frac{I_{xlpe}}{I_{tccxlpe}} \]  

where \( I_{xlpe} \) is the signal detected by the sensor around XLPE cable and \( I_{tccxlpe} \) is the signal detected by the sensor around TCC. Similarly, for the signal from PILC as in Figure 3c, a second transfer function is obtained:

\[ H_2 = \frac{I_{pilc}}{I_{tccpilc}} \]  

where \( I_{pilc} \) is the signal detected by the sensor around XLPE cable and \( I_{tccpilc} \) is the signal detected by the sensor around TCC. In order to retain the pulse from cable XLPE and remove pulse from cable PILC, a filter can be constructed as:

\[ I_{filter} = H_{f1}(I - H_2 I_{tcc}) \]

where \( H_{f1} = \frac{H_1}{H_1 - H_2} \)

In practice, the reflection patterns may not be that clear as in Figure 2. Sometimes it is not straightforward to align reflections in the pattern with cable joints or RMUs, since they can not always be clearly recognized. To facilitate the pattern correlation between the “reference pattern” and “PD pattern”, a ferrite core can be clamped at the other end of the cable under test to increase the far end reflection as shown in Figure 2a. The ferrite provides a reference reflection point in the “reflection pattern” and the “PD pattern”, which makes the alignment between the two patterns easier. The two patterns with and without ferrite will be different starting from the reflection where the ferrite locates, because ferrite will add extra impedance to the RMU. The ferrite effect is illustrated in Figure 5 for the “reflection pattern” in Figure 2b, where the solid line represents the pattern without ferrite and the dotted line is for the pattern with ferrite. Reflection from RMU 2 can be recognized in the patterns by comparison of both records. The ferrite acts also for the “PD pattern”. To recognize the
ferrite, at least two PDs have to be recorded with and without ferrite.

![Diagram of injected pulse with and without ferrite](image)

**Fig. 5:** Conceptual illustration for ferrite effect to the reference reflection pattern.

For field application, the ferrite needs to be remotely controlled to appear or disappear in the circuit to provide the reference reflection point. In other words, the state of the ferrite can be set “on” or “off” during the cable monitoring process. This can be achieved by opening or short circuiting a coil around the ferrite core with a relay, as shown in Figure 6. The ferrite together with the extra coil controller are shown in the left figure. The ferrite can be modeled by the equivalent circuit shown in Figure 6 (right) [7]. Normally $Z_m$ is much bigger than $Z_1$ and $Z_2$. $Z_{wire}$ stands for the extra coil impedance. By opening or short circuiting $Z_{wire}$, the impedance introduced by the ferrite material can be varied.

![Diagram of control ferrite state “on” and “off” with an extra coil](image)

**Fig. 6:** Control ferrite state “on” and “off” with an extra coil.

### E. Discussion

The procedure of the single-sided PD location methodology is summarized in the flow chart of Figure 7. The directional sensing based on pulse polarities, as described in Section II-B, is used to check whether the PD originates from the cable under test or not. The transfer function to remove reflections from the cable under test is applied to the recorded “reference pattern”. Afterwards, the method of Section II-C is used to get the location result with “Approach 1”. Ferrite state switching discussed in Section II-D is applied to provide a reference point in the “reference pattern” and “PD pattern”, which makes PD locating straightforward. Both methods are susceptible to noise since both methods look at small signal variations. Thus noise will have a significant influence. “Approach 2” is in general more robust than “Approach 1” due to the reference ferrite. The comparison of the two methods is summarized in Table I.

In order to verify the proposed methodology, measurements are conducted in the full scale test set-up with typical Dutch RMU and MV cables at DNV KEMA in Arnhem, the Netherlands. In the test circuit shown in Figure 8, A and B are two cable joints. Note that the left far end is short and the right far end is open. The cable from the left far end to the RMU is the cable under test.

**TABLE I: PD locating approaches**

<table>
<thead>
<tr>
<th>Approach 1</th>
<th>Approach 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>based on transfer function and reflections removal</td>
<td>based on ferrite location recognition</td>
</tr>
<tr>
<td>immediately locating for each PD</td>
<td>need for more than one PD to locate ferrite before locating a PD occurring spot</td>
</tr>
<tr>
<td>long calculation time</td>
<td>short calculation time</td>
</tr>
<tr>
<td>noise can affect the result</td>
<td>more robust</td>
</tr>
<tr>
<td>limited by whether there is clear reflection(s) along the cable under test to make the cross correlation work</td>
<td>limited by whether the ferrite effect can be seen in the reflection pattern</td>
</tr>
</tbody>
</table>

### III. APPLICATION

In order to verify the proposed methodology, measurements are conducted in the full scale test set-up with typical Dutch RMU and MV cables at DNV KEMA in Arnhem, the Netherlands. In the test circuit shown in Figure 8, A and B are two cable joints. Note that the left far end is short and the right far end is open. The cable from the left far end to the RMU is the cable under test.

#### A. Approach 1

Directional sensing is verified by injecting a pulse at joint B, which is labeled as “artificial PD”, and from the right side far open end in Figure 8. The recorded signal in the sensors...
around XLPE cable and the TCC as in Figure 3 are shown in Figure 9. It can be seen from Figure 9a that for the signal from the cable under test, the polarities of the first pulse for the two sensors are opposite while for the signal from the other cable, the polarities are the same, which is shown in Figure 9b. Following the flow chart in Figure 7, the signal from the right far end will be discarded and the signal from the cable under test will be processed further. The “reference pattern” is derived by injecting a pulse signal with the injection probe at the XLPE cable in the RMU. The “PD pattern” is obtained from the “artificial PD” in Figure 8. The “reference pattern” and “PD pattern” are treated with Approach 1 in Section II-C and shown in Figure 10. The “reference pattern” is processed with directional sensing filter. Note that the negative reflection from the right open end immediately after the injection pulse around 1.5 $\mu$s is eliminated from the pattern, as shown in Figure 10a. The “PD pattern” is handled by removing the reflections with the same locations as the “reference pattern”. Only two main reflections are left in this case, shown in Figure 10b. The grey patterns in Figure 10 will be used for cross correlation and the matching points between the two patterns are indicated with dotted circles in the patterns. Correlation result resulted in the PD “location” of 6.1 $\mu$s while the actual PD locates around 6.2 $\mu$s as shown in Figure 10. It should be noted that the removal length of the PD pattern may influence the location result, which indicates that robustness of “Approach 1” has room for improvement.

**B. Approach 2**

In order to better compare the patterns, ferrite is applied at the left far end as shown in Figure 8. The two patterns (“reference” and “PD”) with and without ferrite are both shown in Figure 11. It can be seen that for “reference pattern”...
in Figure 11a, the ferrite location (left far end in Figure 8) appears around 10.0 µs while for “PD pattern” in Figure 11b, it locates around 4.0 µs. With this reference reflection point, the “reference pattern” and “PD pattern” can be aligned to locate the PD. Result shows the PD location is 6.3 µs.

The comparison of the location result from two approaches is listed in Table II.

### Table II: Location from two approaches

<table>
<thead>
<tr>
<th>PD origin</th>
<th>Approach 1</th>
<th>Approach 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>location</td>
<td>6.1 µs</td>
<td>6.3 µs</td>
</tr>
<tr>
<td>uncertainty</td>
<td>2%</td>
<td>2%</td>
</tr>
</tbody>
</table>

Uncertainty is derived by [6.1 – 6.2] and [6.3 – 6.2] µs.

![Reference pattern and PD pattern with and without ferrite](image)

Fig. 11: Reference pattern and PD pattern with and without ferrite as in Approach 2.

**IV. CONCLUSION**

Two approaches are proposed for single-sided PD location for long distance MV cable system. Each of them is based on comparing a reference pattern obtained from an injected signal to patterns from a PD. In case of on-line recordings, the reference pattern should not be impeded by a PD event at the same time. The likelihood that a PD occurs during the tens of microseconds recording upon the injected signal is rather small. Moreover, PDs occur randomly so it is feasible to get a PD free reference pattern by selecting similar responses upon multiple pulse injections. The first approach relies on transfer function calculation for directional sensing to the “reference pattern” and pulse removal from the “PD pattern”; while the second approach is based on the help of ferrite to provide a reference reflection point. Experiments show that both approaches can locate the PD origin successfully with uncertainty in the range of 2% with respect to the time.

Robustness of the first approach has space for improvement; the second approach seems promising for field application although it needs to wait several PDs with and without ferrite to allow for location. However in this paper, “Approach 2” assumes that there is one PD location. For field application there may be more PD origins which makes the ferrite recognition non-trivial.

Partial discharge location with sensor on one end of the cable provides economic and operational advantage with respect to double sided system. It can increase the possibility to monitor power cable online. However, there are also limits for single-sided system. For “Approach 1”, it demands for a second sensor to do the directional sensing while for “Approach 2”, it requires ferrite. Also because the algorithm is based on pulse detection and location, the maximum length of the cable that can be monitored is shorter and the noise to signal ratio limit would be smaller compared to double-sided system.

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**REFERENCES**