Detecting Electromagnetic Disturbances on Transmission Lines Using Time Reversal

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Abstract

Transmission lines can suffer a variety of electromagnetic disturbances. These can range from intentional interference, due to malicious intent, through to the effects of lightning strikes or partial discharge. Given a high-fidelity model of the transmission line, it is possible to take measurement data and 'run time backwards' to identify the source of the disturbance. This paper reviews the theory and implementation of electromagnetic time reversal, provides some examples from the literature, and illustrates its operation with current research to identify the source of a partial discharge event on Medium and High Voltage cables.

Keywords: numerical modelling, Transmission Line Matrix (TLM) method, electromagnetic time reversal (EMTR), partial discharge on-line location; power cables; powerline.

1. Introduction

Power transmission and distribution networks are frequently subject to a range of unexpected electromagnetic disturbances arising from both natural and man-made disturbances. Natural disturbances are due to lightning strikes, faults induced by weather conditions, such as ice, falling trees, storms, geomagnetic effects, contact by flying objects or animals, and man-made disturbances are due to switching operations of networks components and to acts of sabotage such as conducted intentional electromagnetic interference (IEMI). These events cause diverse effects on power supply quality and reliability, ranging from voltage sags, damage to sensitive loads, insulation deterioration, supply interruption and also blackouts.

The on-line aggressive environment accelerates cable insulation aging producing defects on power cables [1]. The failure of cable insulation can have severe social and economic consequences and statistics indicate that more than 85% of equipment failures are related to insulation failure, as shown in Fig. 1[2]. Therefore, the adoption of on-line diagnostic methods that can locate insulation degradation is the most effective solution for condition monitoring of networks to prevent faults and interruption of supply.

Insulation degradation is often caused by partial discharge (PD) events. PD is "a localized electrical discharge that only partially bridges the insulation between conductors" [3] and it starts in discontinuities or defects of the insulation system. For this reason, PD is widely regarded as one of the best 'early warning' indicators of insulation degradation [4] and the on-line PD location as the most suitable monitoring method of network integrity assessment. On-line PD localization is, then, a desired feature in modern network protection schemes being a cost-effective tool to enhance networks resilience. The PD location problem in power cables has been a topic widely investigated in the literature. Most on-line location methods are reflectometry or traveling wave-based techniques [1][5][6][7], based on the principle that a PD event produce electromagnetic waves that travel in either direction towards the cable ends. The incident wave, and the reflected wave from the other cable end, are measured at one cable end and the delay between these pulses allows one to locate the PD source. Due to attenuation and dispersion phenomena that affect the localization accuracy, time domain reflectometry (TDR) methods can only be used for short cables. To solve this problem, multi-end measurement methods, i.e. the time of arrival (ToA) methods [8], are used, but their implementation is difficult due to the complexity in the synchronization procedure, often realized using laborious global position systems (GPS). Despite the high performance of existing on-line reflectometry-based PD location methods, their accuracy is still affected by the following factors:

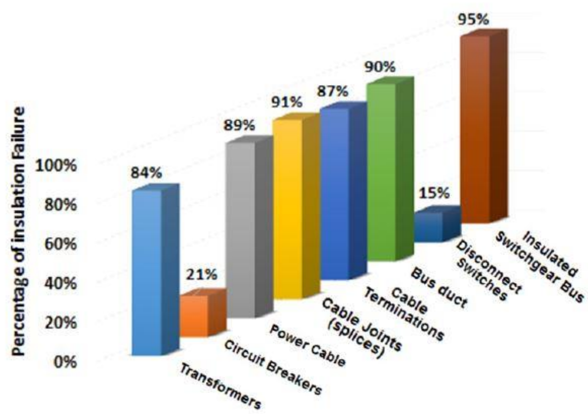

Figure 1. Percentage of insulation failure[2].

1. Assessment of the number of observation points versus the number of possible multiple PD location solutions for long cables and for complex and branched networks.

2. Requirement of a precise time recording for methods that require multiple synchronized measurements.

3. Loss of GPS signal impacting the location accuracy.

4. Requirement of large bandwidth measurement systems with high sensitivity and high resolution and low internal noise.

5. De-noising the PD signal.

Recently, electromagnetic time reversal (EMTR) theory has been successfully applied in the field of electromagnetic compatibility (EMC), specifically in power systems, with the development of technologies in electromagnetic disturbance source-location identification with significantly improved performance compared to classical approaches [9].

In this paper a review of the theory and implementation of electromagnetic time reversal is given from the literature and some results of the research under development at De Montfort University, Leicester, UK, to identify the source of partial discharge events on Medium and High Voltage cables using EMTR theory are presented.

2. Electromagnetic Time Reversal to locate sources of Electromagnetic Disturbances

Electromagnetic time reversal methods to locate the sources of electromagnetic disturbances are based on the Maxwell's equations invariance under time reversal [9].

Mathematically, time reversal implies making the substitution $t \rightarrow -t$. Considering Maxwell's equations in a vacuum:

$$\nabla \cdot \left(\varepsilon(\vec{r})\vec{E}(\vec{r},t)\right) = \rho(\vec{r},t) \quad (1.1)$$

$$\nabla \cdot \left(\mu(\vec{r})\vec{H}(\vec{r},t)\right) = 0 \quad (1.2)$$

$$\nabla \times \vec{E}(\vec{r},t) = \mu(\vec{r})\frac{\partial \vec{H}(\vec{r},t)}{\partial t} \quad (1.3)$$

$$\nabla \times \vec{H}(\vec{r},t) = \varepsilon(\vec{r})\frac{\partial \vec{E}(\vec{r},t)}{\partial t} + \vec{J}(\vec{r},t) \quad (1.4)$$

where E and H are the electric and magnetic field, ρ the charge density, J the electric current density, ε and μ the electric permittivity and magnetic permeability, applying a time-reversal transformation, the following equations are obtained:

$$\nabla \cdot \left(\varepsilon(\vec{r})\vec{E}(\vec{r},-t)\right) = \rho(\vec{r},-t) \quad (2.1)$$

$$\nabla \cdot \left(\mu(\vec{r})\left(-\vec{H}(\vec{r},-t)\right)\right) = 0 \quad (2.1)$$

$$\nabla \times \vec{E}(\vec{r},-t) = \mu(\vec{r})\frac{\partial \vec{H}(\vec{r},-t)}{\partial -t} \quad (2.1)$$

$$\nabla \times \vec{H}(\vec{r},-t) = \varepsilon(\vec{r})\frac{\partial \vec{E}(\vec{r},-t)}{\partial -t} + \left(-\vec{J}(\vec{r},-t)\right) \quad (2.4)$$

As the equations show, expressions (2) are identical to equations (1), except that magnetic field and current density have changed sign. Then, to make Maxwell's equations invariant under time reversal, the magnetic field and the electrical current density should change sign as well [9]:

$$H(r,t) \rightarrow -H(r,-t) \quad (3.1)$$

$$J(r,t) \rightarrow -J(r,-t) \quad (3.2)$$

EMTR methods in electromagnetic disturbances source-location identification take advantage of the time reversibility of wave equations and the spatial correlation property of the time-reversal theory to refocus the time reversed back-propagated electromagnetic waves into the original disturbance location. In more detail, when the electromagnetic transient disturbance is time reversed and back injected into the original system, it refocuses back to the location of its source[9]. For example, Figure 2, at the top, shows a source that emits electromagnetic impulsive waves in free space and three sensors that record the cylindrical wave generated by the source in three points in the space. Time reversing the recorded waves and re-emitting them back into the free space, a maximum value of the field can be observed, in the free space, at the location of the source, as shown in figure 2, at the bottom. The time reversed waveforms will give, in fact, the maximum contribution to the total field in the location of the source where they are in phase.

Based on this theory, EMTR theory has been used in locating the sources of electromagnetic disturbances in the field of power systems and in particular, methods to locate lightning strikes, lightning-originated flashovers [10] and faults [10] (i.e. open and short circuits that stop signals from propagating further along a cable) in transmission and distribution networks.

For the on-line location of faults in power networks, the EMTR-based methods, compared with the existing techniques, have presented the following advantages [9]:

1. Applicability to inhomogeneous and complex networks.
2. Robustness against the presence of noise and limited observation time window.
3. Use of a single observation point.

While for the EMTR-based method designed to locate lightning interference, it has been observed that:

1. it can be considered a more general case compared to ToA methods.

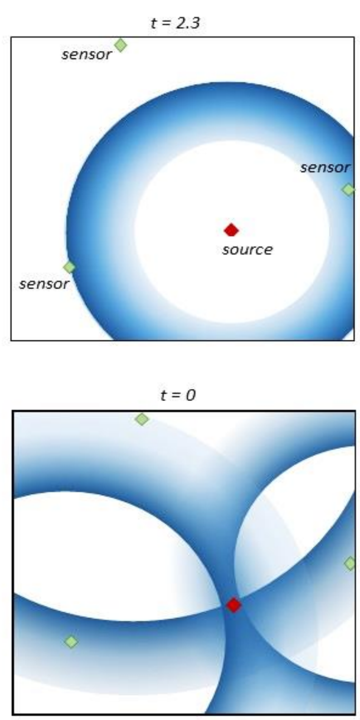

Figure 2. Time reversed waveforms [9].

2. it is able to give information about the wave shape of the lightning interference, in addition to the propagation time.

The described characteristics of EMTR-based techniques, observed in the previous applications, make it a good method to solve all the factors affecting the accuracy of the existing PD location methods.

3. EMTR-based method to locate Partial Discharge using a 1D TLM model

The design of a new method to locate PD source in power networks based on EMTR theory is under development by the authors [12]. A detailed description of the design procedure of the method is given in [12], here a brief description of the basic concept is recalled together with some results obtained in simulations that show the effectiveness of the method to locate PD sources in power cables.

The new method has been designed in simulation using the 1D Transmission Line Matrix (TLM) method to model the propagation of PD signal on power cables.

The propagation of a PD signal in a transmission line is described by the Telegrapher's equations [13], that evaluate the voltage *v(x,t)*, and current, *i(x,t)*, waves on the line as functions of time *t* and distance *x*:

$$\frac{\partial v(x,t)}{\partial x} + L\frac{\partial i(x,t)}{\partial \mathrm{t}} + Ri(x,t) = 0 \qquad (1.1)$$

$$\frac{\partial i(x,t)}{\partial x} + C\frac{\partial v(x,t)}{\partial \mathrm{t}} + Gv(x,t) = 0 \qquad (1.2)$$

where *L*, *C*, *R* and *G* are, respectively, the series inductance, the shunt capacitance, the series resistance, and the shunt conductance per unit length of the line. For non-dissipative transmission line (lossless lines) the partial differential equations (1) becomes time-invariant equations [9]. It means that voltage and current, *v(x,t)*, and *i(x,t)*, and their symmetric values in time, *v(x,-t)*, and *i(x,-t)*, are both solutions of the Telegrapher's equations [9]. In this condition, the Telegrapher's equations become invariant under time reversal, ($t \longrightarrow -t$), by changing the sign of the current as follows [9]:

$$\frac{\partial v(x,-t)}{\partial x} + L\frac{\partial(-i(x,-t))}{\partial(-t)} = 0 \qquad (2.1)$$

$$\frac{\partial(-i(x,-t))}{\partial x} + C\frac{\partial v(x,-t)}{\partial(-t)} = 0 \qquad (2.2)$$

The mathematical change of the current sign, under time reversal theory, means that the charge speed is changed in sign.

Fig. 3 shows the equivalent circuit of a lossless transmission line, characterized by a propagation speed, *u*, and a characteristic impedance, Z_0 given by[13]:

$$u = \frac{dx}{dt} = \frac{1}{\sqrt{LC}} \qquad (3)$$

$$Z_0 = \sqrt{\frac{L}{C}} \qquad (4)$$

For the purpose of illustration, a PD signal represented by a double exponential equation [12], shown in Figure 4, has been considered and its propagation is analyzed in the simple system shown in Figure 5.a, formed by an homogeneous HV cable connected to the impedances, Z_1 and Z_2 at its ends.

The TLM method has been used to evaluate the voltage and current waves given by Telegrapher's equations. TLM method is a

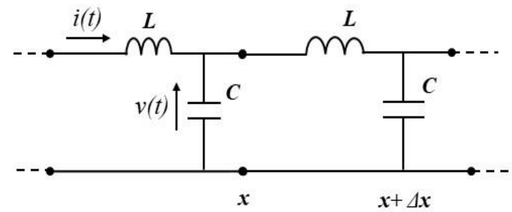

Fig. 3 Equivalent circuit of a lossless transmission line.

differential equation-based method in time domain that discretizes the transmission line mesh in *n* segments, of length *Δx*, connected by nodes. A scheme of the 1D TLM transmission line is shown in Figure 5.a. The wave pulses are scattered in the nodes and propagate in the transmission lines, generating incident, $VL^i_n(k)$ and $VR^i_n(k)$, and reflected, $VL^r_n(k)$ and $VR^r_n(k)$, voltages. The voltage, $V_n(k)$, and current, $I_n(k)$, at time-step *k*, at the node *n*, of the line are given by [13]:

$$V_n(k) = \frac{\frac{2VL_n^i(k)}{Z_0} + \frac{2VR_n^i(k)}{Z_0}}{\frac{1}{Z_0} + \frac{1}{Z_0}} \qquad (5.1)$$

$$I_n(k) = \frac{V_n(k) - 2VR_n^i(k)}{Z_0} \qquad (5.2)$$

When a PD event occurs, in a node, x_{PD}, of the line, an electromagnetic disturbance is produced that propagates towards the cable ends, as schematized in Figure 5.a.

During the direct time (DT) simulation, at two observation points (OPs), shown in Figure 5.a, the signals, $s_i(x, t)$, with i = 1, 2, generated by the PD event, are measured. The measured signals are time-inversed as follows:

$$s_i(x,t) \rightarrow s_i(x,t') \quad \text{with} \quad t' = T - t \qquad (6)$$

where *i*=1, 2 and *T* is the observation time during which the signals are measured.

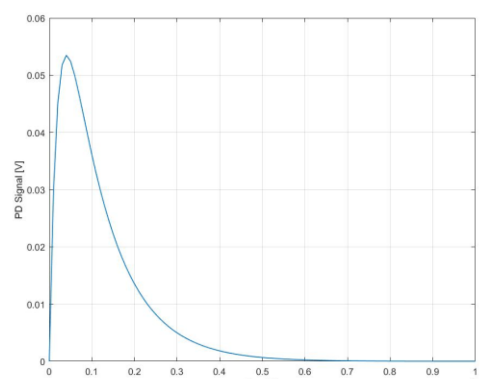

Fig. 4 PD signal in a node of the line.

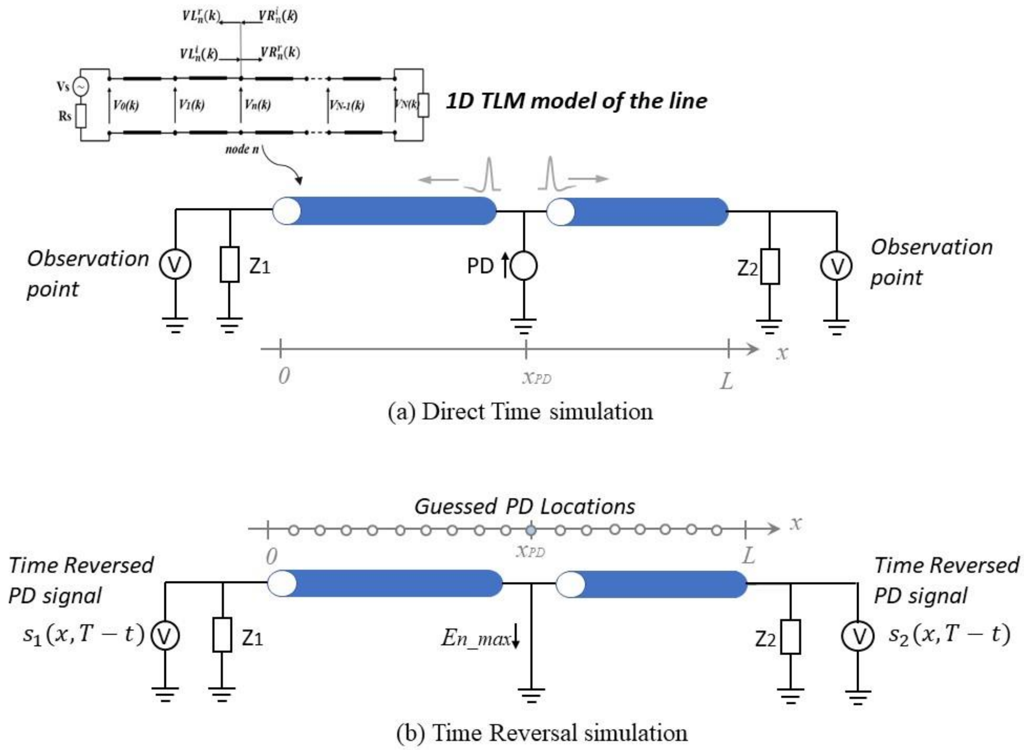

Fig. 5 Schematic representation of the line with a PD event at x_{PD} location along the cable and two OPs at the cable ends, during the Direct Time simulation (a) and the Time reversal simulation (b).

Then, the time reversed signals are back injected in the line from the two OPs, as shown in Figure 5.b, where the model used for the time reversal TR simulation is shown. Several TR simulations are run, considering in each of them a guessed partial discharge location (GPDL), where a variation of the transversal impedance of the TLM node is realized in order to simulate the modified capacitive impedance, between the inner conductor of the cable and the external shield, due to the PD event that occurs inside the insulator. PD discharge events, in fact, occur in insulator defects characterized by a capacitance. In the well-known three capacitors model of PD events [14], this defect capacitance is short-circuited during the discharge event, so modifying the shunt capacitance of the line. A detailed description of the definition of the GPDL impedance and its representation in a 1D TLM model of the line is given in [12].

Finally, for each GPDL, the energy stored in the transversal capacitive impedance is evaluated. The GPDL characterized by the maximum value of the energy is the location PD source. The time reversed back-injected signals, in fact, will add up in phase at the real PD location.

To prove the effectiveness of the method some simulation results are here shown.

The proposed simulations have been performed considering a transmission line formed of a homogeneous cable of length l=250m, connected to the impedances Z_1 and Z_2 at its ends., with $Z_1=Z_2=100$ kΩ, representing the impedance of power transformers at high frequency. A 11-kV aluminum power cable has been considered with Cross-Linked Polyethylene (XLPE) insulation and cross-sectional area of 150 mm^2.

Figure 6 shows the signals measured at the two OPs, during the DT simulation, when the PD source is 60 m far from the left end of the cable, and the time reversed signals. Figure 7 shows the normalized energy, evaluated with respect to the maximum energy in the GPDLs, in each GPDL during the TR simulations. As the

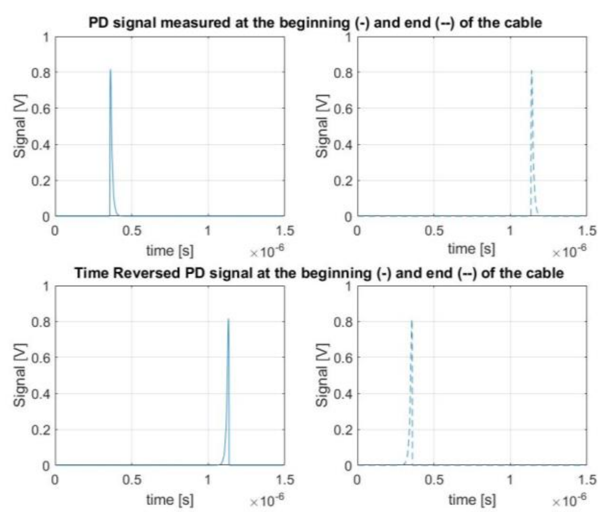

Fig. 6 PD signals measured at the two OPs in DT simulation with a PD source 60 m far from the left end of the cable and the Time Reversed signals.

figure shows, the maximum energy is obtained at GPDL=x_{PD}=60m that is the location of PD source. Figure 8 shows the voltages, in the time domain, in three GPDLs of the line during the TR simulation, respectively, at 60m from the left end of the cable, that coincides with the PD source location, and at 20m and 200m from the left end of the cable. As the figure shows, the voltage signal is maximum in GPDL coincident with the PD source location, as expected. While, Figure 9 shows the signal at the GPDL=60m along the line at the time $t'=T$, where it is clear that the two time-reversed back injected signals, $s_1(x, t)$ and $s_2(x, t)$ add up in phase, at the time $t'=T$ that means t=0, then going back in time at the time it had been generated.

Figures 10-12 show the normalized energy evaluated in the GPDLs when the PD source is, respectively, 20m, 100m and 200m

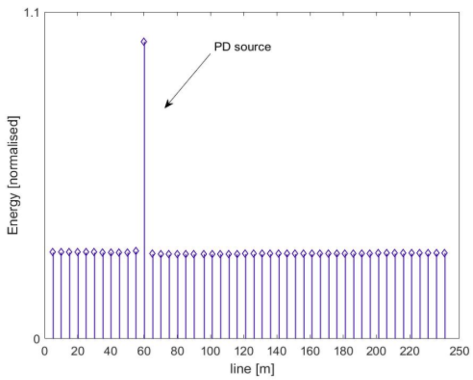

Fig. 7 Normalized energy in several GPDL when PD source is 60 m from the left end of the cable.

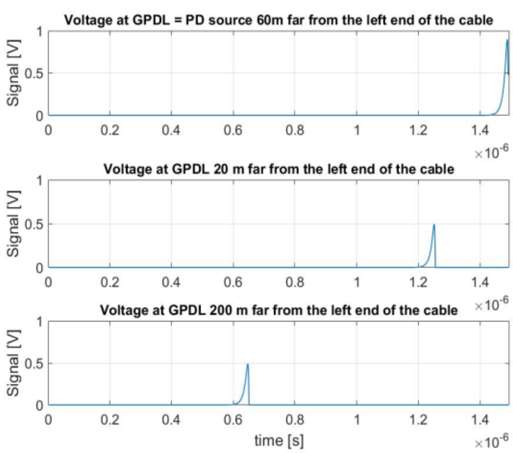

Fig. 8 Voltage at three GPDLs and the normalized energy in several GPDLs in the TR simulation.

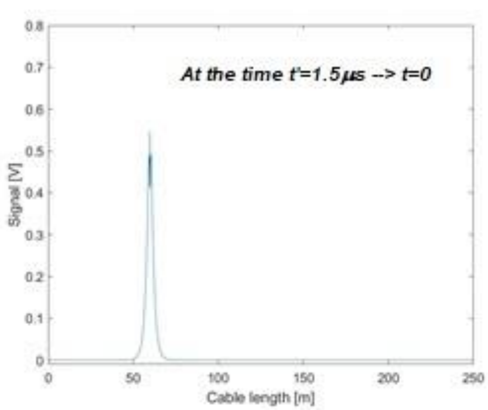

Fig. 9 Time reversed back-injected signals along the line, back to *t = 0.*

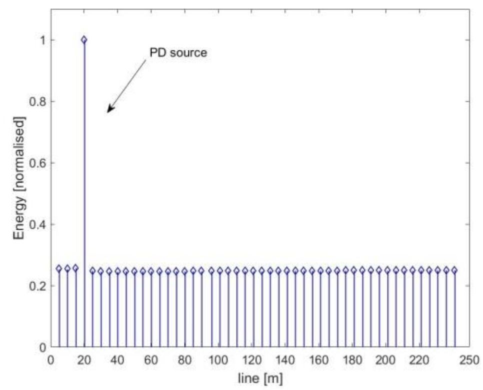

Fig. 10 Normalized energy in several GPDL when PD source is 20 m from the left end of the cable.

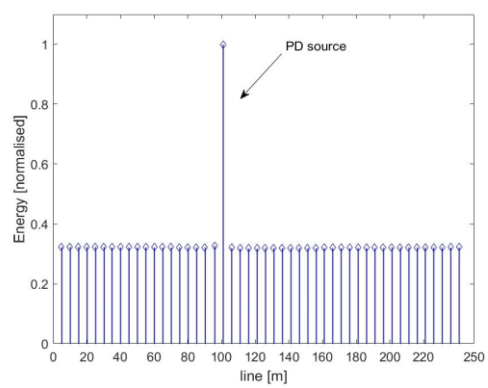

Fig. 11 Normalized energy in several GPDL when PD source is 100 m from the left end of the cable.

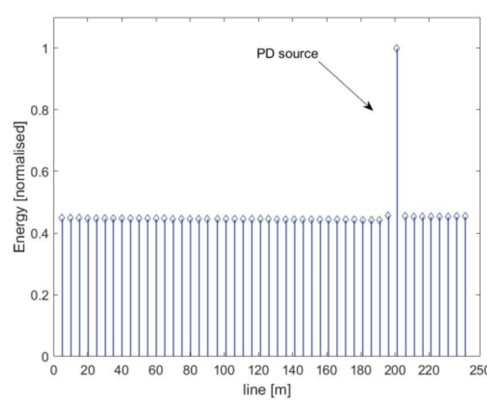

Fig. 12 Normalized energy in several GPDL when PD source is 200 m from the left end of the cable.

from the left end of the cable. As the figures show the method is able to locate exactly the source of PD event along the cable.

In [12], the authors have proved that the method works also using only one observation point, then measuring the signal generated by PD event only at one cable end.

4. Conclusion

This paper deals with the theory of electromagnetic time reversal (EMTR) and describes its implementation in locating electromagnetic disturbance source as defined in the literature. Then, the use of EMTR theory to locate partial discharge (PD) source in medium and high voltage power networks is discussed. The first results of a research activity, under development, with the aim to design a EMTR-based method to locate PD sources in power networks, are illustrated. In particular, the simulation results that show the effectiveness of the EMTR-based method to locate PD sources in homogenous HV XLPE cables using two observation point (OPs) are given and described. The ability of the method to locate PD using only one observation point has been also verified by the authors and new research activities are under development. More in detail, the validation of the method in complex network topologies (inhomogeneous cables and branched networks) is under study together with the analysis of the effectiveness of the EMTR-based method to locate multiple PD sources in power networks.

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