Electromagnetic Time Reversal to Locate Partial Discharges in Power Networks with Inhomogeneous cables using the Transmission Line Matrix Method

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Abstract:

This paper describes a method for the on-line location of partial discharges (PD) in power networks based on the electromagnetic time reversal (EMTR) theory. PDs are localized electrical discharges that partially bridge the insulation between conductors and that start in cable insulation defects. Since the insulation degradation is often caused by PD, PD is regarded as a symptom of insulation degradation and on-line PD location is considered the most suitable monitoring method of network integrity assessment to prevent faults and improve network resilience. The proposed method, reversing in time the measured PD signals, refocuses them to their source allowing the location of PD site. The method uses the Transmission Line Matrix modelling approach to solve the backward propagation equations. In this paper, the effectiveness of the EMTR-based method to locate PDs in inhomogeneous power lines, using only one measurement point at a line end, is investigated and proved in simulation.

Keywords— Partial Discharges on-line location; Transmission Line Matrix method; Electromagnetic Time Reversal theory; Power Network reliability; Power Network resilience, Electricity Security.

1. Introduction

INSULATION failures in power transmission and distribution cable networks range from faults to supply interruption and blackouts and can have severe social and economic consequences. Statistics indicate that more than 85% of equipment failures are related to insulation failure [1]. Thus, the adoption of on-line diagnostic methods that can locate insulation degradation is an effective solution for condition monitoring of networks to improve their reliability and resilience. Insulation deterioration is often caused by partial discharge (PD) events. A PD is "a localized electrical discharge that only partially bridges the insulation between conductors" [2] and it starts in discontinuities or defects of the insulation system caused during the manufacturing process, or in cable deteriorated with age, or by thermal or electrical over-stressing. Since PD is a symptom of insulation degradation and widely regarded as one of the best 'early warning' indicators of cable failure [3], on-line PD location is the most suitable monitoring method of network integrity assessment and it is a desired feature in modern network protection schemes as a tool to prevent faults and the interruption of supply, enhancing network reliability and electricity security.

The PD location problem in power networks is a topic widely investigated in the literature. Most on-line location methods are reflectometry or traveling wave-based techniques [4]-[7]. Time of arrival (ToA) methods use multi-end measurement techniques based on the principle that a PD event produces electromagnetic waves that travel in either direction towards the cable ends. The incident wave, and the reflected waves from the cable ends, are measured at different points of the line and the difference in the times of arrival of these pulses allow one to locate the PD source. However, their practical implementation is difficult due to the need for synchronization. Moreover, their accuracy in locating PDs is influenced by the distortion phenomenon that characterize the propagation of PD signals on power cables and by the presence of electromagnetic interference on networks. Wavelet techniques [8] are adopted to overcome some of the shortcomings associated with reflectometry method, but these require a considerable amount of computational effort.

EMTR (Electromagnetic Time Reversal) theory has been recently used to locate sources of electromagnetic disturbances in power systems, and methods to locate lightning strikes, lightning-originated flashovers [9] and faults [10] have been developed from it. EMTR methods present the following advantages [11] with respect to traditional traveling wave-based techniques: 1. applicability to inhomogeneous and complex networks.; 2. robustness against the presence of noise and a limited observation time window; 3. use of a single observation point. A new method to locate PDs based on EMTR theory was

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proposed in [12] where the first results of the design procedure have been given and the effectiveness of the method to locate PD sources in a homogeneous line has been shown in simulation. The method has been designed using a 1D Transmission Line Matrix (TLM) model of the signal propagation. The TLM technique has been chosen for its flexibility, high efficiency, and its numerical stability. In [12] the design of the method using two observation points (OPs) is described and a proof that the method works also using one OP at one end of the network is also given. In this paper, after a brief introduction of the proposed EMTR-TLM technique to locate PD on power networks, the effectiveness of the method to locate PD in non-homogeneous lines using only one OP is investigated and demonstrated in simulation.

2. Electromagnetic Time Reversal theory to locate electromagnetic sources

Electromagnetic time reversal methods to locate the sources of electromagnetic disturbances are based on the invariance of Maxwell's equations under time reversal [11]. 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 $\vec{E}$ and $\vec{H}$ are the electric and magnetic field, ρ the charge density, $\vec{J}$ the electric current density, ε and μ, are respectively, the electric permittivity and magnetic permeability. Applying the time-reversal transformation, the following equations are obtained:

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

$$\nabla \cdot \left(\mu(\vec{r})\left(-\vec{H}(\vec{r},-t)\right)\right) = 0 \quad (2.2)$$

$$\nabla \times \vec{E}(\vec{r},-t) = \mu(\vec{r})\frac{\partial \vec{H}(\vec{r},-t)}{\partial -t} \quad (2.3)$$

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

Expressions (2) are identical to (1), except for the magnetic field and the current density that have changed sign (see Chapter 1 of [11] for a discussion on the necessity of the sign change).

The time reversibility of wave equations and the spatial correlation property of the time-reversal theory allow the refocusing of the time reversed back-propagated electromagnetic waves into the original disturbance location. In more detail, when the electromagnetic waves are time reversed and back injected into the original system, they refocus back to the location of their source, arriving in phase at the location of the source [2], as illustrated in Figure 1. The figure shows a source that emits electromagnetic waves in free space and three sensors that record the wave at three points in space. After time reversing the recorded waves and re-emitting them back into the free space from just those three points, a maximum value of the field can be observed at the location of the source [11].

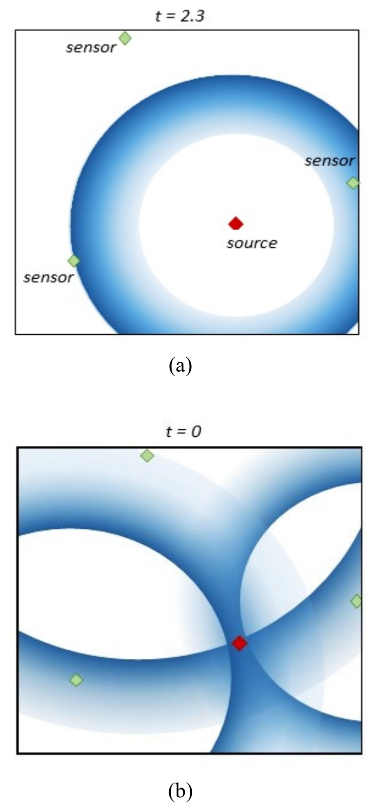


Fig. 1. Electromagnetic source in free space (a) and the time reversed waveforms (b) [2].

In the following sections, the designed EMTR-based method to locate PD in non-homogeneous power lines using only one observation point is described.

3. Electromagnetic Time Reversal method to locate Partial Discharge

The basic steps of the proposed EMTR method to locate PD are the following [12]:

1. recording of the PD-originated signals at one observation points (OP) along the line under study.
2. Simulation of the back-injection of the time-reversed collected PD signals for different guessed PD locations (GPDLs) using a 1D Transmission Line Matrix (TLM) model of the line under study.
3. Locating the PD source by identifying the GPDL characterized by the highest energy concentration.

The first step of the above described EMTR procedure to locate PDs, in practical implementation, is carried out experimentally, i.e. the PD-generated signal is measured at the OP. Here, to the aim of proving the effectiveness of the method in line with inhomogeneous cable sections, the first step of the procedure is developed in simulation, i.e., in the Direct Time simulation, using a model of the propagation of PD signals in the power line under investigation.

In the following sections a description of the EMTR-based method to locate PD in non-homogeneous lines is given

3.1 Direct Time simulation

The Direct Time (DT) simulation is developed using a lossy model of the power network. The propagation of a PD signal in a power network is described by the telegrapher's equations [13], that evaluate the voltage *v(x,t),* and current, *i(x,t),* waves as functions of time *t* and distance *x*:

$$\frac{\partial v(x,\ t)}{\partial x} + L\frac{\partial i(x,t)}{\partial t} + Ri(x,t) \ = 0 \qquad (3.1)$$

$$\frac{\partial i(x,\ t)}{\partial x} + C\frac{\partial v(x,t)}{\partial t} + Gv(x,t) \ = \ 0 \qquad (3.2)$$

where *L, C, R* and *G* are, respectively, the per unit length series inductance, the shunt capacitance, the series resistance, and the shunt conductance of the line. In a first approximation, the line per-unit-length resistance and conductance are assumed to be independent of frequency.

The TLM method is used to model the PD signal propagation on power lines. The TLM method is a differential equation-based method, operating in the time-domain, that discretizes the transmission line, of length *L*, into a series of *N* segments or nodes, of length Δx, shown in Figure 2.(a). Each *LC* section of the line can be represented by a transmission line with a propagation speed, *u*, a characteristic impedance, Z_0, [15] given by:

$$u = \frac{1}{\sqrt{LC}} \quad ; \quad Z_0 = \sqrt{\frac{L}{C}} \qquad (4)$$

and a transit time Δt given by:

$$\Delta t = \frac{\Delta x}{u} = \Delta x \cdot \sqrt{LC} \qquad (5)$$

Connecting the N sections, the TLM equivalent model of the line is obtained, shown in Figure 2(b). At each node, the wave pulses, $V_n(k)$, are scattered and propagate in the lines, generating incident voltages, $VL^i_n(k)$, $VR^i_n(k)$, and reflected voltages, $VL^r_n(k)$, $VR^r_n(k)$, respectively on the left and on the right side of the node *n*. Replacing the lines to the right and to the left of the node by their Thevenin equivalent circuits (shown in Figure 2(c)), the voltage $V_n(k)$, and the current, $I_n(k)$, at time step k, are given by the Millman theorem as follows:

$$V_n(k) = \frac{\dfrac{2VL^i_n(k)}{Z_0} + \dfrac{2VR^i_n(k)}{Z_0 + R}}{\dfrac{1}{Z_0} + \dfrac{1}{Z_0} + G} \qquad (6.1)$$

$$I_n(k) = \frac{V_n(k) - 2VR^i_n(k)}{Z_0 + R} \qquad (6.2)$$

and they are defined by the knowledge of the incident voltages

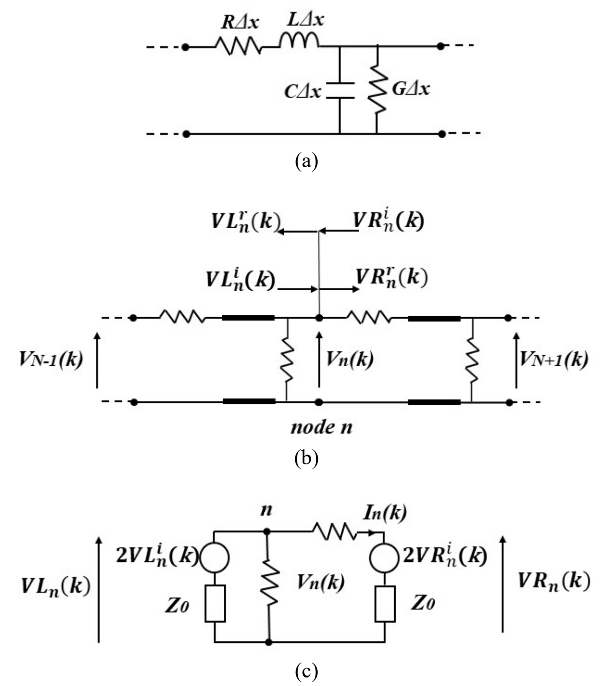


Fig. 2. Transmission line node (a), TLM model (b) and the Thevenin equivalent circuit (c) at the node *n*.

at the time *k*. The incident voltages at the time *k+1* are evaluated by the knowledge of the node condition at time k. The incident voltages at the node *n* are, in fact, coincident with the reflected voltages from the nodes *n-1* and *n+1* at time *k*.

A schematic of the inhomogeneous line under study is shown in Figure 3.

The line is formed of two different cable sections, respectively l_1 and l_2 long, characterized respectively by L_1, C_1, R_1, G_1 and L_2, C_2, R_2, G_2 electrical parameters per unit length, and then by the characteristic impedances, Z_{01} and Z_{02}, and the propagation speeds, u_1 and u_2, of each section evaluated by (4). In order to maintain the same time-step Δt throughout the simulation, the length, Δx_1, Δx_2, of the TLM model of the two cable sections are given by:

$$\Delta x_1 = u_1 \Delta t \qquad \text{for the cable section } l_1 \text{ long} \qquad (7.1)$$

$$\Delta x_2 = u_2 \Delta t \qquad \text{for the cable section } l_2 \text{ long} \qquad (7.2)$$

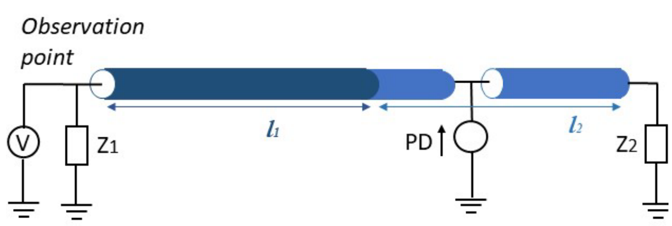


Fig. 3. Schematic representation of the system under study.

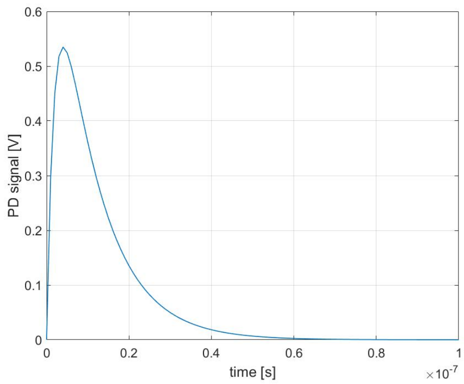


Fig. 4. Double exponential impulse used to simulate PD signal.

The line is connected to the load impedances, Z_1 and Z_2. Under the hypothesis that the line is connected to power transformers at both ends, Z_1 and Z_2 are chosen to be equal to 100 kΩ, which is a reasonable approximation for the input impedance of power transformers at high frequencies.

The PD event, occurring at a given location along the line, generates an impulsive signal that, for the purpose of illustration, is represented by a double exponential signal with a rise time of 2ns and a pulse length of 10ns [12], shown in Figure 4. The PD event occurs inside the insulation between the inner conductor and the external shield, ground connected. The PD-generated signal, $s(x,t)$, is evaluated at the observation point (OP), and it is used to locate the PD source with the EMTR-based method as described in the following section.

3.2 TLM EMTR location method

The telegrapher's equations for a non-dissipative medium are time reversal-invariant equations [11]. 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 equations. For non-dissipative lines, equations (3) become:

$$\frac{\partial v(x,\ t)}{\partial x} + L\frac{\partial i(x,t)}{\partial t} = 0 \qquad (8.1)$$

$$\frac{\partial i(x,\ t)}{\partial x} + C\frac{\partial v(x,t)}{\partial t} = 0 \qquad (8.2)$$

with a propagation speed, u, and a characteristic impedance, Z_0, of the line given by (4).

Equations (8) are invariant under time reversal transformation with a change in sign of the current [11]:

$$\frac{\partial v(x,\ -t)}{\partial x} + L\frac{\partial(-i(x,-t))}{\partial(-t)} = 0 \qquad (9.1)$$

$$\frac{\partial(-i(x,\ -t))}{\partial x} + C\frac{\partial(v(x,-t))}{\partial(-t)} = 0 \qquad (9.2)$$

The TLM method, described in the previous section, has been also used to solve equations (9) and to describe the time reversal of the PD signal.

The PD signal, $s(x,t)$, collected at the OP during the DT simulation, for an observation period T, is time reversed as follows:

$$s_i(x,\ t) \rightarrow s_i(x,t') \quad \text{with} \quad t'=T-t \qquad (10)$$

and, from the same OP of the line where it was collected, it is back injected into the TLM model of the line without losses. Then, several Time Reversal (TR) simulations are performed.

A schematic of the line used for the TR simulations is shown in Figure 5.

In each TR simulation different guessed partial discharge locations (GPDL) are considered, in a node of the TLM model of the line, and the energy stored in the transversal impedance is evaluated. In the TLM GPDL node, the line transverse impedance is modified to simulate the new shunt capacitive impedance due to the PD event. The well-known three capacitors model of PD and the generalized PD model of Niemeyer have been used to define and evaluate the GPDL impedance [12]. This impedance has been realized using a stub[15] capacitor at the node, where the voltage, $V_{GPDL}(k)$, at time k, is given by:

$$V_{GPDL}(k) = \frac{\frac{2VL_n^i(k)}{Z_0} + \frac{2VR_n^i(k)}{Z_0} + \frac{2Vc_n^i(k)}{Z_{pd}}}{\frac{1}{Z_0} + \frac{1}{Z_0} + \frac{1}{Z_{pd}}} \qquad (11)$$

where Z_{pd} is the impedance of the stub capacitor in the Thevenin equivalent circuit [12] of the line and Z_0 is the characteristic impedance of the line section where the PD occurs, i.e. $Z_0=Z_{01}$ if the PD is in the l_1 line section and $Z_0=Z_{02}$ in the l_2 section.

The Energy, E_n, stored at the GPDL, normalized with respect to the maximum Energy, is evaluated as follows [12]:

$$En = \frac{\frac{1}{2}C_{pd}\sum_{k=1}^{M} V_{GPDL}^2(k)}{\frac{1}{2}C_{pd}\sum_{k=1}^{M} V_{GPDL\_m}^2(k)} \quad with \quad M = T/\Delta t \qquad (12)$$

with $V_{GPDL\_m}(k)$ being the maximum voltage of the GPDLs, C_{pd} is the shunt capacitance at the GPDL, M the number of samples and Δt the sampling time. The GPDL characterized by the maximum energy corresponds to the PD location. This is because, the pulses of time reversed PD signal will add up in phase at the real PD location during the backward propagation.

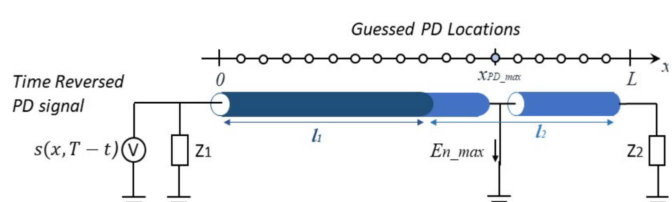


Fig. 5. Schematic representation of the line used for the TR simulations.

4. Results and Discussion

The method has been tested in a single-phase non-homogeneous line with the characteristics given in Table 1.

The line is formed of two sections of 11-kV Cross-Linked Polyethylene (XLPE) cables, with a length, respectively, of l_1 and l_2, as shown in Figure 5.

For the TLM simulation, the time-step, Δt, and space step, Δx, have been chosen as follows. PD signals are pulses with a frequency content extending to hundreds of MHz. The IEC 60270 standard gives indications about the wide and narrow-bandwidth detectors that should be used to perform PD measurements. For these detectors, the IEC-recommended value for the lower cutoff frequency is in the region of 50-100 kHz and, for the upper frequency, it is in the high frequency region of up to 100 MHz [2].

The 1D TLM model has to reverse in time the PD signals measured in this frequency range. Considering the highest frequency of interest f_{max}=100 MHz, a $\Delta t \leq 10^{-8}$ s must be chosen with the values of Δx_1 and Δx_2 obtained by relation (7). A value of $\Delta t = 10^{-9}$s has been chosen to have a space discretization Δx_1=0.1675m and Δx_2=0.2093m along the line sections, allowing to obtain a localization accuracy in the order of 20 cm.

The recording period, T, to measure the PD signal during the DT simulation, has to be defined in order to measure at the OP the direct signal, coming from the PD source, and some reflections from the other cable end. The amount of the reflected signal from the cable end is defined by the reflection coefficient, Γ:

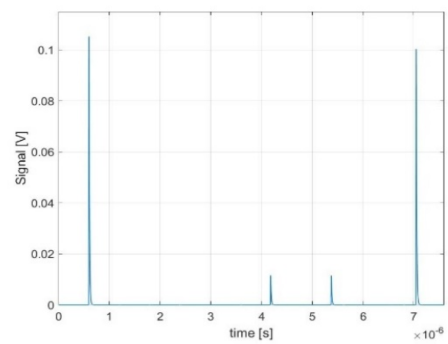
$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \qquad (13)$$

with Z_L being the impedance at the cable end. In this case, the impedances at the line ends, Z_1, Z_2 are much greater than the characteristic impedance, as shown in Table 1, corresponding to a reflection coefficient $\Gamma \cong 1$.

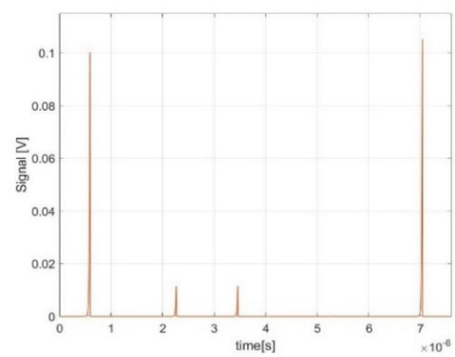
To prove the effectiveness of the method to locate PD, a DT simulation has been performed considering a PD source located at x_{PD}=100m from the left end of the cable, in the first section of the line, l_1, and the PD-generated signals have been evaluated at the OP located at the left end of the cable, as Figure 3 shows. Then, the TR simulations have been performed with a GPDL every 2m along the line.

Figure 6 shows the calculated PD signal and the time reversed signal. The Figure shows the direct signal, a reflection from the right end of the line and two smaller reflections due to the discontinuity of the line.

Figure 7 shows the normalized energy in the GPDLs during TR simulations. As Figure 7 shows, the maximum energy is obtained at GPDL = x_{PD}=100 m. Then, TR simulations have been performed around the maximum location, identified in the



(a)



(b)

Fig. 6. PD signal calculated at the OP during the DT simulation with a PD source 100 m from the left end of the line (a) and the TR signal (b).

TABLE I
CHARACTERISTIC PARAMETERS OF THE LINE AND OF THE SIMULATIONS

Parameter	Value	Unit
R	$0.206 \cdot 10^{-3}$	Ω/m
L	$91.34 \cdot 10^{-9}$	H/m
C_1, C_2	$0.39 \cdot 10^{-9}$, $0.25 \cdot 10^{-9}$	F/m
G	$1 \cdot 10^{-13}$	S/m
u_1, u_2	$1.675 \cdot 10^{8}$, $2.092 \cdot 10^{8}$	m/s
Z_{01}, Z_{02}	15.3038, 19.114	Ω
Z_1, Z_2	$100 \cdot 10^{+3}$	Ω
l_1, l_2	400, 300	m
Δt	$1 \cdot 10^{-9}$	s
Δx_1, Δx_2	0.1675, 0.2093	m

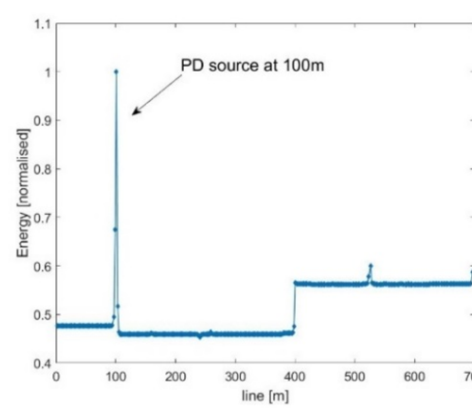


Fig. 7. Normalized energy in several GPDLs in the inhomogeneous line when the PD source is 100 m from the left end of the line.

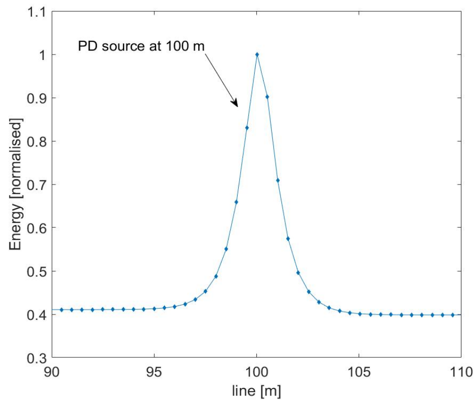


Fig. 8 Normalized energy in several GPDLs, when the PD source is 100 m from the left end of the line, with a 0.5m distance from each other.

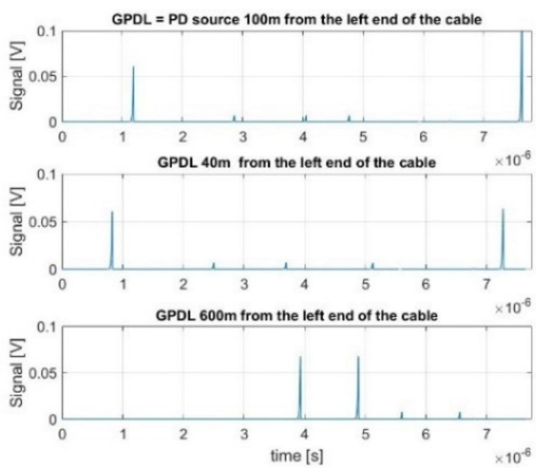


Fig. 9. Voltage at three GPDLs during the TR simulations when PD source is 100 m from the left end of the line.

previous TR simulations, reducing the distance among the GPDLs to 0.5 m.

Figure 8 shows an expanded view in the localization identifying the source with an accuracy of 0.5 m.

Figure 9 show the voltages in three GPDLs. As the figure shows, the voltage signal is maximum when the GPDL is coincident with the PD location, as expected.

Finally, Figures 10 and 11 show the normalized energy evaluated in GPDLs when the PD is, respectively, 350m and 650m from the left end of the line. In the second case, shown in Figure 11, the PD is in the second section of the line*, l_2*.

The results prove that the proposed EMTR-based method is able to locate source of PDs in inhomogeneous lines. The effectiveness and accuracy of the proposed method in real power lines is strongly affected by the distortion of PD signals during their propagation along the cables, caused above all by the skin effect, and by the presence of electromagnetic interference (EMI) on the line. A numerical validation of the effectiveness of the method considering the PD signal distortion has been developed in [16], reproducing in the DT simulation the effect of PD distortion in extruded MV power cables. The experimental validation of the method is under development in real MV networks and its accuracy in the PDs localization in the harsh electromagnetic environment of real lines is under analysis. Future works include, also, the validation of the method in more complex power lines and the evaluation of the maximum length of the line where it can be expected the method keeps efficient results. With respect to the classical reflectometry or traveling wave-based techniques, the proposed method has the need to perform several TR simulations to localize the PD source and the need to know the RLCG characteristic of each line sections. Even given the significant number of TR simulations, the method locates PDs with a computational time of a few minutes also for line some kms long. Moreover, the EMTR-based method presents important advantages against the traveling wave-based techniques that are: the use of only one observation point, avoiding the complexity of synchronisation in the reflectometry multi-end measurements methods and the robustness against the presence of noise avoiding the considerable amount of computational effort of the Wavelets transform (WT) techniques, used in the traveling wave-based methods to denoise the measured PD signals. A detailed analysis of the experimental validation of the presented method will be published later.

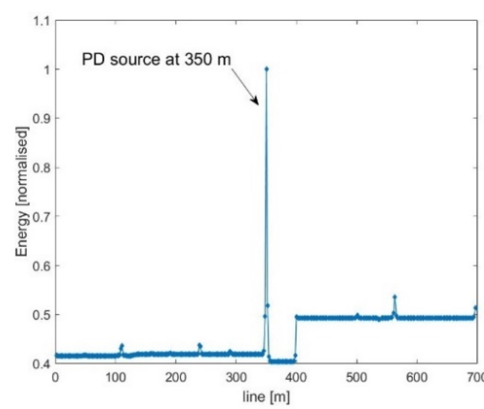


Fig. 10. . Normalized energy in several GPDL when PD source is 350 m from the left end of the line.

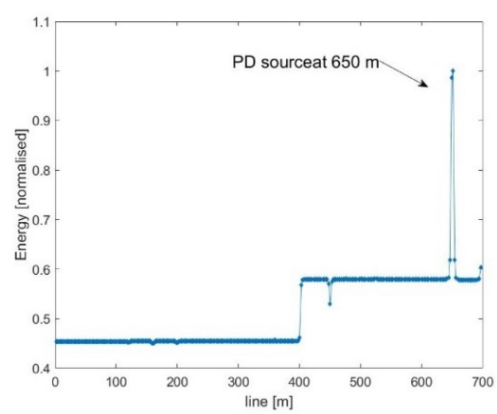


Fig. 11. Normalized energy in several GPDL when PD source is 650 m from the left end of the line.

5. Conclusion

A new method to locate partial discharges (PDs) in power transmission and distribution networks is presented. The basic steps of the location procedure based on the electromagnetic time reversal (EMTR) theory are described. The Transmission Line Matrix (TLM) method is used to solve the propagation equations and the 1D TLM modelling procedure to describe the propagation in the time reversal domain of the PD signals in non-homogeneous power networks is detailed. Then, the effectiveness of the method to locate PD in non-homogeneous lines is shown and demonstrated in simulation. Finally, a discussion about future works is detailed in the final section.

6. Acknowledgements

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under the Marie Skłodowska-Curie grant agreement No 838681.

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