Time Reversal for Partial Discharge Localization on Power Lines with Different Termination Impedances

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***Abstract*—This paper describes a new method for the on-line location of partial discharges (PDs) in power transmission and distribution networks based on Electromagnetic Time Reversal (EMTR) theory and on the Transmission Line Matrix (TLM) method in order to describe the time reversed propagation. In particular, the paper shows the effectiveness of the method in localizing the PD source when the impedances at the terminations of the line are unknown and describes the procedure to be followed in this case. The analysis is performed in simulation, and a model of the PD signal propagation that is able to reproduce the distortion phenomenon that affect the PD signal propagation on power lines and thus the accuracy of the on-line PD location methods is also described.**

Keywords*—*Partial discharges, cable system, electromagnetic time reversal, TLM, high voltage power grid reliability.

I. Introduction

High voltage power grids are subject to a wide range of electromagnetic disturbances, both natural, such as lightning strikes, geomagnetic effects, and man-made disturbances, such as harmonics, partial discharges (PD), overvoltages, intentional electromagnetic interference (IEMI), that affect the power quality and the reliability of the power networks. This aggressive on-line environment causes the acceleration of the aging and deterioration of the power cables insulation[1]. The insulation failure of a power cable has severe social and economic consequences since the statistics indicate that more than 85% of equipment failures are related to insulation damage[2]. The deterioration of cable insulation is often caused by partial discharge (PD) events, that are localized electrical discharges, partially bridging the insulation between conductors [3] and starting in defects of the insulator. Thus, the adoption of methods for the on-line localization of PD, widely considered as one of the best early warning indicators of insulation degradation, is regarded as one of the most suitable methods to perform the network integrity assessment useful to improve its reliability and to guarantee electricity supply security[1]. The authors have designed a new on-line PD location method based on the electromagnetic time reversal theory and on the use of the Transmission Line Matrix (TLM) numerical method [4]. The proposed method overcomes the shortcomings of the currently adopted reflectometry or traveling wave-based PD location methods [5]-[7]. These methods, based on the principle that PDs produce electromagnetic waves travelling in either direction towards the cable ends, perform simultaneous multi-end measurements of the PD signals at different points of the line and evaluate the PD source from the times of arrival of the measured signals (time of arrival, ToA, methods). Their practical implementation is difficult due to the need for synchronised measurements and their accuracy is strongly influenced by the distortion phenomenon that affect PD signals during their propagation on power cables and by the presence of EMI on power networks. The use of wavelet techniques [6][7] is usually adopted to solve these problems but they require a considerable amount of computational effort. The EMTR-based PD location technique proposed by the authors in [4] and experimentally validated in [8] has shown a significantly improved performance with respect to the traditional location techniques, presenting the following advantages: the use of a single observation point, applicability to inhomogeneous networks [9][10] and robustness against the presence of EMI[8]. The new method is under development and its effectiveness in more complex networks is under analysis. The basic steps of the method are: 1. Measuring of the electromagnetic signal generated by the PD at one observation point (OP) along the line; 2. Simulating using a lossless 1D TLM model the time-reversed injection of the measured PD signal for different guessed PD locations (GPDLs); 3. Localizing the PD source by identifying the GPDL characterized by the maximum energy concentration.

In this paper the method is briefly described and its effectiveness in localising PD sources in power networks when the impedances at the line terminations are unknown and the procedure to be followed in this case is described. In particular, in Section II a model of the power line, that is able to reproduce the distortion of the PD signals, is described. This model is used to perform the direct time (DT) simulation that takes place in step 1, related to the PD signal measurement on a real system, and it is useful to design, in simulation, new on-line PD location methods. Section III gives a brief description of the EMTR-based method and, finally, in Section IV the analysis of the simulation results is presented.

II. Model of the System under Study

To perform the DT simulation, a model of the system under study is developed that is able to reproduce the PD signal distortion that is the most significant phenomenon in the real system that can affect the accuracy and effectiveness of the on-line PD location methods. To this aim, the simple power line shown in Fig. 1 is considered. It is formed by a 11kV single-phase coaxial cable[11], 1km long, with aluminum conductor and a Cross-Linked Polyethylene (XLPE) insulator. Table I shows the cable characteristics.

The ends of the line are connected to the impedances, Z_1 and Z_2. The PD event occurs at a location, x_{PD}, of the line and

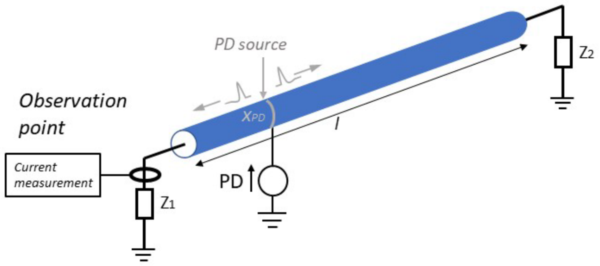

Fig. 1. Schematic of the power transmission line under study.

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TABLE 1. CABLE CHARACTERISITCS

Parameter	Value
Cross section of inner conductor, S	150 mm^2
Inner conductor conductivity, σ	$3.7 \cdot 10^7$ S/m
Relative permittivity of the insulator, ε_r	2.2
Series inductance per unit length, L	91.34 nH/m
Shunt capacitance per unit length, C	0.39 nF/m

the generated signal, propagating in both directions along the line, is recorded at the observation point (OP) on its left end.

The propagation of PD signals in power lines is described by the Telegrapher's equations [12][14]:

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

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

where R, L, G and C are respectively the per unit length series resistance and inductance and the shunt conductance and capacitance of the line.

PD pulses are very short, (typically 1-5ns wide), with a significant frequency component of up to 1 GHz at its source. For the purpose of illustration, the PD pulse can be represented with a double exponential equation [4]:

$$s_{PD}(t) = A_0\left(-e^{-\frac{t}{\tau_1}} + e^{-\frac{t}{\tau_2}}\right) \qquad (2)$$

with A_0=0.1, τ_1 = 2 ns, τ_2=10 ns. During its propagation along the line, the PD pulses are distorted above all by the skin effect, that is a nonuniform distribution of the current density inside the conductor. The skin effect produces an increase of the conductor resistance and a reduction of the cable inductance due to the finite conductivity of the conductor. These impedance variations affect the propagation speed and the propagation constant of the line causing a greater attenuation and a quicker propagation of the higher frequency components of the PD pulse than the lower frequency components, so reducing the signal frequency bandwidth[9][12]. This power line behaviour, as a low pass filter, can be modelled using the ladder network shown in Fig. 2(a) [9][13]for a section Δx of the cable. The cross section of the inner conductor of the coaxial cable is divided in 4 rings, representing the nonuniform distribution of the current density, modelled by a ladder network of resistances, R_i and inductances, L_j, (i=1, 2, 3, 4; j=1, 2, 3). The skin effect in the outer conductor of the coaxial cable is here neglected. In Fig. 2(a), C is the shunt capacitance of the line and L is the inductance component of the cable related to time-varying flux between the inner and outer conductor, that is frequency independent and equal to the per unit length inductance of the line[9]. A complete model of a power line with skin effect has been developed in [9] using the TLM method[14]. In the TLM model the line is discretized into a series of N nodes, of length Δx, as shown in Fig. 2(a). Each LC section is represented by a transmission line with propagation speed, u, characteristic impedance, Z_0, and transit time Δt given by:

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

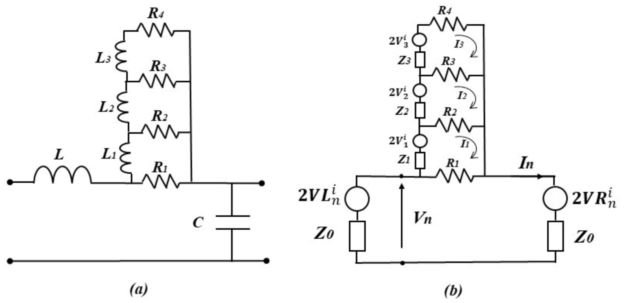

Fig. 2. Skin effect model of a cable section Δx (a) and the Thevenin equivalent circuit of the TLM model of the line at a node n.

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

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

Connecting the N nodes, the TLM equivalent model of the line is obtained. At each node, the wave pulses, $V_n(k)$, are scattered and propagate in the line, generating incident voltages, $VL^i_n(k)$, $VR^i_n(k)$, and reflected voltages respectively on the left and on the right side of the node n. The voltage, $V_n(k)$, and the current, $I_n(k)$, at time k, in each node are evaluated replacing the lines to the right and to the left of the node by their Thevenin equivalent circuits, as shown in Fig. 2(b). In Fig. 2(b), the inductances of the ladder circuit are modelled using the TLM stub model of an inductor, characterized by the impedance, Z_j, with j=1,2,3[14].

Table II shows the electrical parameters of the cable model. A detailed description of the skin effect model, the procedure to evaluate the model parameters and the TLM equations of the signal propagation are described in[9].

The TLM code has been developed in MATLAB.

Fig.3 shows the distortion of the PD signal, $s_{PD}(t)$, during its propagation along the line under study.

During the DT simulation the PD pulse is recorded at the observation point OP, shown in Fig.1, for a time window T, large enough to record the direct PD pulse and some of its reflections from the right end of the line. In a real power line, the PD pulses are measured using sensors, one of the most used is the HFCT (high frequency current transformer) sensor. Then, during the DT simulation the PD current wave $I(k)$, is recorded at the OP. The HFCTs currently used for the on-line PD location are characterized by passbands from a few hundred kHz to a few MHz[8][15]. Considering an

TABLE II. ELECTRICAL PARAMETERS OF THE TLM MODEL

Parameter	Value
Z_0	15.30 Ω
u	$1.6755 \cdot 10^8$ m/s
R_1, R_2 R_3, R_4	0.0288, 0.0060, 0.0012, 0.00025 Ω
L_1, L_2, L_3	1.134, 8.592, 6.510 nH

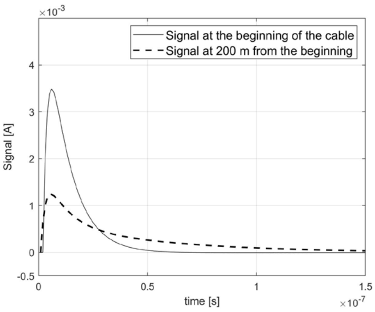

Fig. 3. Distortion of the PD signal during propagation along the line.

100kHz-20MHz HFCT, the sensor can be simulated using a passband FIR digital filter realized in MATLAB with the "designfilt" tool. In Fig.4 its response is reported together with its effect on the filtered PD signal, $s_{PD}(t)$. The HFCT measures the direct PD signal and some reflections from the other cable end. The amount of the reflected signal at the cable ends is given by the reflection coefficient, Γ:

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{6}$$

where Z_L is the impedance at the cable end, equal to Z_1 on the left end and to Z_2 at the right end.

III. EMTR-based PD Location Method

The EMTR-based method [4][8] is now briefly described. The method is based on the invariance under TR of the telegrapher's equations (1) for a non-dissipative medium. Equations (1) for a lossless line and under TR transformation, i.e. applying the substitution $t \rightarrow -t$. and changing the current sign[16], become:

$$\frac{\partial v(x,\ -t)}{\partial x} + L\frac{\partial(-i(x,-t))}{\partial(-t)} = 0 \tag{7.1}$$

$$\frac{\partial(-i(x,\ -t))}{\partial x} + C\frac{\partial(v(x,-t))}{\partial(-t)} = 0 \tag{7.2}$$

The TLM method is used to solve equations (7). The PD wave voltage $V_n(k)$, and current, $I_n(k)$, at time step k in a node n of the lossless 1D TLM model of the line (the node is the same as that one shown in Fig. 2(a) but without the skin effect ladder circuit) are given by[14]:

$$V_n(k) = \frac{\frac{2VL_n^i(k)}{Z_0} + \frac{2VR_n^i(k)}{Z_0}}{\frac{1}{Z_0} + \frac{1}{Z_0}} \tag{8.1}$$

$$I_n(k) = \frac{V_n(k) - 2VR_n^i(k)}{Z_0} \tag{8.2}$$

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

The PD signal, $s(x,t)$, recorded during DT simulation (or measured in a grid when the method is used in a real system), at the OP (Fig.1) for an observation period T, is time reversed:

$$s(x,\ t) \rightarrow s(x, T - t) \tag{9}$$

and it is back injected, from the same OP, into the lossless TLM model of the line. Then several TR simulations are performed. In each TR simulation several guessed partial discharge locations (GPDL)[4] are considered in the nodes of the line, that are characterised by a transversal impedance, Z_{PD}, [4] due to the effect of the PD inside the insulator. The energy stored in Z_{PD} of each GPDL node is evaluated as follows:

$$En = \frac{\frac{1}{2}C\sum_{k=1}^{M} V_{GPDL}^2(k)}{\frac{1}{2}C\sum_{k=1}^{M} V_{GPDL\_m}^2(k)} \quad with \quad M = T/\Delta t \tag{10}$$

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

IV. Simulation Results

The effectiveness of the method to locate PD sources is shown considering the line reported in Fig. 1, 1km long and realised with the coaxial cable of Table 1. In particular, different conditions of the line terminations are considered. As previous stated, the amount of the reflected PD signal at the cable ends is given by the reflection coefficient Γ. To localise the PD source an estimation of the line terminations' impedances should be necessary to develop the 1D TLM model of the line and perform the TR simulations but often, in a real application, this information is unknown. The authors in [8] have demonstrated that a good accuracy in the PD source localisation is obtained also in the absence of this information. Here the analysis of the possible reflection conditions at the cable ends is considered and analysed.

Performing the DT simulations, using the model of the line described in Section II, with a $\Delta t = 1\cdot10^{-8}$s, when the PD source is at 620m from the OP, the PD signals shown in Fig.6 are recorded in a time window T=18µs, long enough to acquire two signal reflections together with the direct pulse. The figure shows the recorded signals considering the four possible working conditions for the reflection behaviour at the line terminations. In particular, to simulate a positive reflection an impedance at the cable end equal to 10kΩ has been used (to reproduce the impedance offered by a power transformer to high frequency signals) and to obtain a negative reflection (to simulate the case where the line is not directly connected to a power transformer but to a load with an impedance lower than the Z_0 of the line) a value of the impedance at the cable end equal to 1Ω has been used. Analysing the characteristic of the recorded PD pulses, the direct one and the reflected ones, for each case shown fig. 6, it is possible to define the characteristic of the reflections at the cable ends. Hence it is possible to define the value of Γ_1 and Γ_2 to be used in the TR simulations, equal to ≅ 1 or ≅ -1 if, respectively, a positive or a negative reflection is observed at the cable end. Once the line terminations behaviours are defined, the recorded signals are time reversed, as shown in Fig. 6, and the TR simulations are performed to localise the

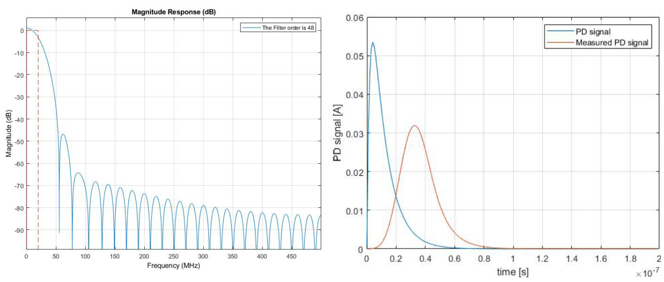

Fig. 4. Bandpass filter representing the HFCT sensor (on the left) and the filtered PD signal (on the right).

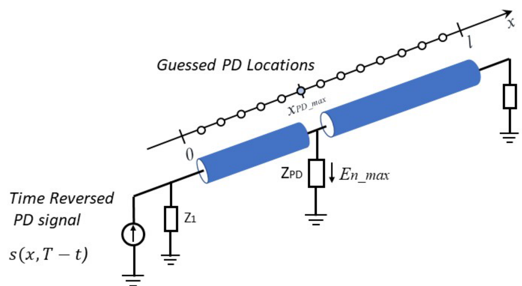

Fig. 5. Schematic representation of the line used for the TR simulations.

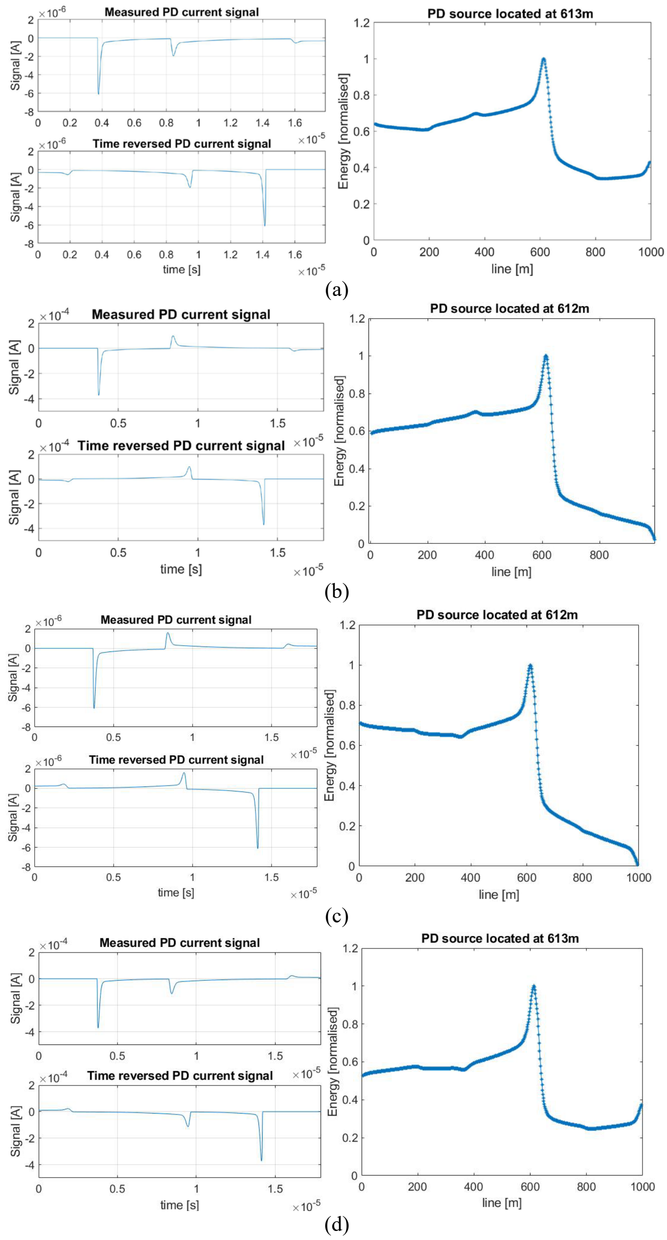

Fig. 6. Measured PD signals at the OP, time reversed signals and the energy evaluated at the GPDLs during the TR simulations when: $\Gamma_1 = \Gamma_2 \cong 1$ (a), $\Gamma_1 = \Gamma_2 \cong -1$ (b), $\Gamma_1 \cong 1$ and $\Gamma_2 \cong -1$ (c) and $\Gamma_1 \cong -1$ and $\Gamma_2 \cong 1$ (d).

PD source. The TR simulations, for each of the four cases, have been performed using a step of 1.6m between the GPDLs. Finally, in Fig. 7 the results when $\Gamma_1 = \Gamma_2 \cong -1$ with PD at 480m and $\Gamma_1 = \Gamma_2 \cong 1$ with PD at 804m are shown. As Figs. 6 and 7 show, the method is able to localise the PD source with a relative error ≤1% in the line under study. This error is caused above all by the distortion of the PD signal due

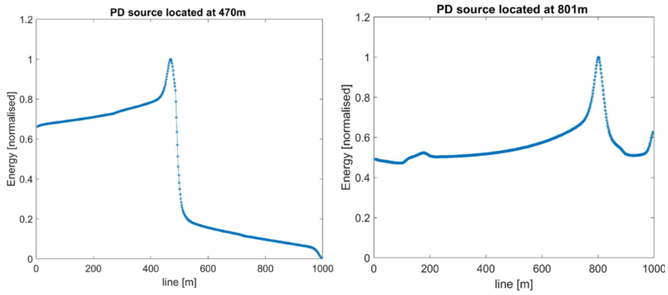

Fig. 7. Energy at the GPDLs when $\Gamma_1 = \Gamma_2 \cong -1$ with PD source at 480m (a) and $\Gamma_1 = \Gamma_2 \cong 1$ with PD source at 804m.

to the line skin effect and to the sensor, described in Section II. A computational time of about 3 minutes is necessary to localise the PD source.

V. CONCLUSIONS

The paper describes a new method to localize PD sources on high voltage power grids based on the EMTR theory and on the use of the TLM method to describe the time reversal propagation. The paper shows, in particular, the effectiveness of the method in localizing the PD source when the terminations of the line are unknown and how to apply the method when this condition, often, occurs in localizing PDs in a real power network. The results show also that the method is able to localize the PD source with a computational time of about 3 minutes and with an error less than 1%, in the line under study, also in the absence of a detailed estimation of the line terminations.

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