TIME REVERSAL TO LOCALISE MULTIPLE PARTIAL DISCHARGES IN POWER CABLES

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Abstract

The paper studies the suitability of the electromagnetic time reversal (EMTR) technique to localise multiple sources of partial discharges (PD) in power cables. In particular, the localisation of two PDs in a homogeneous power line is investigated both in the presence or absence of noise. The investigation, which is based on numerical simulations, shows that an EMTR-based PD localisation method is able to localise two PDs occurring simultaneously in a line using only a measurement at one observation point (OP), indiscriminately collecting the direct and reflected signals coming from the two PD sources. The EMTR procedure to localise multiple PD sources, using a Transmission Line Matrix model digital twin for the time reversal simulations, is described and the challenges that must be addressed to develop an EMTR-based device for the on-line location of multiple PDs are discussed.

1 Introduction

Partial Discharge (PD) diagnosis in power systems allows the monitoring of the insulation degradation and, if used in conjunction with planned maintenance, the avoidance of faults due to insulation damage. PDs are localised electrical discharges that partially bridge the insulation between conductors [1]**Error! Reference source not found.**. They can occur under normal working conditions in the insulation that has defects or voids produced during the manufacturing process or that has deteriorated by ageing or by thermal, mechanical or electrical over-stress during the operation. PDs produce, at the beginning, only a localised heating in the cable but after a period of activity, they can break the insulation between conductors, producing a fault and often causing a cable to fail prematurely (within 3 years of operation), resulting in the interruption of power supply and even blackouts. Therefore, PDs are regarded as one of the best early warning indicators of insulation degradation and the PD source location is the most suitable method for network integrity assessment and maintenance [2]**Error! Reference source not found.**.

Currently, the increasing use of underground cables in transmission and distribution networks, and submarine cables in the high voltage direct current (HVDC) lines for interconnection with the new offshore wind plants or between European countries is creating new challenges related to the power lines' maintenance. Commonly, indeed, these types of cables use, as insulation, polyethylene-based materials that are highly degradable. Thus, more sophisticated solutions for the monitoring and maintenance of these systems are required [2][3].

Conventionally, PD diagnosis is performed through the detection of the electromagnetic pulses generated by PD events, the localisation of the PD sources, and the quantification of the damage level. The detection of PDs is performed with inductive or capacitive sensors at some observation points (OPs) of the power lines, usually at the cable ends. A phase-resolved PD pattern (PRPD) is produced, showing the amplitude versus the phase of each discharge event synchronised with the grid AC voltage at 50 or 60 Hz. Then, the PD localisation is traditionally achieved using time-domain reflectometry (TDR) [1][4][5]. It is a traveling wave technique [6] based on the fact that a PD event generates electromagnetic waves that travel in either direction towards the line ends. The TDR-based methods localise the PD source by evaluating the time of arrival (ToA) at the OPs of the direct PD pulse, coming from the source, and its reflections from the cable ends. Two or more OPs are usually adopted in complex branched lines and long networks with several inhomogeneous sections in order to guarantee the PD source localisation when the signal distortion is high [2][4]. Often, techniques in the time and frequency domains are combined for localisation in the noisy environment of the power distribution and transmission networks where the PD signal is buried in a high level of noise [5]-[7].

When multiple PDs occur simultaneously in the same line, the direct PD signals coming from each PD source and the reflected pulses from the line ends are measured indiscriminately by the sensors at the OPs, complicating the localisation task. In these cases, it is normally necessary to separate the signals from each other and from the noise and then use the TDR method for each signal to localise each source [3][8][9]. The solutions proposed in the literature for the separation of the signals are commonly based on the use of the PRPD patterns to identify the presence of the multiple discharges, due to corona events, discharges in oil, surface or internal discharges, and classifying them in a time-frequency map [8][9]. But the development of PRPD patterns requires a synchronization signal from the grid that is not always available in the AC grids and never in the case of HVDC lines. In [3] a method is proposed using only a single-end measurement of the PD signals coming from multiple sources, together with noise, in which the separation is performed using complex data processing methods based on the spectral characteristics of the measured signals.

This paper explores the suitability of the Electromagnetic Time Reversal (EMTR) theory [10] to localise multiple sources of PDs. An EMTR-based PD location method, based on a Transmission Line Matrix model (TLM) digital twin for the time reversal simulation, designed by the authors [11]-[13], is adopted for this purpose. The numerical investigations show that the EMTR theory is a promising way to overcome the described complexity in localising multiple PD sources.

The paper is organised as follows. In Section 2, the EMTR-based method for PD localisation is introduced. Section 3 describes the system under test and the procedure for the localisation of two PD sources occurring simultaneously in the line using the EMTR method. Section 4 presents the simulation results with special attention to the effect of the noise. Finally, conclusions and open challenges are presented in Section 5.

2. Time reversal for partial discharge location

The EMTR method for the on-line location of PDs is based on the invariance under time reversal of the telegrapher's equations for a non-dissipative medium [9] that describe the propagation of the PD signals along the line.

It is important to note that even though the telegrapher's equations are not rigorously time-reversal invariant for a lossy line, it has been shown that a lossy back-propagation model results in accurate fault locations [14].

The EMTR method, thanks to the time reversibility of telegrapher's equations and the spatial correlation property of the time-reversal theory, is able to refocus the time reversed back-propagated PD pulses into the original PD location. In more detail, when the measured PD pulses are time reversed and back injected into the original system, they are refocused back to the location of the PD source [10].

The basic steps of the EMTR PD location method, detailed in [11], are the following:

1. Measurement of the PD signal at one observation point (OP) along the line.
2. Time reversal of the measured PD signal.
3. Definition of the guessed PD locations (GPDLs) and their shunt impedance in nodes of a 1D Transmission Line Matrix (TLM) [15] model of the network.
4. Simulation of the back-injection of the time-reversed PD signal for different GPDLs using the TLM model.
5. Location of the PD source by identifying the GPDL characterized by the highest energy concentration.

The normalised energy, *En*, stored in the GPDL node, evaluated for each time reversal simulation, is given by:

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

where M is the number of samples and Δt the sampling time, C_{pd} is the shunt capacitance at the GPDL, due to the presence of the PD event which changes the characteristic capacitance at that point. A detailed description on how C_{pd} is defined is given in [11]. Finally, $V_{GPDL\_m}(k)$ is the maximum voltage at the GPDLs at the time step k, that, from the TLM numerical method, is given by [15]:

$$V_{GPDL\_m}(k) = \frac{\frac{2VL_{GPDL\_m}^{i}(k)}{Z_0} + \frac{2VR_{GPDL\_m}^{i}(k)}{Z_0}}{\frac{1}{Z_0} + \frac{1}{Z_0}} \qquad (2)$$

with $VL^{i}_{GPDL\_m}(k)$, $VR^{i}_{GPDL\_m}(k)$ are the incident voltages, respectively, on the left and on the right side of the GPDL node with the maximum voltage.

The EMTR PD location method has been experimentally validated in a Medium Voltage (MV) power line in service [12]. It has been shown that it is able to localise PD sources using only one observation point (OP), avoiding therefore the use of complex synchronization procedures necessary for the classical TDR methods that use more than one OP in power networks with inhomogeneous sections. Moreover, it has also been verified that the method is able to localise PDs on power lines in the presence of noise [12] [13], avoiding also the use of the heavy computational wavelet techniques usually adopted for the de-noising of the PD signals by the classical TDR methods.

3 Multiple partial discharge location

The ability of the EMTR-based method to localise multiple PD events occurring simultaneously in the same line is investigated in this section.

A simple system is used for the analysis as shown in Fig. 1. It is formed by a 1-km long line with an observation point (OP) at the left end of the line.

The line is characterised by the parameters given in Table 1, where L' and C' are, respectively, the longitudinal inductance and transversal capacitance of the line per unit length, Z_0 is the characteristic impedance of the line, and l is the line length. In the case under study, the line is connected at both ends to two load impedances, Z_L, assumed to be much lower than the characteristic impedance of the line, Z_0. So, the voltage reflection coefficient, Γ, at the line ends is close to -1.

For the purpose of illustration, the study is here fully developed in simulation. Therefore, point 1 of the EMTR procedure described in Section 2, i.e. the measurement of the PD signal on a real power line, is substituted by a direct time

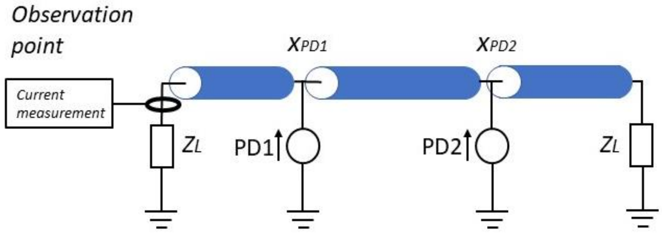

Fig. 1 Schematic representation of the line with two PD events and one observation point at the left cable end.

Table 1 Parameters of the line under study

Parameter	Value	Unit
L'	91.24	nH/m
C'	0.39	nF/m
Z_0	15.30	Ω
l	1000	m
u	1.675 $\cdot 10^{-8}$	m/s

(DT) simulation describing the PD event in the cable and the propagation of the PD signal along the line.

For the DT simulation a lossy model of the line is used, in order to reproduce the PD signal distortion during propagation. The lossy TLM model described in [16] is adopted for the DT simulation. This model is able to reproduce the skin effect of the power cables so reproducing the signal distortion during propagation.

For the first analysis, two PD events are considered. They are simulated at two points of the line, x_{PD1} and x_{PD2}, injecting, as shown in Fig. 1, two double exponential pulses, PD1 and PD2, whose waveform is given by

$$s(t) = A\left(-e^{-\frac{t}{\tau_1}} + e^{-\frac{t}{\tau_2}}\right) \qquad (3)$$

with amplitude, *A*, respectively equal to 0.08 V and 0.1 V and with $\tau_1 = 2$ ns and $\tau_2 = 9$ ns.

When the two PD events occur simultaneously, the current sensor at the OP measures indiscriminately the direct signals coming from the two sources and the reflected signals from the line ends, as shown in Fig. 2.

The EMTR-based method is used as described in Section 2. The method is adopted directly using the recorded PD signals shown in Fig. 2 without the separation of the two signals coming from the two different PD sources.

Thus, the recorded signal is time reversed and back-injected into a 1D lossless TLM model of the line and several time reversal simulations are performed evaluating with (1) the normalised energy *En* stored at the GPDLs.

A power line in the absence of noise is firstly analysed. Then, white noise is added to the signal and the effectiveness of the method in localising two PD sources is investigated also when noise is superimposed on the recorded PD signals.

4 Simulation results

The numerical codes of the two TLM models for the simulations of the propagation of the PD signals in the direct time domain and the time reversal domain have been developed in MATLAB.

Considering two PD events occurring simultaneously along the line at 201 and 620 m from the left end of the cable in absence of noise in the line, the signals PD recorded at the OP, in a time window of 25 µs, are shown in Fig. 2.

Fig 3 shows the time reversed signal originated from the two partial discharges.

The time-reversed signal is injected into the TLM model of the line for the time reversal simulations.

The GPDLs have been defined along the line with steps of 3 m and the stored normalised energies, *En*, have been evaluated and normalised with respect to the maximum Energy.

Fig. 4 presents the normalised energy distribution of the time-reversed, back-injected signal along the line. The energy distribution shows a concentration at the two PD locations, at 201 m and 620 m, localising the two PD sources.

The same analysis was repeated in the presence of noise on the power line.

Fig. 5 shows the recorded PD signal at the OP produced by two PD sources, located respectively at 302 and 620 m from the left end of the line, and when white noise with an SNR of -2 dB is present.

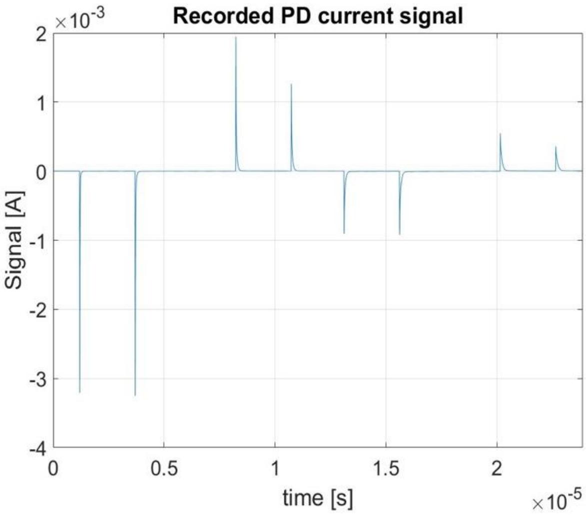

Fig. 2 PD signals recorded at the OP when two PD events occur simultaneously at 201 m and 620 m from left end of the line.

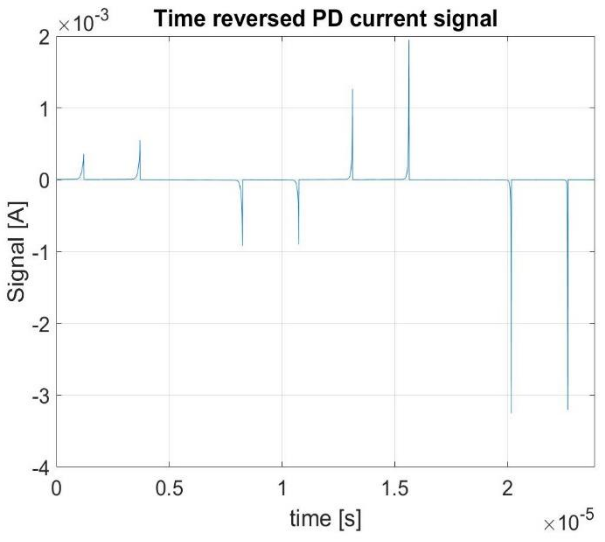

Fig. 3 Time reversed PD signals related to the case with two PD sources at 201 m and 620 m from the left end of the line.

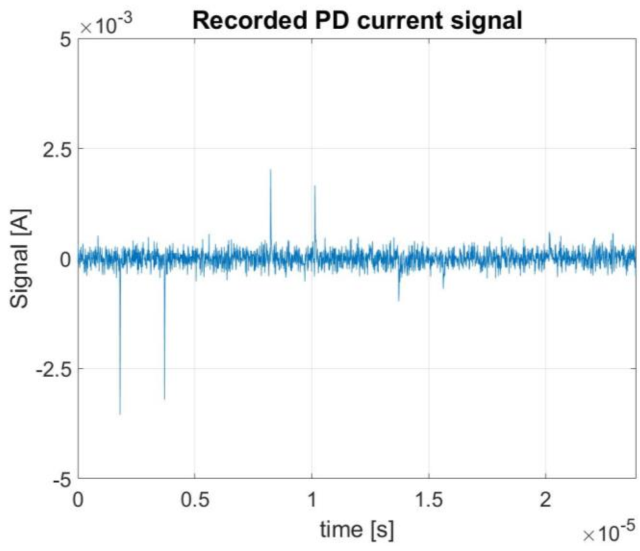

Fig. 5 PD signals coming from two PDs located at 302 m and 620 m from the OP in the presence of noise, SNR = - 2 dB.

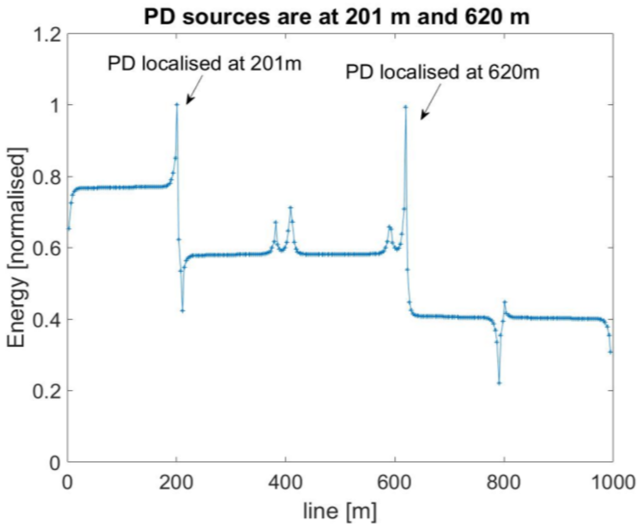

Fig. 4: Localisation of two PDs along the 1-km long line.

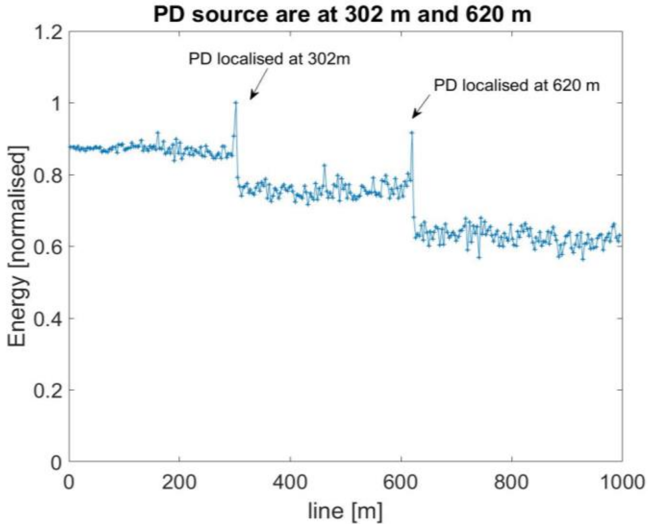

Fig. 6 Localisation of the two PDs at 302 m and 620 m from the OP in the presence of noise, SNR = - 2 dB.

The resulting normalised energy distribution is shown in Fig. 6, with its two distinctive peaks corresponding to the positions of the two PD sources.

The same result can be seen in the case shown in figures 7 and 8.

The top panel of Fig. 7 shows the recorded PD signals when two PDs occur simultaneously at, respectively, 302 m and 650 m from the left end of the line in the presence of white noise with an SNR equal to - 4 dB. The time reversed PD signal is shown in the bottom panel of the figure.

Fig. 8. shows the resulting normalised energy distribution with the two identified PD sources.

The simulations have been performed using an Intel® Core™ i7-8550U CPU at 1.80 GHz, 8 GB RAM and 237 GB disk.

The computational effort for the localisation of the PD sources is modest, being the computational time equal to 1 minute and 50 sec, using steps of 3 m between each GPDL in the 1 km long power line.

Therefore, also when more than one PD source is present in the same line section, the measured, time reversed and back-PD signals injected into the original system are refocused to their sources. The EMTR theory seems to be a promising solution to address this challenge in a simple and elegant way.

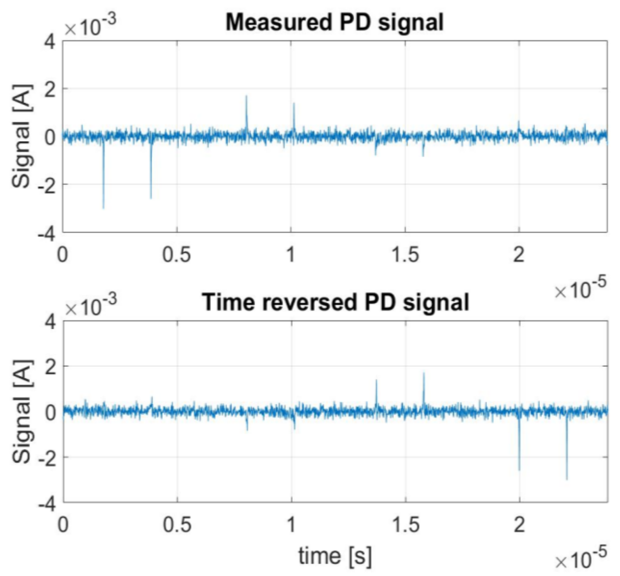

Fig. 7 PD signals coming from two PD sources located at 302 m and 650 m from the OP in the presence of noise, SNR = - 4 dB.

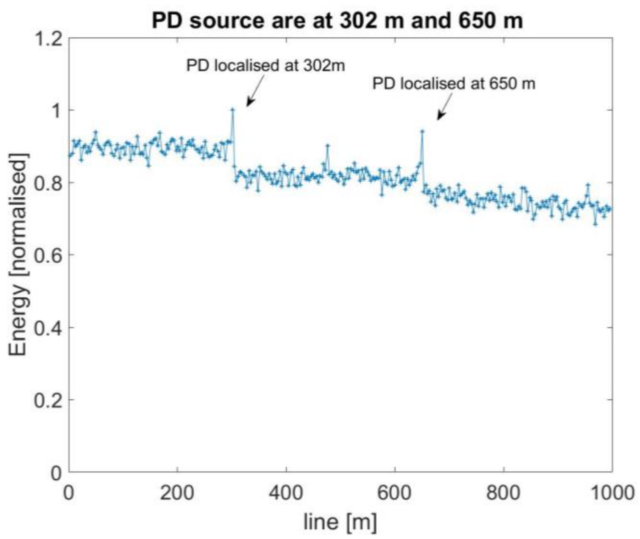

Fig. 8 Localisation of the two PDs at 302 m and 650 m from the OP in a line with the presence of a SNR = - 4 dB noise.

5 Conclusion and future work

The paper shows that an EMTR-based technique can localise two PDs that occur simultaneously in the same section of a power cable. The method was able to localise two PDs directly using the measured PD pulses coming from both sources and their reflections from the cable ends, detected at one OP, without the need to identify and separate the PD signals coming from each PD source. Moreover, the method is effective also when the recorded PD signals coming from the two sources are buried in noise.

The necessary computational time for a 1-km long line is about 1 minute and 50 seconds. The presented numerical results show that the EMTR theory is promising for the localisation of multiple sources, overcoming the complexity of the currently used location methods.

Future works on this topic include the analysis of the EMTR-based method's effectiveness in more complex system configurations with increasing numbers of PDs and different types of noise, determining how these affect the performance of the technique. All the above will need to be achieved whilst maintaining a high computational efficiency.

6 References

[1] EN 60270 - High-voltage test techniques - Partial discharge measurements (IEC 60270:2000) – 2001.

[2] F. Auzanneau: "Wire Troubleshooting and diagnosis: Review and perspectives", *Progress in Electromagnetics Research B*, Vol. 49, 2013. Pgs. 253-279.

[3] G. Robles, M. Shafiq, J. M. Martínez-Tarifa: "Multiple Partial Discharge Source Localization in Power Cables Through Power Spectral Separation and Time-Domain Reflectometry", IEEE Trans. on Instr. and Meas., Vol. 68, No. 12, Dec. 2019.

[4] F. P. Mohamed, W. H. Siew, J. J. Soraghan, et al: "Partial Discharge Location in Power Cables using a Double Ended Method Based on Time Triggering with GPS", IEEE Trans. on Dielectrics and Electrical Insulation, Vol. 20, No. 6; Dec. 2013.

[5] H. Min Lee, G. Seok Lee, G.-Y. Kwon, et al: "Industrial Applications of Cable Diagnostics and Monitoring Cables via Time–Frequency Domain Reflectometry", IEEE Sensors Journal, Vol. 21, No. 2, Jan. 15, 2021.

[6] M. S. Mashikian, R. Bansal, R. B. Northrop: "Location and Characterization of Partial Discharge sites in Shielded Power cables" - IEEE Trans. on Pow. Del., Vol. 5, No.2, April 1990.

[7] J. Zhon, X. Bi, Q. Shu, et al.: "Partial Discharge Signal Denoising Based on Singular Value Decomposition and Empirical Wavelet Transform", IEEE Trans. on Instrum. and Measur., Vol. 69, No. 11, Nov. 2020.

[8] J. Singsathien, T. Suwanasri, C. Suwanasri et al.: "Partial discharge detection and localization of defected power cable using HFCT and UHF sensors," Proc. 14th Int. Conf. on Electrical Eng./Electr., Computer, Telecommunications and Information Technology, Phuket, Thailand, 27-30 June 2017.

[9] M. Wu, H. Cao, J. Cao et al.: "An overview of state-of-the-art partial discharge analysis techniques for condition monitoring," IEEE Elect. Insul. Mag., vol. 31, no. 6, pp. 22–35, Nov./Dec. 2015.

[10] F. Rachidi, M. Rubinstein, M. Paolone: Electromagnetic Time Reversal, Application to Electromagnetic Compatibility and Power System - John Wiley & Sons Ltd, 2017.

[11] A. Ragusa, H. Sasse, A. Duffy, F. Rachidi, M. Rubinstein: "Electromagnetic Time Reversal Method to Locate Partial

Discharges in Power Networks Using 1D TLM Modelling", IEEE L-EMCPA, Vol. 3, Issue 1, March 2021.

[12] A. Ragusa, H. Sasse, A. Duffy et al.: "Application to Real Power Networks of a Method to Locate Partial Discharges Based on Electromagnetic Time Reversal", IEEE Trans. on Power Delivery, Vol. 37, issue 4, August 2022.

[13] A. Ragusa, H. Sasse, A. Duffy: "Practical Evaluation of Electromagnetic Time Reversal to Locate Partial Discharges on Power Networks in the Presence of Noise", Proc. 2022 IEEE Int. Sym. on EMC & Signal/Power Integrity, 01-05 Aug.2022, Spokane, WA, USA.

[14] Razzaghi, G. Lugrin, F. Rachidi et al.: "Assessment of the influence of losses on the performance of the electromagnetic time reversal fault location method", IEEE Trans. on Power Delivery, Vol. 32, No. 5, Oct. 2017

[15] C. Christopoulos, The transmission-line modeling method – TLM, Institute of Electrical and Electronics Engineers, 1995.

[16] A. Ragusa, H. Sasse, A. Duffy: "On-Line Partial Discharge Localization in Power Cables Based on Electromagnetic Time Reversal Theory - Numerical Validation", IEEE Trans. on Power Delivery, Vol. 37, issue 4, August 2022.