The Effect of the Ring Mains Units for On-line Partial Discharge Location with Time Reversal in Medium Voltage Networks

A. Ragusa¹, Member, IEEE, P. A. A. F. Wouters², H. Sasse¹ and A. Duffy¹, Fellow, IEEE

¹ School of Engineering and Sustainable Development, De Montfort University, Leicester LE1 9BH, UK.
² Department of Electrical Engineering, Eindhoven University of Technology, Eindhoven 5600 MB, The Netherlands

Corresponding author: A. Ragusa (e-mail: antonella.ragusa@dmu.ac.uk).

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ABSTRACT The performance of a new on-line partial discharge (PD) location method based on the Electromagnetic Time Reversal (EMTR) theory and the Transmission Line Matrix (TLM) method are investigated for characterization of Medium-Voltage (MV) networks. The distortion of the PD signal during its propagation along a cable connection including network components modelled based on experimental data is reproduced in simulation and the effectiveness of the EMTR-based method to localize the PD source is analyzed. In particular, the effects of the ring main units (RMUs), that behave as a complex impedance, the variation with frequency of the MV cable impedance and the reflection patterns, due to impedance mismatches, are considered and investigated. Simulation results are given showing the performance of the EMTR method in two different networks configurations: the former one with a RMU at the end of a MV cable and the latter one with a second MV cable connected to the RMU of the first configuration having a distribution transformer at its far end. The results show that the EMTR method is able, with only a single observation point, to localize PDs also in the presence of RMU with a relative error, with respect to the line length, of approximately 1%.

INDEX TERMS Partial Discharge, On-line partial discharge location methods, Electromagnetic Time Reversal, Medium Voltage Networks, PD signal distortion.

I. INTRODUCTION

Partial discharge (PD) events, that are localized electrical discharges starting in discontinuities or defects of the insulation system [1], are often the cause of the power cables insulation degradation in power networks [2]-[3]. The failure of power cables’ insulation in power networks leads to severe social and economic consequences producing effects ranging from faults to blackouts and supply interruption. Because statistic indicates that more than 85% of equipment faults are linked to insulation failure[4], PD is widely considered as one of the best ‘early warning’ indicators of cable failure [2] and, the adoption of on-line PD location is regarded as the most suitable method to monitor the network integrity and improve its resilience and reliability [2]. The on-line PD location methods is, indeed, a desired feature in the protection schemes of the modern power networks to prevent faults and guarantee the electricity security [5].

Currently, the on-line PD location is performed mostly using methods based on reflectometry or traveling wave techniques [6]-[11]. These techniques work on the fact that a PD event produces electromagnetic waves that travel towards the cable ends. Most of the used methods are based on multi-end measurements [6]-[7], simultaneously in two or more observation points (Ops) of the line, of the direct PD wave, coming directly from the PD source, and the reflected waves from the cable ends. The PD source is located evaluating the times of arrival of the measured signals (time of arrival, (ToA), methods).

But the need for synchronization makes their practical implementation more costly as communication provisions between the detection ends are required. Furthermore, the accuracy of the reflectometry methods is affected by the distortion of PD signal during its propagation along the line and by the presence of electromagnetic interference (EMI) on power networks [12]. Signal distortions are caused by the impedance mismatches and the variation with the frequency
of the impedances of cables and components [13]. Wavelet techniques (WTs) [14]-[15], that are powerful signal processing tools that can be implemented in both time and frequency domains, are often used to solve some of the shortcomings of the classical reflectometry methods, but WT algorithms require a huge amount of computational effort.

A new method for the on-line PD location has been proposed [16]-[19] based on the use of the EMTR (Electromagnetic Time Reversal) theory and the Transmission Line Matrix (TLM) method to describe the EMTR propagation of the PD signals. EMTR theory [20] has been adopted, recently, for the localization of electromagnetic disturbance sources on power systems [21]-[22], showing improved performances with respect to the traditional location techniques, due to the fact that it is possible to apply them in inhomogeneous and complex networks, they need only one observation point to localize the source and are robust against the presence of noise.

In [16] the basic design of the new EMTR-based PD location method has been proposed and its effectiveness to locate PDs using only one observation point has been theoretically demonstrated. In [17] its experimental validation is given, showing its effectiveness to locate PDs in real Medium Voltage (MV) homogeneous power cables, and its robustness against the presence of noise has been also analyzed and proved. The EMTR-based PD location method has also been shown to allow a PD location with good accuracy without excessive constraints on the input parameters, requiring only the knowledge of the signal velocity and the cable lengths. Moreover, in [18]-[19] the effectiveness of the method has been verified in simulation also when the PD signal is distorted due to the presence of inhomogeneous line impedance mismatches caused by the presence of inhomogeneous cable sections.

This paper investigates the effectiveness of EMTR when the waveform is distorted from PD signal attenuation and dispersion during propagation along a transmission line. Power cables on MV grids terminate at ring main units (RMUs) and further distortion occurs, caused by the impedance mismatches due to their presence. The distribution transformer at the RMU together with the cable connecting the transformer to the busbar behaves as a complex impedance. This is a cause of distortion of the PD signal and, consequently, the signal transfer to the measurement sensor is imprecisely known. In addition, other outgoing MV cables may affect the reflection patterns further distorting the PD signal [23]-[24]. In this work the effect of these distortions on the performance of the EMTR PD location method are analysed in two different line configurations. The used models have been developed using experimental measurements [23]-[24] in order to simulate a PD signal distortion close to the real one and to test the effectiveness of the EMTR method in working conditions close to the real behaviour.

The paper is organised as follows. In Section II, the EMTR-based method is briefly introduced. Section III the distortion of the PD signal due to the grid components, complex impedance of cables and of RMUs, is described and the adopted models to reproduce it are detailed. In Section IV the performance of the EMTR method is discussed in the two considered line configurations.

II. TIME REVERSAL METHOD FOR PD LOCALIZATION

The PD location method based on EMTR theory is based on the invariance under time reversal of the Telegrapher’s Equations for non-dissipative lines [20]. For non-dissipative lines, the telegrapher’s equations are given by:

\[
\frac{\partial v(x,t)}{\partial x} + L \frac{\partial i(x,t)}{\partial t} = 0 \tag{1.a}
\]
\[
\frac{\partial i(x,t)}{\partial x} + C \frac{\partial v(x,t)}{\partial t} = 0 \tag{1.b}
\]

where \(L\) and \(C\) are the per unit length series inductance and shunt capacitance of the line. The propagation speed, \(u\), and a characteristic impedance, \(Z_c\), of the line are given by:

\[
u = \frac{1}{\sqrt{LC}}; \quad Z_c = \sqrt{L/C} \tag{2}
\]

Applying the time-reversal transformation, equations (1) become:

\[
\frac{\partial v(x,-t)}{\partial x} + L \frac{\partial (-i(x,-t))}{\partial (-t)} = 0 \tag{3.a}
\]
\[
\frac{\partial (-i(x,-t))}{\partial x} + C \frac{\partial (v(x,-t))}{\partial (-t)} = 0 \tag{3.b}
\]

Equations (3) are identical to equations (1), except for that the current sign that has changed [20]. The invariance under time reversibility implies that the 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.

The invariance under time reversal of the propagation equations and the spatial correlation property of the time reversal theory allow the refocusing of the time reversed back-propagated PD signals into its original source.

The designed EMTR PD location method uses the Transmission Line Matrix (TLM) numerical method [25] to solve the equations (3) describing the time reversal propagation of the PD signals. In particular, the EMTR simulations are performed using a 1D lossless TLM model of the system under study. The TLM method is a time-domain differential-equation-based method, that discretizes the transmission line, of length \(L\), into a series of \(N\) segments, of length \(\Delta x\), connected as shown in Fig. 1 (a). Each \(LC\) section is represented by a transmission line of impedance \(Z_c\), given by relation (2), and characterized by a transit time \(\Delta t\) given by:

\[
\Delta t = \frac{\Delta x}{u} = \Delta x \cdot \sqrt{LC} \tag{4}
\]
Connecting the $N$ sections, the TLM equivalent model of the line is obtained, as shown in Fig. 1 (b). At each node, the voltage pulses, $V_d(k)$, are scattered as they propagate in the lines, generating incident voltages, $VL_n(k)$ and $VR_n(k)$, and reflected voltages, $VL'_n(k)$ and $VR'_n(k)$, respectively on the left and on the right-hand side of the node. Replacing the lines to the right and to the left of the node $n$ by their Thevenin equivalent circuits, and applying Millman’s theorem, the right-hand side of the node. Replacing the lines to the right and to the left of the node $n$ by their Thevenin equivalent circuits, and applying Millman’s theorem, the impedance of the GPDL is evaluated numerically evaluating the harmonic cable impedance $Z(\omega)$ with electromagnetic simulation software (Oersted and Electro from IES [26]). The applied cable geometry and material properties are provided in Table I. The characteristic impedance $Z_c$ and the propagation coefficient $\gamma$ are obtained from:

$$\gamma = \frac{1}{2} \left( \frac{1}{Z_c} \right)$$

TABLE I DESIGN AND MATERIAL PARAMETERS OF THE MODELLED XLPE CABLE

| Cable parameter          | Value  |
|--------------------------|--------|
| outer jacket radius      | 19.0 mm|
| earth screen radius      | 16.6 mm|
| insulation screen radius | 15.6 mm|
| XLPE insulation radius   | 14.5 mm|
| conductor screen radius  | 11.0 mm|
| conductor radius         | 10.3 mm|
| resistivity of conductor (Al) | 3.69 × 10^{-7} S/m |
| resistivity of earth screen (Cu) | 2.23-0.001 j |
| relative permittivity of XLPE | 2.23-0.001 j |
| relative permittivity s.c. screens conductivity of s.c. screens | 1000 |
| conductivity of s.c. screens | 33 S/m |

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The characteristic impedance, the phase velocity \( u = \omega / \beta \) and the per-unit-length attenuation \( \alpha \) are shown in Fig. 3. The curves are smooth and therefore simulation for only a limited number of frequencies (1-2-5 sequence from 1 kHz to 100 MHz) suffices. The curves are linearly resampled with 1 kHz steps to allow for calculation of the time-domain responses via the inverse Fourier transform.

The characteristic impedance is close to constant for the relevant frequency range for signal propagation in power cables. A constant real value of 13.6 \( \Omega \) was used. The propagation velocity amounts to about 163 m/\( \mu \)s. The attenuation arises from the conductor losses and losses from the semi-conductive (s.c.) layers. The latter becomes dominant as from about 8 MHz.

The reflection pattern from a pulse starting from one side in a single cable segment can be modelled by the transfer function:

\[
H(\omega) = \frac{\tau_{obs}(\omega)\rho_1(\omega)e^{-2\gamma_1(\omega)L_1}}{1 - \rho_1(\omega)\rho_{obs}(\omega)e^{-2\gamma_1(\omega)L_1}}
\]  

(7)

The numerator accounts for the signal propagation up and down the cable with length \( L_1 \), the reflection coefficient \( \rho_1(\omega) \) at the far end and the transmission coefficient \( \tau_{obs}(\omega) \) from the detection impedance at the observation point. The denominator accounts for multiple reflections, which involves, besides \( \rho_1(\omega) \), the reflection coefficient \( \rho_{obs}(\omega) \) at the observation point. It will be assumed that the initial pulse is narrow, meaning that after travelling some distance along the cable its waveform is fully determined by the cable propagation coefficient \( \gamma_1(\omega) \). Then, the initial pulse can be approximated as a Dirac pulse and the transfer function \( H(\omega) \) directly represents the reflection pattern in the frequency domain.

The reflection pattern depends on the transition between the cable characteristic impedance \( Z_c \) and the impedance seen at the far end. This can, e.g., be a lumped impedance or the input impedance \( Z_{in} \) of a connected cable (length \( L_2 \), propagation coefficient \( \gamma_2(\omega) \) and characteristic impedance \( Z_{c2} \)):

\[
Z_{in}(\omega) = Z_{c2}(\omega) \frac{1 + \rho_2(\omega)e^{-2\gamma_2(\omega)L_2}}{1 - \rho_2(\omega)e^{-2\gamma_2(\omega)L_2}}
\]  

(8)

The reflection coefficient \( \rho_2(\omega) \) depends on the load at the end of the second cable. Further cable cascading can be accomplished by substituting the reflection coefficient at the next cable segment here.

**B. RMU MODEL**

Small RMUs are usually only a few meters in size containing one or a few medium-voltage cables connected to a busbar and a distribution transformer that feeds a local low-voltage grid. A lumped component model is proposed in [23] aiming to describe the influence of an RMU on partial discharge propagation, see Fig. 4. The values of the model parameters were determined by injecting a pulse at the far end of one of the cables and measuring the responses at several locations inside the RMU [24]. The RMU model is subdivided in compartments, each containing a single network component. The cables in compartments 1 and 2 are each modelled with its characteristic impedance and inductances related to loops from the connection to the busbar:

- \( Z \): The characteristic impedance determined by the cable model.
- \( L \): The contribution to the loop inductance from the cable connection to the busbar.
- \( L_{bus} \): The contribution to the loop inductance from the busbar.

Compartment 3, which contains the distribution transformer, includes:
TABLE II

| Parameter | Value |
|-----------|-------|
| $Z_c$ (Ω) | 13.6  |
| $L_c$ (μH) | 0.34  |
| $C_{tr}$ (nF) | 2.5  |
| $R_{tr}$ (Ω) | 2.6  |
| $Z_{pre}$ (Ω) | 1.9  |
| $L_{pre}$ (μH) | 1.2  |
| $R_{pre}$ (Ω) | 8.6  |

1. Characteristic impedance $Z_c$ is obtained from electromagnetic modelling the cable design.
2. Capacitance $C_{tr}$ is determined from the cable length and its specifications.

- $C_{tr}, L_{tr}, R_{tr}$: The transformer behaves mainly capacitively for the main frequency components present in partial discharge signals. It is modelled as a capacitance in series with the inductance and resistance.
- $C_{tcc}, L_{tcc}, R_{tcc}$: The transformer is connected to the busbar through power cables. These cables provide a capacitive load and are modelled together with inductance and resistance.
- The connection to the busbar is modelled with $L_c$ and $L_{bb}$.

Beyond the resonances, the substation impedance increases due to the inductances.

Modelling of the reflection pattern from an RMU at the cable termination is accomplished by using the RMU impedance in the calculation of the far end reflection coefficient. When there is a second cable connected that also adds reflections from its far end, it can be modelled using its input impedance $Z_{in}$ rather than its characteristic impedance $Z_c$ in the scheme of Fig. 4.

The parameters in the RMU model were determined accounting for frequencies up to about 5 MHz [24]. For higher frequencies, connection details become important, which are specific for each RMU. In practice for power cable diagnostics, these frequencies hardly contribute due to signal attenuation and the generic model of Fig. 4 provides a representative picture of the influence of RMUs on partial discharge waveforms.

**C. REFLECTION PATTERNS**

The signal distortion by an RMU can be illustrated by injecting a signal at one end of the cable and simulating its reflections when the cable is terminated by an RMU. For illustration purposes, the near end is terminated with a real valued detection impedance making $Z_{pre}$ and $\rho_{pre}$ real as well. The applied initial signal is a Dirac pulse and the detection is bandwidth limited (50 kHz – 5 MHz). For the two cases, shown in Fig. 6, the reflections due to the RMU impedance are depicted in Fig. 7. The two cases are described in the following:

![Figure 4: RMU compartment model [19]](image-url)
- **CASE 1**: The cable length is 1000 m and the RMU only consists of the distribution transformer (blue curve). The pattern shows periodic recurring reflections. The inset shows the peak distortion by the complex RMU impedance. For later reflections, the cable propagation characteristics quench the higher frequencies. For the remaining frequency range, the impedance is high, and the far end reflection coefficient approaches one. This results in less distorted peaks, which broaden and attenuate further because of the cable characteristics.

- **CASE 2**: A second cable is connected to the RMU at the far end with 800 m length having a distribution transformer at its far end (red curve). Cables and distribution transformers are modelled with the parameters in Tables I and II. The first reflection at the RMU is only easily observable for the first reflection. Multiple reflections disappear since for the relatively low remaining frequencies the impedance from the second cable dominates, which closely terminates the first cable characteristically. The far end reflections from the second cable remain contributing since this cable is connected to a transformer only, which behaves like an open circuit for low frequencies.

Partial discharges which arise at some position $X$ cause waves running in both directions. The total reflection pattern can be modelled from the sum of the contributing transfer functions:

$$H_X(\omega) = \tau_{0,BS}(\omega) e^{-\gamma_1(\omega)X} + \rho_1(\omega) e^{-\gamma_1(\omega)(2L_1-X)} \frac{1 - \rho_1(\omega) \rho_{0,BS}(\omega) e^{-2\gamma_1(\omega)L_1}}{1 - \rho_1(\omega) \rho_{0,BS}(\omega) e^{-2\gamma_1(\omega)L_1}}$$

**FIGURE 6**: Schematic of the two cases under analysis.

**FIGURE 7**: Reflection pattern from 1000 m cable terminated with an RMU with only a distribution transformer (blue) and with, in addition, a cable with 800 m length (red); the insets show the first reflection peak over a 2 μs time scale.
can be evaluated as follows
approximated by the parallel connections of the characteristic
and the equivalent circuit of the RMU/substation can be
the PD location, simplified models of the
lengths and RMU configuration). Therefore, for pinpointing
specification (such as cable impedance and signal propagation
analysis can usually be based on general data from the cable
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Application of PD locating techniques should not
rely on
detailed information that is hard to obtain in practice. The
analysis can usually be based on general data from the cable
specification (such as cable impedance and signal propagation
velocity) and on the cable connection topology (such as cable
lengths and RMU configuration). Therefore, for pinpointing
the PD location, simplified models of the network components
need to be adopted and the effectiveness of the methodology
must be verified. For application of EMTR, a lossless 1D TLM
model of the line has been developed for each case under
analysis to perform the time reversal simulations for the PD
location, as described in Section II. To define the characteristic
of the 1D TLM model of the line the following considerations
have been made.

When PD signal propagates over distances of 1–2 km, most of
the remaining energy is in the frequency range up to 1 MHz or
few MHz [19], decreasing further for longer distances. Then,
the PD signal, measured at the OP and used to perform the
EMTR simulations, is characterised by a frequency content up
to a few megahertz. At these low frequencies, the inductances,
and capacitances in RMU/substation can be neglected
compared with the characteristic impedance of the cable Z_c,
and the equivalent circuit of the RMU/substation can be
approximated by the parallel connections of the characteristic
impedances of the N-connected MV cables [23]. With this
approximation, in the frequency range of interest, the input
impedance of the RMU/substation, seen by the PD signal,
Z_{RMU}, and the reflection coefficient at the RMU input, \( \Gamma_{RMU} \),
can be evaluated as follows [19]:
\[
Z_{RMU} \approx \frac{Z_c}{N - 1}
\]
\[
\Gamma_{RMU} = \frac{Z_{RMU} - Z_c}{Z_{RMU} + Z_c} \approx \frac{2 - N}{N}
\]

Hence, for the cases under analysis shown in Fig. 6, in the 1D
TLM model the input impedance of the RMU at the line
termination, \( Z_{RMU,T} \), is \( Z_{RMU,T} >> Z_c \), then the reflection
coefficient is equal to \( \Gamma_{RMU,T} = 1 \). While when the RMU is in
the middle of the line, it has been modelled with a TLM model
3 m long with a characteristic impedance, \( Z_{RMU,L} \), chosen
equal to \( Z_{RMU} = 2 Z_c \), so with a relative reflection coefficient
equal to \( \Gamma_{RMU,L} = 0.5 \). This is because, the RMU only causes
a distortion mainly for high frequencies. It becomes invisible
when the wavelengths associated with the remaining
frequencies after signal attenuations are clearly exceeding the
RMU size. A similar distortion occurs when modelling
the RMU as a short transmission line (TL) with different
characteristics. To illustrate this, two cables (1000 m and
800 m) are connected via a short cable length of 3 m with a
characteristic impedance double that of the cable. The far end
is kept open, and a signal is injected at the observation point.
As shown in Fig. 8, a somewhat less oscillatory response but
still quite similar with decaying peaks as in Fig 7 (red curve)
is obtained for the reflections at the short TL (at 12, 24, 32 and
34 \( \mu \)s), whereas the far end reflections (at 22 and 44 \( \mu \)s) remain
clearly visible.

Finally, from the electromagnetic modelling of the cable, and
considering the frequency range up to few MHz, for the design
of the 1D TLM model the following characteristic impedance
of the cable and propagation speed have been employed:
\( Z_c = 13.6 \Omega, \ u = 1.625 \times 10^8 \) m/s.

In each of the two analyzed cases described in Section III,
providing the time responses including realistically modelled
signal distortion, the PD signal has been collected at the
observation point (OP) at the left end of the line. Then, the
collected PD signal is time reversed and injected into the 1D
lossless TLM model of the system and time reversal
simulations are performed, as described in Section II.

For the two analyzed cases the following results have been
obtained:

- **CASE 1**: Fig. 9 shows, for example, the collected PD
  signal at the OP and the time reversed signal when the PD
  source is 280 m from the OP. In Fig. 10-11 the simulation
  results, showing the performance of the of the EMTR-
  based PD location method are shown for cable lengths
  of respectively 1 km and 2 km.

- **CASE 2**: Fig. 12 shows the collected and time reversed PD
  signal when the PD source is at 300 m from the OP. The
  EMTR results are shown in Fig.13. The cable lengths are
  1 km and 0.8 km.

Figs 9 and 12 show the distortion of the PD signals due to the
impedance mismatches of the lines caused by the presence of
the RMUs and by the variation with frequency of the
impedance of each component of the system.

Figures 10-11 and 13 show that the method is able to localize
the PD source despite the distortion of the PD signal and the
reflections at the impedance’s mismatches.

Moreover, Fig. 13 shows that also despite the signal distortion
from the RMU between the two cable segments, the PD
location can be retrieved accurately, independently of whether
the PD originates from the 1 km or the 0.8 km cable segment.

**FIGURE 8**: Reflection pattern from a 1000 m connected via a 3 m
diameter to an open ended 800 m cable; the inset show the first
reflection peak over a 2 \( \mu \)s time scale
The accuracy of the localization is summarized in Table III. Table III summarizes the results for four PD positions (source) together with the located positions (EMTR) and the relative error. The relative error in the localization, evaluated with respect to the line length, is generally below 1%, which is an acceptable error in practical applications. The error increases a little, but remains always $\leq 1.5\%$, at the terminations in CASE 1 with the line length $L = 1$ km.

To locate the PD source, a first scan of the system has been carried out choosing GPDLs 8 m apart from each other. After that, a refined search has been performed, reducing the distance between the GPDLs to 1 m only in the section of the line where the maximum concentration of the energy associated to the time reversed signals propagation has been detected during the first scan.

A computational time of about 30 s is necessary for the line 1 km long and of about 50 s for the line 2 km long, using a 64-bit pc with an Intel® Core™ i7-8700K, CPU at 3.70GHz, 32GB RAM and 1TB disk.

### TABLE III

| CASE 1: 1 km | CASE 1: 2 km | CASE 2: 1 / 0.8 km |
|-------------|-------------|-------------------|
| Source | EMTR | $\varepsilon_{\%}$ | Source | EMTR | $\varepsilon_{\%}$ | Source | EMTR | $\varepsilon_{\%}$ |
| 80 m | 65 m | 1.5 | 120 m | 113 m | 0.3 | 300 m | 281 m | 0.5 |
| 280 m | 284 m | 0.4 | 300 m | 292 m | 0.4 | 700 m | 683 m | 0.3 |
| 500 m | 505 m | 0.5 | 630 m | 624 m | 0.3 | 1200 m | 1183 m | 0.3 |
| 800 m | 782 m | 1.8 | 1800 m | 1782 m | 0.9 | 1450 m | 1434 m | 0.8 |

**FIGURE 9:** PD signal collected at the OP (upper) and the time reversed PD signal (lower) in CASE 1 when the PD source is at 280 m from the OP.

**FIGURE 10:** Simulation results of the EMTR-based PD location method in the CASE 1 with 1 km length of the line.
V. CONCLUSION

The performance of the EMTR-based method to locate PD with the presence of ring main units (RMUs) on the grid has been analysed in simulation. A description of the EMTR-based method is given and the models used to simulate the grids components, RMU and power cable, useful to reproduce the PD signal distortion are described. The effectiveness of the EMTR method to localize the PD source has been analyzed in two different configurations: 1) a homogeneous line, both 1 km and 2 km long, with one RMU at the far end and 2) Two cable section with an RMU in between and an RMU at the far end of the second cable section. The simulation results show that the EMTR method is able to localize PDs with a computational time less than a minute. For online monitoring, if this duration would be critical, the technique can be applied when pre-localization, e.g. by threshold discrimination, shows that certain PDs are concentrated or arise near a critical location. More accurate pinpointing of the defect can then be achieved with EMTR. The relative error, with respect to the total cable length, usually is below 1%, except when the PDs arise close to the cable terminations, where the error increases but never exceeded 1.5%. With respect to the big challenge of the EMI on power networks, the authors in a work of under publication, show that noise can be tackled effectively by the EMTR method, allowing the PD localization with errors less than 1% and, in [16], the authors have already shown theoretically that the proposed technique works with an SNR of -7dB using injected white noise.

FIGURE 11: Simulation results of the EMTR-based PD location method in the CASE 1 with 2 km length of the line.

FIGURE 12: PD signal collected at the OP (upper) and the time reversed PD signal (lower) in CASE 2 when the PD source is at 300 m from the OP.
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Antonella Ragusa, (M’08) received the Master and Ph.D. degrees in Electrical Engineering from the University of Palermo, Italy, in 2001 and 2006, respectively. In 2007, she worked at FIAT. She has been a permanent researcher at the Institute of Marine Engineering (INM) of National Research Council (CNR) of Italy, Palermo since 2008. Currently, she is a Marie Curie Researcher Fellow (MSCA-IF) at De Montfort University of Leicester, UK. Her research interests include electromagnetic compatibility, computational electromagnetics and smart grids.

Peter A. A. F. Wouters studied physics at Utrecht University (UU), Utrecht, the Netherlands, until 1984, from where he received the Ph.D. degree for a study on elementary electronic transitions between metal surfaces and low energetic (multiple) charged ions in 1989. In 1990, he joined the Electrical Energy Systems (EES) Group, Eindhoven University of Technology, as a Research Associate. Since 2003, he has been an Assistant Professor in the field of diagnostic techniques in HV systems. From 2018 until 2021, he was appointed as a Visiting Professor with the College of Chemical and Biological Engineering, Zhejiang University in Hangzhou, China. His research interests include partial discharge techniques, vacuum insulation, and LF electromagnetic field shielding.

Hugh G. Sasse, received the B.Sc. (Hons) degree in electronic engineering from the University of York, York, U.K., in 1985, and has received his PhD. degree in 2010 from De Montfort University, Leicester, U.K. His research is on optimization of physical layer components for communications systems at De Montfort University.

Alistair Duffy, (SM’04, F’14), is Professor of Electromagnetics and Director of the Institute of Engineering Sciences at De Montfort University (DMU), Leicester, UK. He received his BEng (Hons) and MEng degrees in 1988 and 1989, respectively, from University College, Cardiff, University of Wales. He read for his PhD with professors Christopoulos and Benson at Nottingham University, graduating in 1993. He also holds an MBA from the Open University, UK, graduating in 2004. He was awarded his DSc from Cardiff University in 2019 for his body of research on the validation of computational electromagnetics. He is a Fellow of the IEEE and President of the IEEE EMC Society. He has published approximately 300 papers, mostly on his research interests of validation of computational electromagnetics; physical layer components, particularly communications cabling, and electromagnetic compatibility testing.