A Full-Scale Experimental Validation of Electromagnetic Time Reversal Applied to Locating Disturbances in Overhead Power Distribution Lines

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***Abstract*— Electromagnetic time reversal (EMTR) has emerged as a promising technique to locate disturbances in power grids thanks to its location accuracy and robustness against parameters uncertainties. Furthermore, in a reflective medium, like the one of a power network, it has been shown that the method requires no more than one single observation point. In this paper, we present an experimental validation of EMTR to locate disturbances in real power networks. The validation is performed on a full-scale unenergized 677-m long, double-circuit 10-kV overhead distribution line. The disturbance is emulated by a voltage pulse injected between one of the line conductors and the ground using a high voltage pulse generator. The frequency spectrum of the injected voltage pulse is specified such that the originated electromagnetic transients are compatible with those of power line faults, lightning and conducted intentional electromagnetic interferences. The transient currents generated by the emulated disturbance are measured at one end of the line, considering two different line configurations. According to the EMTR technique, the measured signals are time reversed and back injected into the system that, in our case, is a simulated model of the considered distribution line. More specifically, it is represented by a constant-parameter line model implemented within the EMTP-RV simulation environment. For both cases, the disturbance is accurately located, and the phase of the circuit at which the pulse was injected is also identified.**

***Index Terms*— electromagnetic time reversal, electromagnetic transients, distribution lines, disturbance location, power system protection.**

I. Introduction

POWER networks (both transmission and distribution) are subjected to a range of unexpected momentary voltage variations from both natural and man-made disturbances [1]-[3]. The former category of disturbances is mainly originated by either direct or indirect lightning strikes (e.g., [4], [5]) or weather-induced shunt faults (e.g., ice, falling trees), unintentional contact to power lines by flying objects or animals, etc. [6], [7]. Man-made disturbances refer to switching operations either of network components, or end-user equipment (e.g., [1]-[3]), and, within the contemporary scene, acts of sabotage, such as conducted intentional electromagnetic interference (IEMI) [8], [9]. In general, the above-mentioned disturbances cause adverse effects on the quality of power supply with manifestations ranging from voltage sags and swells, insulation deterioration, sensitive load damage and power supply interruptions and even blackouts.

In this respect, the problem of distribution networks protection and, more generally, quality of power supply has historically received great attention with the aim of developing methods to protect network terminal components (e.g., distribution transformers) as well as power lines and cables [10]-[12].

In view of the above, identifying the location of the source of a generic disturbance is certainly a desired feature in any protection scheme in power systems. More specifically, among the previously-described disturbances, locating lightning strikes, faults, and electromagnetic pulse (EMP) injection is especially needed for coordinated protective maneuvers such as relay operation and fault clearance.

For the specific case of surges due to direct or indirect lightning, a major concern is related to overvoltages causing insulation deterioration and failures of power network components, especially at the location of the surge appearance (i.e., direct lightning strikes) as well as for nearby towers where

This work has been supported by the Swiss Competence Center for Energy Research FURIES (Future Swiss Electrical Infrastructure) and the National Natural Science Foundation of China under Grant 51677148.

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(back-) flashovers are likely to arise [4], [13]. Identifying the locations of these flashovers greatly contributes to reducing time and labor consumption associated with insulation inspection and maintenance.

On the other hand, shunt faults are triggered by undesired electrical connections (mainly referring to phase(s)-to-ground cases) and require, in general, manual clearance. Therefore, indicating fault locations in power networks is needed for an adequate reconfiguration of the networks and expediting the power system restoration.

Finally, the use of high power electromagnetic sources to produce interferences in critical power system infrastructures (e.g., terminal power transformer and its secondary circuits in distribution networks) has become a serious concern. There is an increasing interest in detecting and locating IEMI attacks [14], [15].

Recently, the theory of electromagnetic time reversal (EMTR) has been applied to locate different types of disturbances in power systems and electromagnetic compatibility (EMC) applications [16]. The considered applications include locating lightning flashes (e.g., [17]), lightning-originated flashovers (e.g., [18]), short-circuit faults (e.g., [19]-[23]), and soft faults (e.g., [24], [25]). As known, the EMTR methods take advantage of the time reversibility of wave equations and the spatial correlation property of the time reversal theory to refocus the time-reversed back-propagated electromagnetic waves into the original disturbance location. More specifically, when the observed disturbance-originated electromagnetic transients are time reversed and back injected into the original system, they refocus back to the location of the disturbance.

In this paper, we present the results of a field experiment demonstrating the ability of an EMTR-based location method to identify the location of an injected disturbance along an overhead power distribution line. This experiment was performed on a 677-m long, 10-kV distribution line in Yuncheng city, Shanxi Province, China.

The paper is structured as follows. Section II summarizes the basic principles of EMTR and its application for locating disturbances in power system. In Section III, we present the experimental setup and validation approach. Experimental results associated with two different configurations are presented and discussed in Section IV. Finally, Section V concludes this paper with final remarks.

II. EMTR-Based Disturbance Location Method

A. EMTR and time-reversal invariance of transmission-line equations

A system is time-reversal invariant with respect to a physical quantity if, given a solution $f(t)$ to its underlying equations, the time-reversed function $g(t)$, given by (1) hereunder, is a solution too [26].

$$g(t) = f(-t) \tag{1}$$

In order to ensure the causality requirements, the time-reversed function $f(-t)$ is shifted in time as

$$g(t) = f(-t+T) \tag{2}$$

where, T is the time window during which $f(t)$ is observed.

The time-reversal invariance is readily described and universally embodied in most laws of nature, either in a strict or in a soft sense [26]. Time reversal as a focusing process, first has been theoretically and experimentally studied in the field of acoustics (e.g., [27]-[29]). Later, its application was extended to electromagnetics using the acronym electromagnetic time reversal (EMTR).

Based on the transmission line theory, the propagation of voltage and current waves along the lines is governed by the Telegrapher's equations. With particular reference to the Telegrapher's equation describing the current wave propagation along multi-conductor lossless transmission lines, the current wave equation reads

$$\frac{\partial^2}{\partial x^2}\boldsymbol{I}(x,t) - \boldsymbol{C}'\boldsymbol{L}'\frac{\partial^2}{\partial t^2}\boldsymbol{I}(x,t) = \boldsymbol{0} \tag{3}$$

where $\boldsymbol{I}(x, t)$ is the vector of currents along the lines, and $\boldsymbol{C}'$ and $\boldsymbol{L}'$ are the per-unit-length matrices of capacitances and inductances, respectively.

Because of the second-order time derivative, if $\boldsymbol{I}(x, t)$ is a solution of (3), $\boldsymbol{I}(x, -t+T)$ is also a solution, namely

$$\frac{\partial^2}{\partial x^2}\boldsymbol{I}(x,-t+T) - \boldsymbol{C}'\boldsymbol{L}'\frac{\partial^2}{\partial t^2}\boldsymbol{I}(x,-t+T) = \boldsymbol{0} \tag{4}$$

The same applies to the voltage equation. This implies that the wave equation for a lossless transmission-line system is time reversal invariant. Furthermore, it has been recently shown that the method's performance in terms of location accuracy is not affected in the case of lossy lines for which the wave equations are not rigorously time-reversal invariant [30].

B. Applying EMTR to locate disturbances in power networks

Benefiting from the time reversal invariance of the transmission-line equations and the inherent spatial focusing property of the time-reversal invariant system, EMTR has emerged as an extremely promising technique of detecting and locating various disturbances in power systems.

Theoretically, direct lightning strikes, faults and conducted IEMI disturbances can be represented by an equivalent voltage or current source with specified characteristics (e.g., frequency spectrum) according to each type of disturbance [8], [19], [31].

Locating the source of the disturbance using an EMTR-based method is carried out in two successive steps named *direct-time* and *reversed-time*.

Since the focus of this paper is to provide an experimental validation, in the *direct time*, a voltage or current source is intentionally connected to a specific location along the line (e.g., $x = x_f$), emulating the occurrence of the disturbance at that location. The generated electromagnetic transient (EMT) signals are measured at a single observation point located at the line terminal, on one of the phases or on all of the phases depending on the experiment.

In the *reversed time*, the measured transient signals are time reversed and synchronously back-injected from the respective observation point into the network model using numerical simulations. The simulations are performed for different guessed positions of the original disturbance along the line. At the point corresponding to the real location, the two media in the *direct* and *reverse* phases match and, therefore, the back-injected signals refocus at the original disturbance location.

Different metrics can be used to quantify the wave refocusing property [19], [22]-[25]. In this paper, we will use the metric proposed in [19] that analyzes, as a function of the guessed location, the energy of the signal of the shunt current flowing in a generic location of the disturbance. It has been demonstrated that the transverse branch current signal observed at the true location presents a maximum energy compared to any other location along the line [18]-[21]. This method has been successfully used to locate faults (e.g., [19]-[21]) and lightning flashovers (e.g., [18]]) along power networks.

In the next section, we will present a full-scale experimental validation of the EMTR-based method to locate disturbances in power lines, by making use of a real overhead power distribution line.

III. Experimental Setup and Approach

In November 2016, a field experiment was performed on an unenergized 10-kV three-phase distribution line in Shanxi Province, China, with the objective of validating the capability of the EMTR-based technique to locate a disturbance incident in a real power system environment. In this section, we will introduce the setup and the approach proposed for this experiment.

A. Experimental setup

The transmission-line system considered in the field experiment is a 10-kV double-circuit overhead power distribution line. The cross-sectional geometry and main electrical parameters of the overhead line are respectively described in Fig. 1 and Table I.

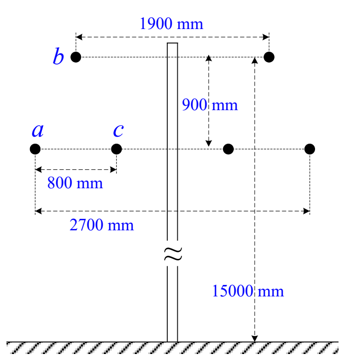


Fig. 1. Cross-sectional geometry of the 10-kV double-circuit overhead power distribution line.

TABLE I
Main Electrical Parameters of the Distribution Line

Parameter	Value
Diameter of the line conductor	18.4 mm
Conductivity of the line conductor (aluminum conductor steel reinforced (ACSR))	3.5×10^{7} S/m
Soil conductivity	0.1 S/m

It should be noted that, in the direct-time phase, the system is unenergized, and the disturbance emulation and measurement were performed by making use of one of the two three-phase single-circuits (see the three-phase conductors indicated by *a*, *b* and *c* in Fig. 1). Another circuit of the line (i.e., the one on the right-hand side in Fig. 1) was left open at both extremities during the experiment. It is worth mentioning that both circuits were included in the reversed-time simulation by taking the existing electromagnetic coupling into consideration.

The experimental setup is illustrated in Fig. 2. As shown, the considered overhead-line section is characterized by a total line length of 677 m, including 11 overhead-line towers (numbered from 22 to 32). To emulate a disturbance occurrence, a voltage pulse generator was connected between the phase *c* of the overhead line and the ground at tower No. 23 (see Fig. 3) situated 68 m away from the origin of the line. The injected pulse signal $V_p(t)$ is characterized by a risetime t_r of 12 ns, and a full width at half maximum (FWHM) of about 1μs.

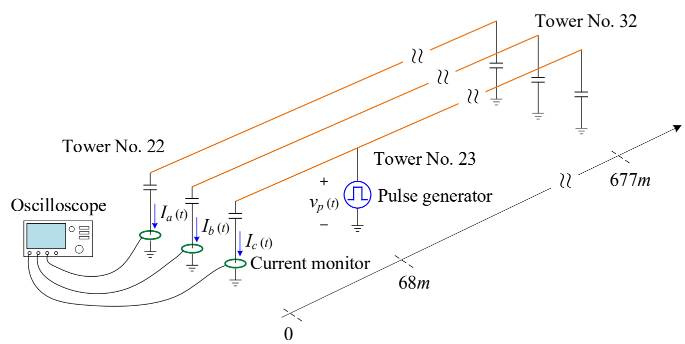


Fig. 2. Schematic representation of the experimental setup. Another three-phase circuit (not shown in this diagram) was in open-circuit at both ends.

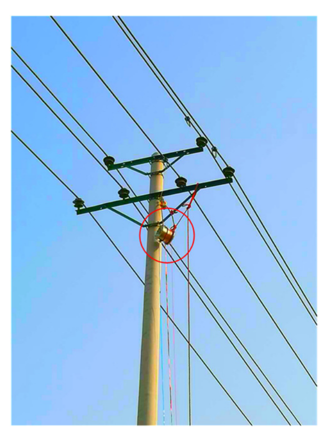


Fig. 3. Picture of Tower No. 23 at which the pulse generator (marked with the red circle) was connected to one of the phase conductors of the overhead line.

In reality, the power network is typically terminated with power transformers. The high-frequency input impedance of power transformer can be represented, to a first approximation, by its winding-to-ground capacitance C_t [32], [33]. Additionally, the power transformers are connected to the substation bus through the bushing, whose electrical characteristics are also dominated by a line-to-ground capacitance C_b during the power transient phenomena of interest. Therefore, the port-characteristics of the transformer (seen from the incoming-line side) can be equivalently represented by a parallel circuit of C_t and C_b.

According to the actual measurements on 10-kV-level transformers operating at the local power network, the capacitances C_t and C_b were found to be in the range 800 pF to 900 pF, and 450 pF to 550 pF, respectively. As a result, we used 1500 pF thin-film capacitors to represent the 10-kV-level terminal power transformers in the field experiment (see Fig. 2).

One of the promising properties of time-reversal theory in a reflective medium is that refocusing is possible using single end/side observation [19], [27]-[29]. As a result, in the field experiment, the disturbance-originated transients were recorded at the left line end (tower No. 22) by means of broadband current monitors (see Fig. 2). The measurement devices and their main characteristics are summarized in Table II.

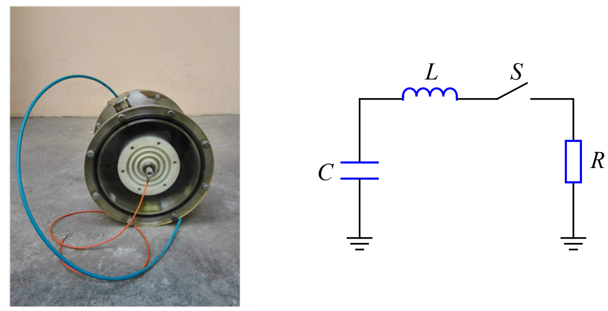
TABLE II
MEASUREMENT DEVICES AND THEIR CHARACTERISTICS

Device	Model	Parameter	Value
Current monitor	Pearson™ 8585C	Sensitivity	0.5 V/A
		Bandwidth	200 MHz
Oscilloscope	Tektronix™ DPO 3054	Sampling rate	2.5 GS/s
		Vertical resolution	11 bits
		Bandwidth	500 MHz

B. Disturbance emulation

In this work, the disturbance is emulated by a voltage pulse injected between one of the line conductors and the ground using a pulse generator. The waveform of the injected voltage has been selected so that its frequency spectrum covers those of the electromagnetic transients caused by power line faults, lightning and conducted IEMI. The frequency spectrum of transients generated by faults in power networks extends to some hundreds of kHz, while lightning-induced overvoltages have significant frequency components up to a few MHz [2]. Conducted IEMI pulses can be characterized by diverse waveshapes. However, due to the high-frequency propagation losses along power lines, the frequency spectrum of these sources generally does not extend beyond 10 MHz or so [8].

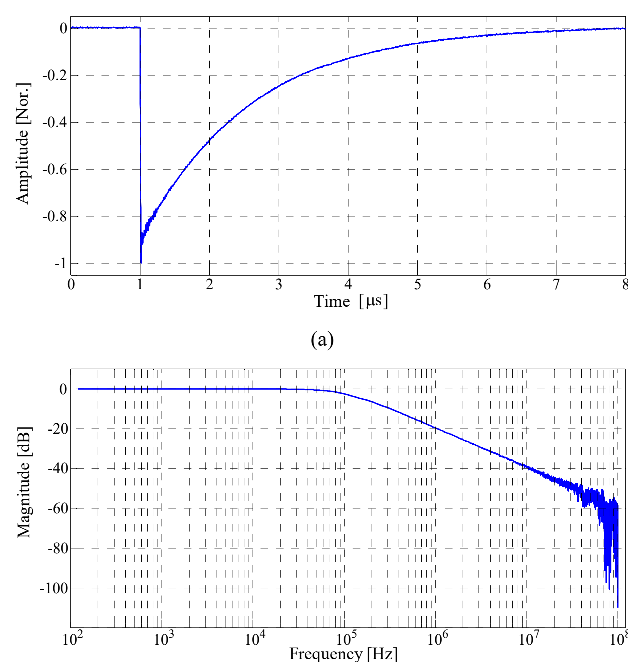
As a result, a compact capacitor-discharging pulse generator was adopted in the study (see Fig. 4a). The pulse generator can be equivalently represented by a simple *RLC* circuit (see Fig. 4b), in which the capacitance C storing the energy to produce the surge has a value of 6.97 nF. The coaxial structure of the generator restricts the discharging-circuit inductance L to some hundreds of nH. The resistance R in the circuit represents the equivalent impedance seen by the generator when connected to the overhead line. More specifically, in the considered experimental configuration, R corresponds to $Z_c/2$, Z_c being the characteristic impedance of phase c of the circuit, which is about 400 Ω. Note that this is an approximated computation since it is ignoring the presence of the other mutual coupling between the conductors. In addition, the discharging voltage of the generator is controlled by a spark gap switch (see S in Fig. 4b). Compressed air is used as dielectric in the switch.



(a) Picture (b) Equivalent circuit

Fig. 4. Picture and equivalent circuit of the adopted coaxial-structure pulse generator

In the laboratory environment, we used a 200 Ω metal oxide film resistor to simulate the discharging condition of the field experiment. As shown in Fig. 5a, the measured waveform of the voltage pulse presents, as mentioned earlier, a risetime of about 12 ns and an FWHM of about 1μs. The spectrum of the pulse extends to significant frequencies, up to a few tens of MHz (see Fig. 5b).



(b)

Fig. 5. Normalized waveform (a) and magnitude spectrum (b) of the voltage pulse characterized by a risetime and an FWHM of 12ns and 960 ns respectively. The spectral components appearing in the frequency exceeding 100MHz are not shown in this figure, as they are considered to be mainly due to quantization noise (sampling rate: 2.5 GS/s).

IV. Experimental Results and Discussion

Recalling the setup described in Fig. 2, we emulated a power system disturbance occurrence by injecting a voltage pulse signal $V_p(t)$ (t_r = 12 ns, FWHM = 1μs) into the line conductor of phase *c*. The injection point was situated at the overhead-line tower No. 23, which is 68 m away from the observation point (OP), namely tower No. 22. The peak value of the injected pulse $V_p(t)$ was about 10 kV.

In what follows, we will present the experimental validation of the EMTR technique, considering two different line configurations.

A. One-phase configuration

1) Direct-time measurements

In the first experiment, only the injected phase *c* was terminated at each end on a 1500 pF thin-film capacitor, whereas the other two phase conductors (*a* and *b*) were left open, as shown Fig. 6.

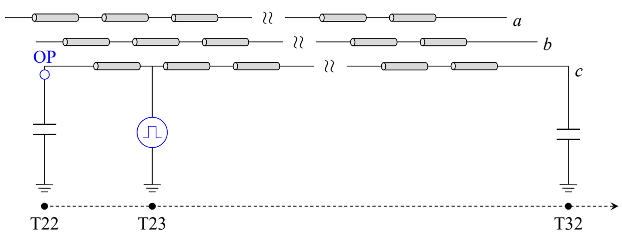


Fig. 6. Direct-time experimental setup of the one-phase configuration. The current transients generated by the source were measured only in the phase at which the disturbance pulse was injected. The second three-phase circuit (not shown in the diagram) was left open at both of its extremities.

The transient current signal generated by the source and measured at the observation point is shown in Fig. 7.

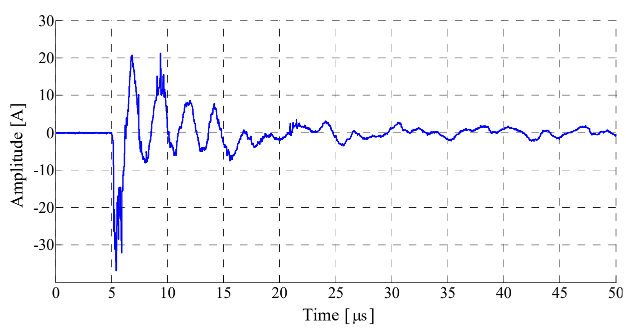


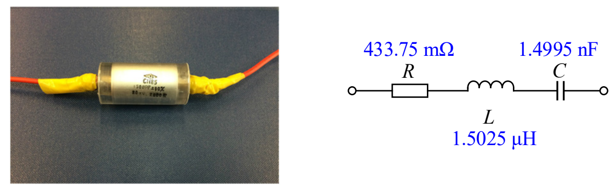
Fig. 7. Transient current waveform in phase *c* measured at the observation point (sampling rate: 2.5 GS/s).

2) Reversed-time simulations

In the reversed-time stage, the measured transients are time reversed and back injected numerically into a simulation model of the studied system.

According to its geometrical and electrical parameters, the line topology considered in the field experiments was modelled in the EMTP-RV environment by making use of the constant-parameter (CP) line module [34], [35]. Note that, for achieving an accurate representation of the actual situation, both circuits of the 10-kV line (see Fig. 1) were considered in the simulation model. The generated per-unit-length parameters of the double circuits are given by (5)-(8), shown in Appendix.

As regards the line boundary conditions, the terminal element composed of the thin-film capacitor and its leading wires was modelled using an *RLC* equivalent circuit (see Fig. 8), which was obtained through actual measurements by means of an impedance analyzer (i.e., Model 6500B of Wayne Kerr™) in a frequency range from DC to 20 MHz.



(a) Picture (b) *RLC* circuit

Fig. 8. Picture and *RLC* equivalent circuit of the terminal element composed of a thin-film capacitor with a nominal value of 1500 pF and its leading wires.

In the simulations, after back-injecting the time-reversed transient current from the initial observation point (i.e., tower No. 22 in the EMTP-RV model), the transverse branch current was evaluated at different *a priori* guessed locations. In the presented line topology, we predefined the location of each tower as a guessed location, resulting in an average distance between two consecutive guessed locations is of 67.7 m.

In Fig. 9, the normalized current energy is presented as a function of the guessed location. The normalization is conducted with reference to the maximum of the energy. In agreement with the EMTR-based method, the location of phase *c* of tower No. 23 is evidently characterized by the highest energy concentration.

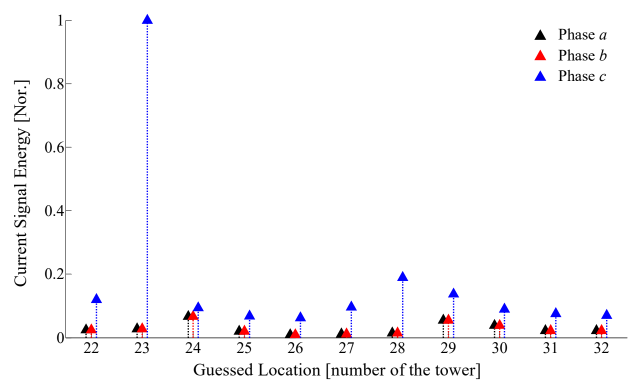


Fig. 9. Normalized energy of the branch current in the one-phase configuration.

B. Three-phase configuration

1) Direct-time measurements

In the second experiment, all three phases of the circuit were terminated at both ends on 1500 pF thin-film capacitors. The transient currents in each phase conductor were simultaneously and synchronously recorded at the observation point (see OP1, OP2, and OP3 in Fig. 10). The pulse signal $V_p(t)$ was again injected into the phase *c*. The measured waveforms of the transient currents in the three phases are shown in Fig. 11.

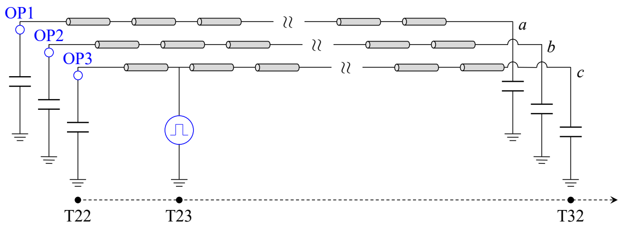
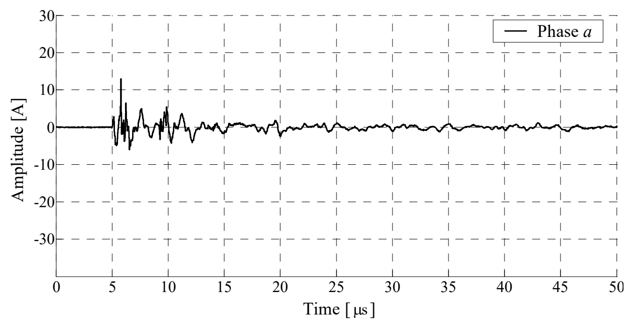
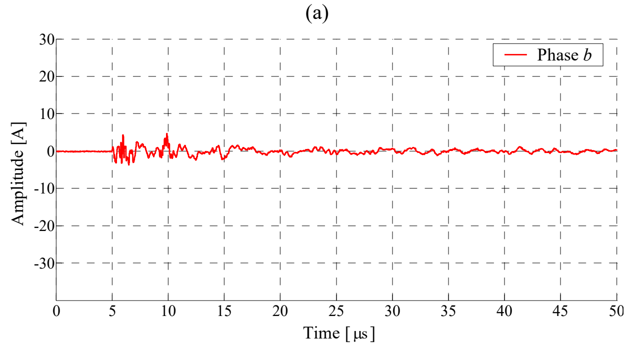


Fig. 10. Direct-time experimental setup of the three-phase configuration. The current transients generated by the source were measured in the three phases at the left line end. The second three-phase circuit (not shown in the diagram) was left open at both of its extremities.



(a)



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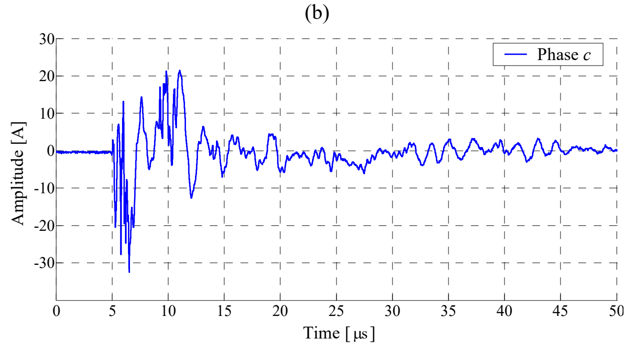

(c)

Fig. 11. Synchronously-measured transient current waveforms in the three phases (sampling rate: 2.5 GS/s), (a) phase a, (b) phase b and (c) phase c.

2) *Reversed-time simulations*

In the three-phase scenario, the back-propagation simulation is conducted by simultaneously injecting the time-reversed transient currents in each phase from their respective observation point.

Fig. 12 shows the normalized branch current energy along the three-phase line (here the normalization has also been implemented by considering the maximum current energy). As can be observed, at each tower location, phase *c* presents a dominant current energy accumulation, compared to the other two phases. More importantly, a maximum is clearly reached at tower No. 23 of phase *c*, at which the pulse $V_p(t)$ was originally injected. Therefore, the method is capable of identifying the excited phase and the location of the disturbance along that phase.

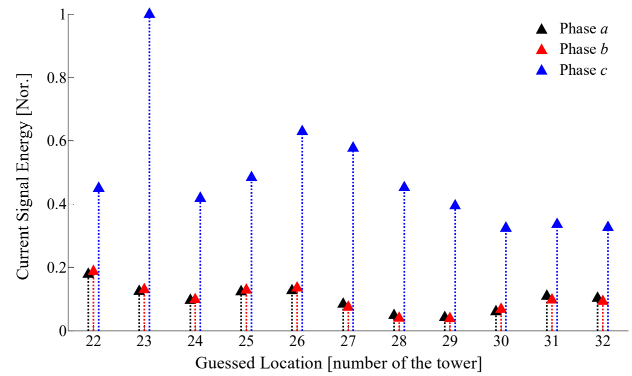

Fig. 12. Normalized energy of the branch current in the three-phase configuration.

V. Conclusion

We presented a full-scale experiment with the purpose of validating the EMTR-based method applied to locate power system disturbances. The pilot power network refers to a 677-m long 10-kV double-circuit distribution line.

The disturbance was emulated by a voltage pulse injected between one of the line conductors and the ground using a pulse generator. The waveform of the injected voltage was selected so that its frequency spectrum covers those of power line faults, lightning and conducted IEMI subsequent transients.

The transient currents generated by the emulated disturbance were measured at one end of the line, considering two different line configurations. According to the EMTR technique, the measured signals were time reversed and back injected into an EMTP-RV constant-line model of the studied distribution line. For both cases, the disturbance was accurately located, and the conductor phase at which the pulse was originally injected was also identified.

To the best of the Authors' knowledge, this is the first experimental validation of the EMTR-based disturbance location technique in a real full-scale power line environment.

Appendix

The per-unit-length parameter matrices of resistance, $\boldsymbol{R}$, inductance, $\boldsymbol{L}$, conductance, $\boldsymbol{G}$, and capacitance, $\boldsymbol{C}$ of the considered double-circuit distribution line are shown below.

$$\boldsymbol{R}=\begin{bmatrix} 2.665 & 2.567 & 2.551 & 2.567 & 2.566 & 2.551 \\ 2.567 & 2.665 & 2.551 & 2.566 & 2.566 & 2.551 \\ 2.551 & 2.551 & 2.634 & 2.551 & 2.551 & 2.536 \\ 2.567 & 2.566 & 2.551 & 2.665 & 2.567 & 2.551 \\ 2.566 & 2.566 & 2.551 & 2.567 & 2.665 & 2.551 \\ 2.551 & 2.551 & 2.536 & 2.551 & 2.551 & 2.634 \end{bmatrix}\times 10^{-3}\,\frac{\Omega}{\mathrm{m}} \tag{5}$$

$$
\boldsymbol{L}=\begin{bmatrix}1.927 & 1.034 & 0.993 & 0.970 & 0.861 & 0.879\\ 1.034 & 1.927 & 0.993 & 0.861 & 0.791 & 0.810\\ 0.993 & 0.993 & 1.929 & 0.879 & 0.810 & 0.863\\ 0.970 & 0.861 & 0.879 & 1.927 & 1.034 & 0.993\\ 0.861 & 0.791 & 0.810 & 1.034 & 1.927 & 0.993\\ 0.879 & 0.810 & 0.863 & 0.993 & 0.993 & 1.929\end{bmatrix}\times 10^{-6}\,\frac{\mathrm{H}}{\mathrm{m}} \tag{6}
$$

$$
\boldsymbol{G}=\begin{bmatrix}0.200 & 0 & 0 & 0 & 0 & 0\\ 0 & 0.200 & 0 & 0 & 0 & 0\\ 0 & 0 & 0.200 & 0 & 0 & 0\\ 0 & 0 & 0 & 0.200 & 0 & 0\\ 0 & 0 & 0 & 0 & 0.200 & 0\\ 0 & 0 & 0 & 0 & 0 & 0.200\end{bmatrix}\times 10^{-12}\,\frac{\mathrm{S}}{\mathrm{m}} \tag{7}
$$

$$
\boldsymbol{C}=\begin{bmatrix}10.272 & -2.550 & -2.000 & -1.781 & -0.881 & -0.995\\ -2.550 & 9.702 & -2.270 & -0.881 & -0.609 & -0.677\\ -2.000 & -2.270 & 9.627 & -0.995 & -0.677 & -1.200\\ -1.781 & -0.881 & -0.995 & 10.272 & -2.550 & -2.000\\ -0.881 & -0.609 & -0.677 & -2.550 & 9.702 & -2.270\\ -0.995 & -0.677 & -1.200 & -2.000 & -2.270 & 9.627\end{bmatrix}\times 10^{-12}\,\frac{\mathrm{F}}{\mathrm{m}} \tag{8}
$$

ACKNOWLEDGMENT

The authors would like to thank the contributions of experimental participants including Yi Zhang, Jiangwu Liu of Shanxi Electric Power Company of State Grid of China, and Yanpeng Ge, Hong Zhang, Hongye Zhang of Xi'an Jiaotong University.

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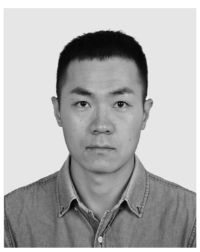

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