Locating Lightning-Originated Flashovers in Power Networks using Electromagnetic Time Reversal

R. Razzaghi, M. Scatena, M. Paolone, F. Rachidi, G. Antonini

Abstract-- **This paper presents a method to locate lightning-originated flashovers in overhead transmission lines. The proposed method is based on the electromagnetic time-reversal theory and uses the voltage transient signals initiated by the flashover to identify its location. The method relies on the use of a single observation (measurement) point located at the primary substation and can be applied to different power network topologies. The performance of the proposed method is validated by using several numerical simulation case studies and by analyzing the impact of the surge arresters on the location accuracy of the flashover.**

Keywords: lightning flashovers, electromagnetic time reversal, transmission lines, power systems protection.

I. Introduction

Lightning is one of the main sources of power systems outages and is considered as one of the main sources of unscheduled maintenance in the operation of power networks. Reliability studies have identified a clear correlation between lightning and power systems outages [1].

When lightning strikes directly transmission lines, it can easily lead to an insulation breakdown or conductor damage resulting in an interruption of the electricity supply. Nonetheless, despite the high correlation between lightning and power outages, there are also other natural factors (e.g., wind, rain, falling trees, etc.) that might cause power outage. As a consequence, the assessment of the correlation between power quality problems and lightning events has a crucial importance for the verification of the insulation coordination, protection system design, and planning maintenance [2].

The correlation between faults and lightning events has been widely investigated in the literature. The topic has been studied for both transmission lines and distribution networks using different techniques including lightning-activated camera systems (e.g., [3]) or correlation using a time window and spatial distance criteria (e.g., [1]).

With particular reference to the latter methods, it has been shown that the effect of lightning events on power networks can be assessed by using distributed measurement systems recording the high frequency voltage transients associated with a lightning event (e.g., [1], [4]). As shown in [1], using the high frequency voltage transients, a high correlation between the events detected by lightning location systems (LLSs) and the sequence of protection relays operations was observed.

The mentioned research works are mainly dedicated to the assessment of the correlation between lightning events and power network failures rather than finding the flashover location. The knowledge of the flashover locations can provide valuable information to plan early maintenance for power utilities. Despite the importance of the problem of lightning location in transmission lines, research on this topic is quite scarce. A wavelet multiresolution-based analysis to locate the lightning strike point on a transmission line was presented in [5]. Another method to locate the lightning strike point was presented in [6], which is based on the time of arrival algorithm. This method requires synchronized measurements at each end of the transmission line.

The aim of this paper is to use the high frequency voltage transients associated with lightning events to identify the flashover location in the overhead transmission lines. Based on the Authors' previous experience on the use of the Electromagnetic Time Reversal (EMTR) theory (e.g., [7]) to identify different type of disturbances in EMC and power systems applications (e.g., [8]), in this paper the applicability of this theory to locate lightning-originated flashovers is explored.

The basic idea of the EMTR is to take advantage of the reversibility in time of the wave equations [9], [10]. It was shown that, when electromagnetic transients observed in specific observation points are time-reversed and back-injected into the system, or in a simulated version of it, they will converge to the original source location. More specifically, the back-injected signals are focused on the original source that has originated the transients.

Recently, EMTR has been successfully applied to various fields of electrical engineering [8], in particular to locate lightning discharges [11] and faults in power networks [10] [12], [13]. In this paper, we investigate the applicability of the EMTR theory to locate lightning-originated flashovers in power networks. Similar to [12], the method is composed of three steps: (1) measurement of the electromagnetic transient generated by the flashover/lightning event; (2) simulation of the back-injection of the time-reversed measured signals for different guessed flashover locations using a network model capable of representing traveling waves, and (3) identifying the flashover location by finding, in the network model, the point characterized by the highest energy concentration associated with the back-injected time-reversed fault current.

One of the main advantages of the proposed EMTR-based method is the fact that it requires only a single measurement point installed at the primary substation.

The structure of the paper is as follows. Section II explains the modeling hypotheses used for the electromagnetic transient

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(EMT) simulations. Section III summarizes the EMTR theory by making reference to the wave propagation in transmission lines. Section IV describes the flashover location method using EMTR. Section V presents the application case studies together with the performance assessment. Finally, Section VI concludes the paper with final remarks.

II. Modeling Hypotheses

The applicability of the EMTR method to locate flashovers is investigated by means of numerical simulation studies. To this end and in order to simulate the electromagnetic transient (EMT) behavior of the power systems components, the following analysis models and hypotheses are considered.

A. Transmission lines

For the EMT simulations of transmission lines, distributed-parameter line models are necessary to accurately simulate travelling wave propagation. Among different time-domain transmission line models, the constant-parameter model (CP) [14], frequency-dependent (FD) line model [15], and universal line model (ULM) [16] are the most common ones.

The FD line model uses rational function approximations of the characteristic admittance and propagation wave constant [15], [17]. For the case of multi-conductor transmission lines, a single real transformation matrix is used to convert modal and phase quantities. Compared to the CP model, FD model takes into account the frequency dependency of the line parameters (losses, propagation speed, and characteristic impedance) and better represents the travelling wave propagation for signals whose frequency spectrum extends to the MHz region. Therefore, in this study the FD line model is used. The line parameters have been inferred from typical geometries of 220 kV lines.

B. Transformers

For EMT studies which involves a frequency range between tens of kHz to few MHz, a high frequency model for the transformers has to be considered. As known, the high-frequency input impedance of power transformers can be represented, to a first approximation, by a capacitance (e.g., [18], [19]).

The typical values of transformers winding-to-ground capacitances are in the order of some nF [19]. Since electromagnetic transients originated by lightning flashovers are characterized by a spectrum with significant frequencies in the order of hundreds of kHz, the resulting transformer input impedances have magnitudes of some tens to hundreds of kΩ. For this study, the value of $Z_{\mathrm{TL}} = 10\ k\Omega$ is considered.

C. Surge arresters

As known, surge arresters are used to protect power networks against switching and lightning overvoltages by providing a low-impedance path to the current during the overvoltages. Compared to silicon-carbide (SiC) arresters, metal-oxide varistors (MOV) do not need a series gap and provide a highly nonlinear V-I characteristic.

Different modeling procedures can be used for the MOV arresters. A simple approach is to only use the V-I characteristic of the arrester. However, such model might not be accurate for the fast front surges and lightning studies since it does not take into account the parasitic parameters of this device [20]. Therefore, a dynamic model of the arrester is needed which has to consider its frequency dependent behavior. Among different dynamic models proposed in the literature, the one recommended by the IEEE WG.3.4.11 [20] provides efficient and accurate model for the EMT studies of the arresters and has been used in our simulations.

D. Lightning return stroke current

The lightning stroke is represented by a current source in parallel with a resistance. The value of the resistance is varied in the simulations, in the range of 400-1000 Ω.

The current source is modeled using Heidler function [21] using the following parameters:

$$\begin{aligned} I_0 &= 30kA \\ \tau_1 &= 19\text{E-}6 \\ \tau_2 &= 485\text{E-}6 \\ n_1 &= 10 \end{aligned} \tag{1}$$

These values reproduce the waveform of a first-stroke lightning current in accordance to the IEC62305/1. In particular, the adopted waveform is characterized by an amplitude that correspond to the median value of the lightning current distribution given in [22] and a maximum time derivative of 12 $kA/\mu s$.

E. Flashover

As described in [23], several flashover models for EMT simulations have been proposed. Among them, volt-time curves [24] and the leader progression model [25], [26] are the well-studied ones in the literature. The volt-time curves are obtained from the experimental tests by using standard lightning impulses. This model is a simplified approximation of the flashover and may not be accurate for all applications. To overcome the limitations of the volt-time model, the leader progression model has been proposed.

Leader progression models, also called leader development models, consider three different phases of the breakdown process of the air gaps, including corona inception, streamer and leader propagation.

Thus, the time of the flashover is defined by the following expression [27]:

$$t_f = t_c + t_{st} + t_l \tag{2}$$

where t_c is the corona inception time, t_{st} is the streamer propagation time, and t_l is the leader propagation time.

When the voltage level reaches a certain threshold (and therefore the associated electric field), streamers start to propagate from a rod (electrode) into the air gap. When the streamers bridge the gap, the propagation process is completed and a channel is established between the extremities of the gap. Ionizing waves propagate through this channel, and when these waves reach the zone near the electrodes, the leader starts to develop. If the voltage is high enough and also its duration is long enough, the leader interconnects the gap and a flashover occurs.

Based on this principle, several models have been proposed in the literature (e.g., [25], [26]). The main difference is the way to compute the leader velocity which the key element in this model.

In this paper, the flashovers are simulated using the air gap leader model of the EMTP-RV. This model allows the selection of the gap configuration (rod-rod, insulator string) and takes into account the pre-discharge current. The model is based on the Shindo-Suzuki method [26].

III. Review of EMTR Theory

Time Reversal can be thought as a process that reproduces the past behavior of a system in the future [9]. In order to do so, the equations describing the system behavior have to be time reversal invariant. In other words, if *f*(*t*) is a given solution of the systems differential equations, then *f*(-*t*) must also be a solution. In the case of electromagnetic wave propagation in transmission lines, this criterion implies that the Telegrapher's equations describing the wave propagation along transmission lines have to be time-reversal invariant. Let's consider the Telegrapher's equations for a lossless single-conductor transmission line above a perfectly conducting ground:

$$\frac{\partial v(x,t)}{\partial x} + L'\frac{\partial i(x,t)}{\partial t} = 0 \qquad (3)$$

$$\frac{\partial i(x,t)}{\partial x} + C'\frac{\partial v(x,t)}{\partial t} = 0 \qquad (4)$$

where $v(x,t)$ and $i(x,t)$ are voltage and current waves along the line, and where L' and C' are the per-unit-length inductance and capacitance of the line, respectively. By applying the time reversal operator, we get:

$$\frac{\partial v(x,-t)}{\partial x} + L'\frac{\partial i(x,-t)}{\partial(-t)} = 0 \qquad (5)$$

$$\frac{\partial i(x,-t)}{\partial x} + C'\frac{\partial v(x,-t)}{\partial(-t)} = 0 \qquad (6)$$

Comparing the two sets of equations, to mathematically guarantee the time reversal invariance of equations (5) and (6), there is a need to change of the sign of the current $i(x,-t)$. Nonetheless, this negative sign has a physical meaning and is due to the fact that when the direction of time is reversed, the velocity of the charges changes sign. As a result, the associated current density should change sign as well [28].

Therefore, using time-reversal invariance of the Telegrapher's equations, the EMTR process can be applied to reproduce a past event (e.g., fault, lightning, flashover) along the transmission lines in the future. Using this particular property, an efficient method to locate lightning discharges [11] and faults in power networks [12] have been proposed. In this paper, we explore the possibility of applying EMTR process to locate direct lightning strikes or flashovers subsequent to the lightning strike in the transmission lines.

IV. EMTR-Based Locating Method

The method to locate flashovers is the one proposed in [12] (for the location of faults) and is reported here for the reader's convenience. The method is composed of three steps:

I. The voltage(current) transient signals originated by the lighting strike or the flashover are recorded in the given observation point in the network:

$$s_i(t), \quad t \in [t_f, t_f + T] \qquad (7)$$

where $s_i(t)$ is the voltage (current) transient signal on conductor *i*, t_f is the acquisition triggering time subsequent to the event, and *T* is the recording time window.

II. Since, the main unknown is the location of the strike or the flashover, a set of a-priori guessed locations are defined:

$$x_{f,m}, m = 1,\ldots K \qquad (8)$$

The transient signals recorded in step I are time-reversed and, for each $x_{f,m}$, the network back-propagation model is simulated by back-injecting the time-reversed signals from the same observation point.

III. As predicted by the Time Reversal theory, the back-propagated signals will focus in the source point which will result in the highest energy concentration at this point. Therefore, for each $x_{f,m}$ the Fault Current Signal Energy (FCSE) that corresponds to the energy of the currents flowing through the $x_{f,m}$ is computed:

$$\text{FCSE}(x_{f,m}) = \sum_{j=1}^{N}\left[i_{x_{f,m}}(j)\right]^2, \quad T = N\Delta t \qquad (9)$$

where *N* is the number of samples and Δt is the sampling time.

According to the time reversal theory, the FCSE is maximized at the real fault location. Thus, the maximum of the calculated FCSEs will indicate the real event point:

$$x_{f,real} = \arg\Big|_{x_{f,m}} \max\left\{(\text{FCSE}(x_{f,m}))\right\} \qquad (10)$$

The flowchart of the location method is shown in Fig. 1.

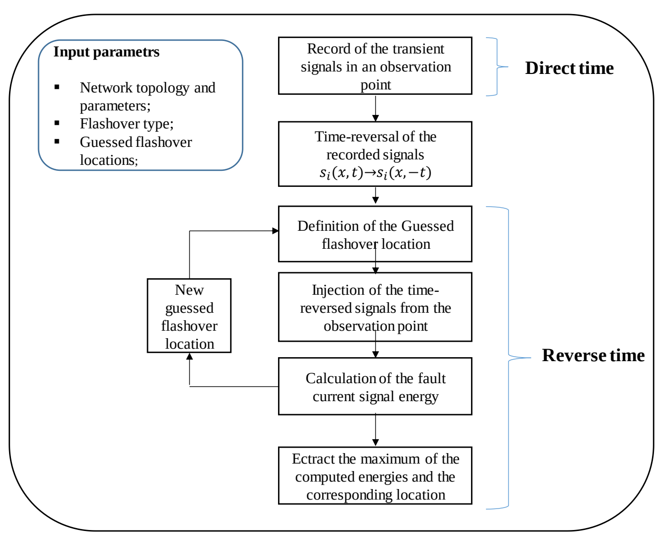


Fig. 1. Flowchart of the flashover location method.

V. Application Case Studies

In the following simulation case studies, the aim is to identify the flashover location subsequent to a lightning strike. To this end, the performance of the proposed method is evaluated by considering three different power network configurations and different flashover scenarios. In addition, the impact of the surge arresters on the performance of the EMTR-based flashover location is evaluated.

A. Configuration”1” - Single flashover in one phase

In this example, a 220kV transmission line is considered which is composed of three phase conductors and one shield. The network topology is shown in Fig. 2. The line length is 14 km and the line is terminated at both ends on power transformers. In this case, a direct lightning is supposed to strike the line on a tower located at 7 km, causing a flashover on the insulator string of the phase *a* on the struck tower.

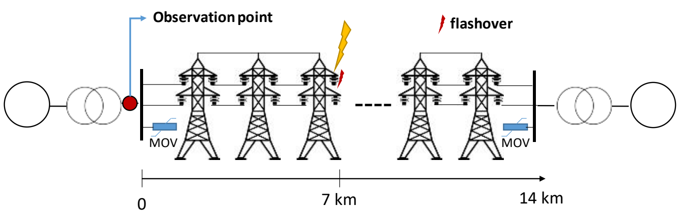
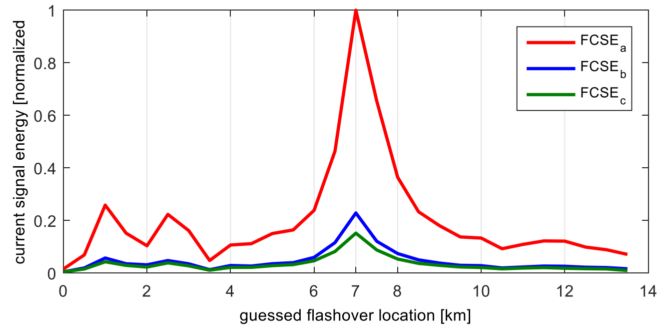


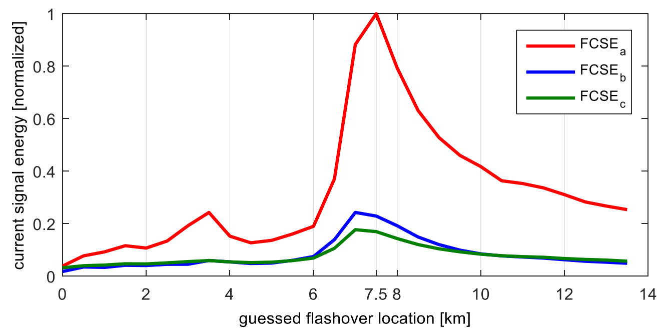
Fig. 2. Schematic of the Configuration”1” composed of a single transmission line.

The flashover and the injected lightning return-stroke current generate transient signals, which travel along the transmission line. These transient signals are recorded in a single observation point located at x=0. After time reversing the recorded signals, in agreement with the proposed procedure, the time-reversed signals are back injected by simulation into the line model, considering different positions for the guessed flashover along the line.

Fig. 3 (a) and (b) show the energy of the fault current signal as a function of the guessed flashover location for the cases without and with surge arresters, respectively. The energies are calculated for all the three phases and are normalized based on the maximum of the faulty phase (i.e., phase *a*). From Fig. 3 (a), the flashover location (i.e., 7 km) can be clearly identified. In other words, the current signal energy reaches a maximum vaue at 7 km which corresponds to the real flashover location. However, as it can be observed in Fig. 3 (b), the presence of the surge arresters introduces an error of about 500m in the flashover location (which corresponds to one pole displacement) due to the nonlinear behavior of the surge arresters that impacts the hypotheses of the EMTR given in Section III (i.e., time-reversal invariance of wave equations). As a matter of fact, the presence of a surge arrester introduces a non-linear behavior in the line terminations that changes the reflection coefficients of the voltage/current waves.



(a)



(b)

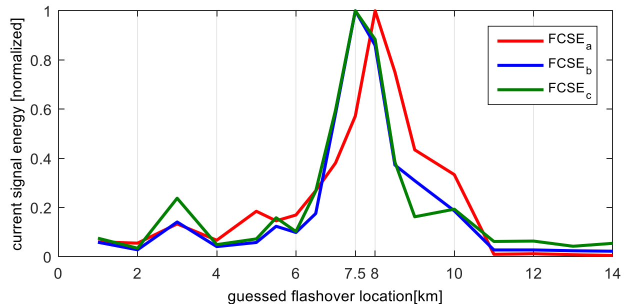
Fig. 3. Normalized energy of the fault current signal as a function of the guessed flashover location. The flashover location is at 7 km and it occurs only in phase *a*. (a) without surge arresters, (b) with surge arresters.

B. Configuration”1” - Multiple flashovers in locations other than the lightning strike

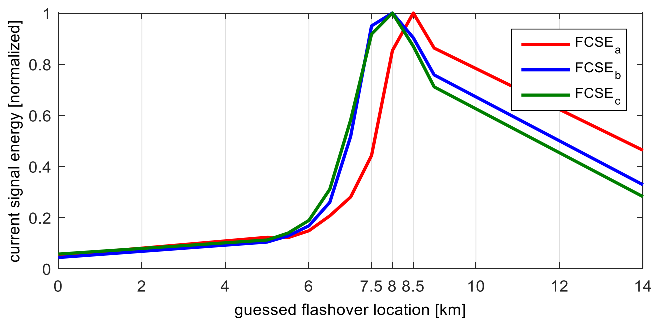
As known, the electric discharge is a probabilistic phenomenon and is a function of several factors including voltage level, air gap, humidity, and presence of other substances in the air. Therefore, a lightning strike at a given point might cause multiple flashovers at different locations.

In this example, we consider the same network topology of the previous case (Configuration 1) and we suppose a scenario in which the lighting strikes directly the line on the tower at 7.5 km. The following sets of flashovers subsequent to this lightning strike are considered: phase *a* at 8 km; phase *b* at 7.5 km and phase *c* at 7.5 km.

For this case, Fig. 5 (a) and (b) show the energy of the current signal as a function of guessed flashover location, for the cases without and with the presence of the surge arresters at the substations, respectively. Fig. 5 (a) shows that when surge arresters are not present, the exact flashover location is identified by the EMTR method. It can also be observed that the maximum of the energy for each phase, is exactly at the location where the flashover has occurred on that phase. As shown in Fig. 5 (b), the presence of the surge arresters leads in one pole (500m) location error for the phase *a*.



(a)



(b)

Fig. 5. Normalized energy of the fault current signal as a function of the guessed flashover location. The flashover occurs in all phases at different locations. (a) without surge arresters, (b) with surge arresters.

C. *Configuration "2" - Single flashover in one phase*

In order to better evaluate the performance of the method, in this example a more complex power network configuration is considered (see Fig. 6).

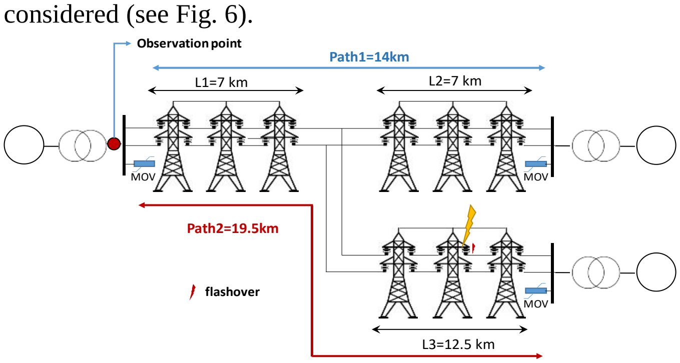
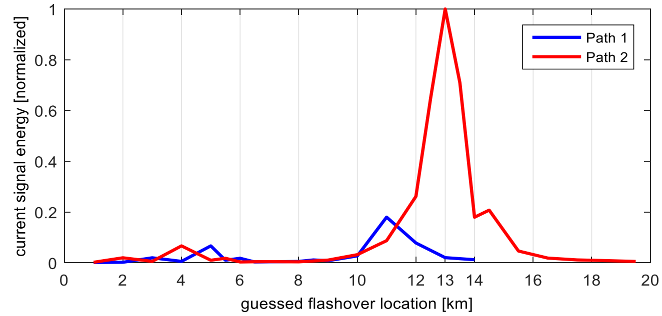
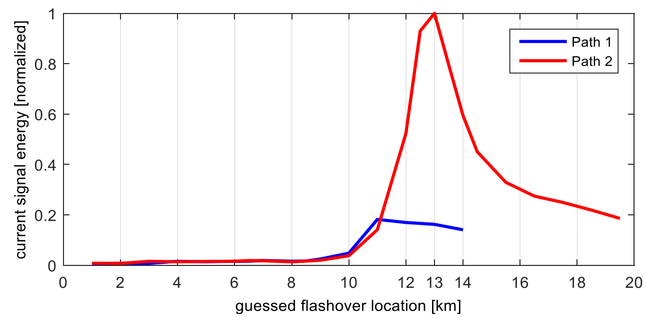


Fig. 6. Schematic of Configuration "2" composed of three transmission lines.

A lightning flash strikes directly the phase conductor *a*, at 6 km along L3. This causes a flashover at the insulator of the phase *a* at the same location. The observation point is located at the main substation and in order to calculate the current signal energy, two paths along the lines are considered as shown in Fig. 6 and the current signal energies are calculated for different guessed flashover locations along these two paths. Fig. 7 (a), (b) show the energies as a function of guessed locations for the considered two paths, without and with the presence of the surge arresters, respectively. From (a) and (b) the maximum value is at 13 km of Path 2 which corresponds to the real flashover location. In addition, in this case the presence of the surge arresters does not influence the accuracy of the method.



(a)



(b)

Fig. 7. Normalized energy of the fault current signal as a function of the guessed flashover location. The flashover location is at 6 km along path 2 (reference Fig. 6) and it occurs only on phase a. (a) without surge arresters, (b) with surge arresters.

D. *Configuration "3" - Single flashover in one phase*

In this example a power network composed of three parallel lines is considered. The schematic of this network is shown in Fig. 8 and a single observation point located at the left side is considered.

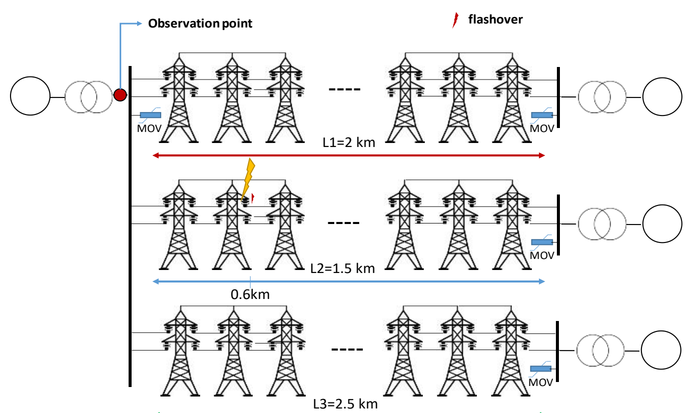


Fig. 8. Schematic of the configuration "3" composed of three parallel lines

A lightning strikes the tower top at 0.6 km of Line 2 which results in multi-phase flashovers at the insulator of the struck tower. The EMTR-based location method is applied by using the transient signals recorded at the observation point. These signals are time reversed and back-injected into the system model for different guessed flashover locations in the back-propagation simulations. Fig 9 (a), (b), and (c) show the current signal energy as a function of guessed locations for phases *a*, *b*, *c*, respectively and without considering the surge arresters. The results show that for all the phases the maximum energy is at the flashover location (i.e., 0.6 km).

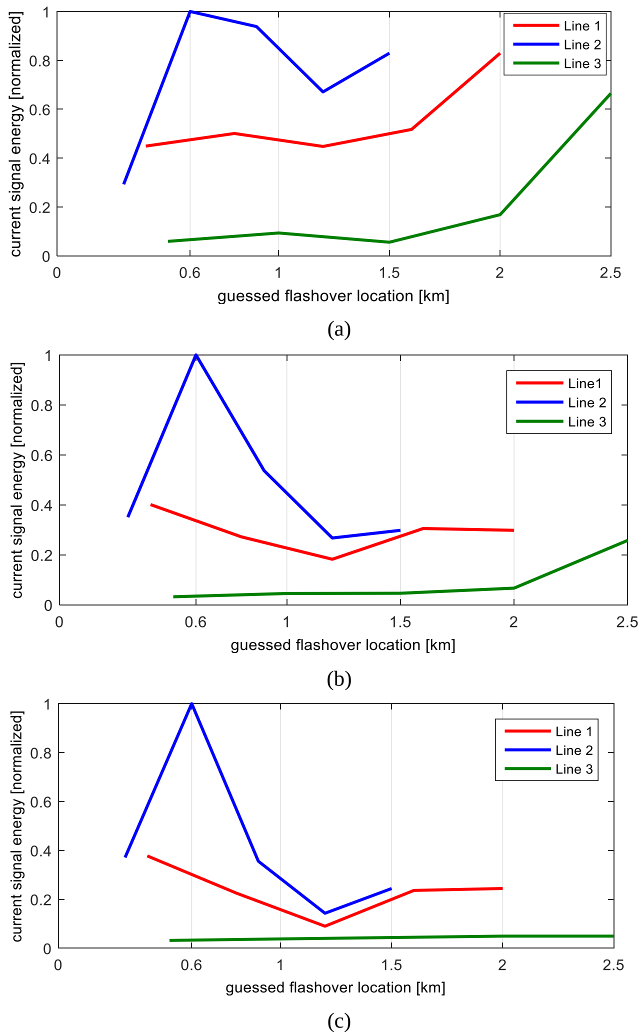


Fig. 9. Normalized energy of the fault current signal as a function of the guessed flashover location for phase *a*, *b*, *c*, respectively. The flashover location is at 0.6 km of Line 2 (reference Fig. 8) and it occurs on all phases. The network is simulated without considering the surge arresters at the substations.

The same case is simulated again by considering the presence of surge arresters at the substations. Fig 10 (a), (b), and (c) show the current signal energy as a function of guessed locations for phases *a*, *b*, *c*, respectively. For this case, the presence of surge arresters does not affect the accuracy of the EMTR flashover location. However, the quality of the provided results (the ratio between the energy at the real location to the other guessed locations) is deteriorated due to the nonlinear behavior of the arresters.

A. Impact of the ground resistivity

To study the impact of the ground resistivity on the accuracy of the proposed flashover location method, the same case study related to the configuration 1 (Fig. 2) was simulated again by assuming values for the ground resistivity of 10, 100, and 1000 Ohm-m. Similar to the previous case study, a direct lightning is supposed to strike the line on a tower located at 7 km, causing a flashover on the insulator string of the phase *a* on the struck tower. By applying the location procedure, and by considering the three assumed values for the ground resistivity, the current signal energy of phase *a* was calculated (see Fig. 11).

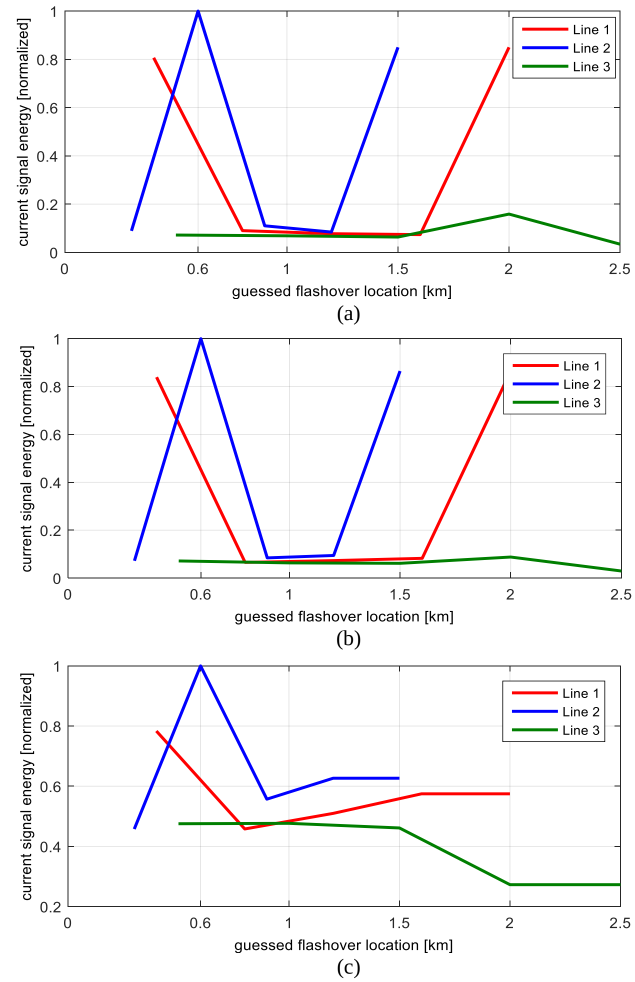


Fig. 10. Normalized energy of the fault current signal as a function of the guessed flashover location for phase *a*, *b*, *c*, respectively. The flashover location is 0.6 km of line 2 (reference Fig. 8) and it happens in all phases. The surge arresters are considered.

As it can be observed, the value of the ground resistivity does not impact the precision of the location method. For all the considered values, the maximum of the current signal energy occurs at the real flashover location (i.e., 7km).

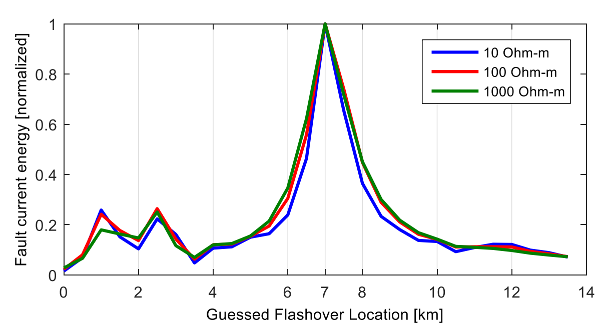


Fig. 11. Normalized energy of the fault current signal as a function of the guessed flashover location for phase *a* for three different ground resistivities. The flashover location is 7km (reference Fig. 2). The surge arresters are not considered.

B. Impact of the transformer model

In the previous case studies, the transformers were modeled with a high input impedance. As discussed in Section II-B, this approximated model relies on the assumption that the high-frequency input impedance of power transformers can be represented, in a first approximation, by a very small capacitance. Nonetheless, to study the impact of the frequency-dependent transformer model on the accuracy of the method, the same case study configuration 1 (Fig. 2) was simulated by considering the frequency-dependent model of the transformer. This aspect is simulated using the Frequency-dependend branch (FDB) model available in EMTP-RV (the data for the fitting are characteristic ones for HV transformers). By comparing Fig. 12 and Fig. 3 (a), it can be observed that the approximate transformer model is sufficient for this application.

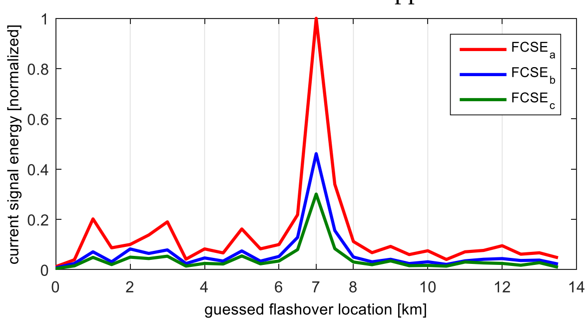


Fig. 12. Normalized energy of the fault current signal as a function of the guessed flashover location for all the phases. The flashover location is at 7 km (reference Fig. 2). A frequency-dependent transformer model is considered.

VI. Conclusion

The applicability of the electromagnetic time reversal method to locate lightning-originated flashovers in transmission lines was investigated. The method relies on the lightning-originated voltage transients measured at a single observation point assumed to be located in a primary substation. The recorded signals are then time-reversed, and by considering different guessed locations, are back-injected into the system model for each guessed location. The energy of the fault current through the guessed location is used as a metric to identify the flashover location.

The performance of the proposed method is validated using different power network topologies and considering various flashover scenarios. In addition, the impact of the surge arresters, the ground resistivity, and the transformer frequency-dependent model on the accuracy of the method are analyzed. The simulation results have confirmed the applicability of the EMTR to identify the location of flashovers for different, yet realistic power network configurations.

Future work is needed to assess the applicability of the method to identify multiple flashovers along multiple poles.

References

[1] F. Napolitano, A. Borghetti, M. Paolone, and M. Bernardi, "Voltage transient measurements in a distribution network correlated with data from lightning location system and from sequence of events recorders," *Electr. Power Syst. Res.*, vol. 81, no. 2, pp. 237–253, 2011.

[2] A. Borghetti, C. A. Nucci, M. Paolone, and M. Bernardi, "A Statistical Approach for Estimating the Correlation between Lightning and Faults in Power Distribution Systems," in *2006 International Conference on Probabilistic Methods Applied to Power Systems*, 2006, pp. 1–7.

[3] P. Barker and C. W. Burns, "Photographs helps solve the distribution lightning problems," *IEEE Power Eng. Rev.*, vol. 13, no. 6, pp. 23–26, Jun. 1993.

[4] K. Yamabuki, A. Borghetti, F. Napolitano, C. A. Nucci, M. Paolone, L. Peretto, R. Tinarelli, M. Bernardi, and R. Vitale, "A distributed measurement system for correlating faults to lightning in distribution networks," in *5th International Symposium on High Voltage Engineering*, 2007.

[5] D. Chanda, N. K. Kishore, and A. K. Sinha, "A Wavelet Multiresolution-Based Analysis for Location of the Point of Strike of a Lightning Overvoltage on a Transmission Line," *IEEE Trans. Power Deliv.*, vol. 19, no. 4, pp. 1727–1733, Oct. 2004.

[6] R. E. Jimenez and J. G. Herrera, "Location of direct lightning impacts to overhead transmission lines by means of a time of arrival algorithm," in *2012 North American Power Symposium (NAPS)*, 2012, pp. 1–6.

[7] J. de Rosny, G. Lerosey, M. Fink, J. De Rosny, G. Lerosey, and M. Fink, "Theory of Electromagnetic Time-Reversal Mirrors," *IEEE Trans. Antennas Propag.*, vol. 58, no. 10, pp. 3139–3149, Oct. 2010.

[8] F. Rachidi, M. Rubinstein, and M. Paolone, *Electromagnetic Time Reversal: Application to EMC and Power Systems*. Wiley, 2017.

[9] M. Rubinstein, F. Rachidi, and M. Paolone, "Time Reversal: A Different Perspective," in *Electromagnetic Time Reversal: Application to Electromagnetic Compatibility and Power Systems*, Wiley, 2017.

[10] R. Razzaghi, G. Lugrin, M. Paolone, and F. Rachidi, "Electromagnetic Time Reversal Applied to Fault Location in Power Networks," in *Electromagnetic Time Reversal: Application to Electromagnetic Compatibility and Power Systems*, Wiley, 2017.

[11] G. Lugrin, N. M. Parra, F. Rachidi, M. Rubinstein, and G. Diendorfer, "On the Location of Lightning Discharges Using Time Reversal of Electromagnetic Fields," *IEEE Trans. Electromagn. Compat.*, vol. 56, no. 1, pp. 149–158, Feb. 2014.

[12] R. Razzaghi, G. Lugrin, H. M. Manesh, C. Romero, M. Paolone, and F. Rachidi, "An Efficient Method Based on the Electromagnetic Time Reversal to Locate Faults in Power Networks," *IEEE Trans. Power Deliv.*, vol. 28, no. 3, pp. 1663–1673, Jul. 2013.

[13] R. Razzaghi, G. Lugrin, F. Rachidi, and M. Paolone, "Assessment of the Influence of Losses on the Performance of the Electromagnetic Time Reversal Fault Location Method," *IEEE Trans. Power Deliv.*, pp. 1–1, 2016.

[14] L. Bergeron, *Du coupde bélier en hydraulique au coupde foudre en électricité*. Paris, Frnace: Dunod, 1949.

[15] J. Marti, "Accurate Modelling of Frequency-Dependent Transmission Lines in Electromagnetic Transient Simulations," *IEEE Trans. Power Appar. Syst.*, vol. PAS-101, no. 1, pp. 147–157, Jan. 1982.

[16] A. Morched, B. Gustavsen, and M. Tartibi, "A Universal Model for Accurate Calculation of Electromagnetic Transients on Overhead Lines and Underground Cables," *IEEE Trans. Power Deliv.*, vol. 14, no. 3, pp. 1032–1038, Jul. 1999.

[17] A. Semlyen and A. Dabuleanu, "Fast and Accurate Switching Transient Calculations on Transmission Lines with Ground Return using Recursive Convolutions," *IEEE Trans. Power Appar. Syst.*, vol. 94, no. 2, pp. 561–571, Mar. 1975.

[18] "IEEE Std. C37.011, IEEE Application Guide for Transient Recovery Voltage for AC High-Voltage Circuit Breakers." p. 2005.

[19] A. Greenwood, *Electrical transients in power systems*. New York: John Wiley and Sons, 1991.

[20] "Modeling of metal oxide surge arresters," *IEEE Trans. Power Deliv.*, vol. 7, no. 1, pp. 302–309, 1992.

[21] F. Heidler, "Analytische Blitzstromfunktion zur LEMP- Berechnung," in *18th Int. Conf. Lightning Protection*, 1985, pp. 63–66.

[22] R. B. Anderson and A. J. Eriksson, "Lightning parameters for engineering application." Electra, p. No. 69, 1980.

[23] A. De Conti, A. F. M. Campos, F. H. Silveira, J. L. C. Lima, and S. E. Costa, "Calculation of lightning flashovers on distribution lines," in *2011 International Symposium on Lightning Protection*, 2011, pp. 205–210.

[24] J. H. Hagenguth, "Volt-Time Areas of Impulse Spark-Over," *Trans. Am. Inst. Electr. Eng.*, vol. 60, no. 7, pp. 803–810, Jul. 1941.

[25] C. F. Wagner and A. R. Hileman, "Mechanism of Breakdown of Laboratory Gaps," *Trans. Am. Inst. Electr. Eng. Part III Power Appar. Syst.*, vol. 80, no. 3, pp. 604–618, Apr. 1961.

[26] T. Shindo and T. Suzuki, "A New Calculation Method of Breakdown Voltage-Time Characteristics of Long Air Gaps," *IEEE Power Eng. Rev.*, vol. PER-5, no. 6, pp. 65–66, Jun. 1985.

[27] "Modeling guidelines for fast front transients," *IEEE Trans. Power Deliv.*, vol. 11, no. 1, pp. 493–506, 1996.

[28] F. Rachidi and M. Rubinsein, "Time reversal of electromagnetic fields and its application to lightning location," in *2013 International Symposium on Lightning Protection (XII SIPDA)*, 2013, pp. 378–383.