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# Locating lightning strikes and flashovers along overhead power transmission lines using electromagnetic time reversal

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ABSTRACT

The paper presents a method to identify the location of direct lightning strikes to overhead transmission lines and potential subsequent flashover(s). The method is based on the electromagnetic time reversal theory and relies on the use of a single measurement point to record voltage transient signals originated by a direct lightning strike either on the phase conductors or shielding wires, and possible flashovers. The measurement system is supposed to be installed on the secondary winding of the transformer located at the line feeding substation. The performance of the proposed method, applicable for different power network topologies, is validated by using different numerical simulations applied to various case studies. The paper also discusses the impact of the grounding system model, high-frequency transformer model, presence of surge arresters as well as soil electrical parameters.



## 1. Introduction

Restrictive requirements of both reliability and power quality in modern electrical networks have increased the attention towards the impact of weather-related failures in power systems [1]. It is generally acknowledged that weather factors can impact the quality of service and can have significant cost consequences for the network utilities (e.g., [2]). Among various natural factors such as wind, rain, falling trees, etc., lightning is the exogenous source to power systems having the largest contribution to outages and unscheduled maintenance in power networks [3]. Reliability studies have identified a clear correlation between lightning and power systems outages (e.g., [4]).

The correlation between faults and lightning events has been widely investigated in the literature for both transmission lines and distribution networks using different techniques such as lightning-activated camera systems (e.g., [5]) and correlation using a time window and spatial distance criteria (e.g., [6]). 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., [6,7]). As shown in Ref. [6], 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.

In addition to the importance of the studies related to the correlation between lightning events and power network failures, the knowledge of the strike and flashover locations can provide valuable information to plan early maintenance for power utilities. In this respect, the high frequency voltage transients originated by a lightning disturbance can also be used to identify the location of the disturbance.

Major concerns associated with direct or indirect lightning strikes are related with the associated temporary overvoltages since they may result in insulation failures such as flashover in insulator strings [8]. In particular, in the case when a return stroke terminates on the shield wire, back-flashovers may occur if the tower-footing grounding system does not provide a sufficiently low impedance path to the lightning current. The subsequent overvoltages result in insulation ageing or deterioration of the network components. Early identification of those incident locations can reduce significantly the inspection, maintenance and repairing time.

The research on this topic is quite scarce and a summary of existing works in this subject is here provided. A wavelet

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multiresolution-based analysis to locate the lightning strike location on a transmission line was presented in Ref. [9]. However, the proposed method is not straightforwardly applicable to power networks with complex topologies. Another method to locate lightning strike locations based on the time of arrival algorithm was presented in Ref. [10]. This method requires multiple and time-synchronized measurements at each end of the transmission line.

Within the above-described context, the aim of this paper is to process the high-frequency voltage transients associated with lightning events to identify the flashover and direct lightning strike location in the overhead power transmission lines. More specifically, Authors of this paper have already presented a preliminary analysis in Ref. [11] on the possibility of using the Electromagnetic Time Reversal (EMTR) theory (e.g., [12]) to locate lightning-originated flashovers. The basic idea of the EMTR is to take advantage of the reversibility in time of the wave equations [13,14]. 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 precisely, 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 [15], in particular to locate lightning discharges [16] and faults in power networks [10,17,18]. In this paper, we explore the applicability of the EMTR theory to locate lightning-originated flashovers and direct lightning strikes in power networks. The current paper aims at discussing more in detail the method presented in Ref. [11], and providing its extension to locate both lightning strikes as well as flashover locations. In addition, more accurate tower-footing and substation grounding systems are considered, and the influence of the grounding system and ground electrical parameters is analysed.

The structure of the paper is as follows. Section 2 summarizes the EMTR theory by making reference to the wave equations in transmission lines. Section 3 explains the proposed method to locate lightning-originated disturbances in the network. Section 4 describes the modelling hypotheses used for the electromagnetic transient (EMT) simulations. Section 5 presents the simulation case studies together with the performance assessment. Section 6 discusses the sensitivity of the proposed method with respect to different parameters and modeling approaches. Finally, Section 6 concludes the paper with final remarks.

## 2. EMTR theory

### 2.1. Time reversal and electromagnetic time reversal theory

The first experiment using time reversal (TR) was first reported by B. Bogert of Bell Labs in 1957 who introduced the TR as a technique to compensate the delay distortion of slow pictures and television signals in wired lines [19]. Later, Mathias Fink et al. presented the TR concept as a new approach for focusing ultrasonic waves (e.g., [20–23]). The TR process can be understood by considering the concept of *Time Reversal Cavity* (TRC) where an acoustic or electromagnetic source, placed within a given propagative medium, is surrounded by a closed surface and the associated generated field(s), and its (their) normal derivative(s), are measured at all points of the closed surface [21]. The procedure consists of two stages: (a) the field is recorded by the transducers which cover completely the cavity surface; (b) the recorded signals are time-reversed and re-injected back into the medium from the cavity transducers. The back-injected field will be a time-revered copy of the fields in the first stage and refocuses back to the initial source point. In principle, in order to effectively focus the back-injected waves to the source point, the process should be performed in the whole space. It has been shown, however, that the refocusing can be still achieved by using limited number of transducers [21], or even using a single transducer for closed reflective medium (e.g., [24]). Therefore, the time-reversal cavity can be reduced by a Time Reversal Mirror (TRM) in which the time-reversal operation is only performed on a limited angular area and a small part of the field radiated by the source is captured and time reversed.

Twelve years after the development of the concept of TRM, its application was successfully extended to electromagnetic waves (e.g., [25]).

It is worth noting that TR process can be interpreted as a time and space correlator [26]. The latter property of the TR can be exploited to estimate the location of a disturbance or to re-create the original source in the medium. With particular reference to the power system applications, the space correlation feature enables the definition of new procedures to locate disturbances such as faults or lightning disturbances. In the next subsection, the applicability of the EMTR theory for power system applications will be explained.

### 2.2. Time reversal invariance and wave propagation along transmission lines

Time reversal invariance is a key concept in the TR process. To explain it, we consider a generic system governed by classical wave propagation equations in which transportation phenomena are taking place. Consider $f(t)$ to represent the evolution of a physical quantity as a function of time for the time period $t \in [t_0, t_0 + T]$. After having imposed appropriate initial conditions on the original system, we consider the back-propagation phase in which the $f(t)$ propagates backward in time. If the system is able to retrace its previous states, the system is time reversal invariant [13].

Mathematically speaking, time reversal operator is given by:

$$t \to -t \tag{1}$$

Then, for the case of equations describing the physical phenomena, time reversal invariance means that if $f(t)$ is a solution of the system equations, the TR function $g(t)$ given by Eq. (2) is also a solution.

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

Note that $T$ is added to the time vector to ensure the system causality. With particular reference to the Telegraphers equations describing the voltage wave propagation along multi-conductor lossless transmission lines, the voltage wave equation reads:

$$\frac{\partial^2}{\partial x^2}\mathbf{U}(x,t) - \mathbf{LC}\frac{\partial^2}{\partial t^2}\mathbf{U}(x,t) = 0 \tag{3}$$

where $\mathbf{U}(x, t)$ is the vector of the conductors' voltages at time $t$ and position $x$, and $\mathbf{L}$ and $\mathbf{C}$ are, respectively, the matrices of the line per-unit-length inductance and capacitance. Having a second-order time derivative means that if $\mathbf{U}(x, t)$ is a solution of the wave equation, $\mathbf{U}(x, -t + T)$ is a solution as well. This implies that the wave equation for a lossless system is time reversal invariant [17]. Note that, The EMTR-based lightning/flashover location method is equally applicable for lossy transmission lines. In Ref. [27] the impact of the losses on the performance of the EMTR fault location method is thoroughly discussed and assessed. More specifically, it is shown that for a lossy medium, both an inverted-loss model, as well as a lossy back-propagation model result in an accurate fault location. The reason is that even though a lossy back-propagation medium is not rigorously time-reversal invariant, in this model the propagation speed, which is the crucial parameter in the time reversal process, is identical to the direct-time model. As a consequence,