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Automatic lightning stroke location on transmission lines using data mining and synchronized initial travelling

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ABSTRACT

The automatic location of lightning stroke impact point on transmission lines is one of the most crucial factors related to the behavior of Electric Power Systems, which can improve the swift recovery of electric power. The usual location of this phenomenon has been based on distance protection relays, which requires operation times of approximately one cycle. This paper presents a high-speed protection approach for the lightning-caused transient automated location on transmission lines or on ground. This work is based on the synchronized initial voltage-travelling waves at both ends of high voltage transmission lines. Lightning strikes at different sections along the 220 kV transmission line are detected at both protection relays by using an algorithm based on the ellipsoidal pattern previously presented in another research project. That methodology uses the projection of original signals. Thus, if these signals are located along the ellipsoidal pattern, the electric power system is operated under normal conditions. Unlike the aforementioned case, if the projected signals are located outside of the ellipsoidal pattern, it represents the presence of lightning strokes. After those signals are detected, initial voltage traveling waves measured by protection relays located at both ends of the transmission line are used in order to localize the lighting stroke impact point. At the instant that a lightning stroke hits either on the phase conductor or the ground, travelling waves propagate along the transmission line. Later on, depending on the impact point of atmospheric discharges, different time instances, which the travelling waves require to arrive at their respective ends, are determined. These times are used to calculate the distance from the impact point to both protection relays. Therefore, this paper presents a concise simple methodology for lightning stroke location on transmission lines or ground based in data mining to perform the signal detection and travelling wave times to determine the location along the transmission line. Simulations of lightning stroke signals on a 220 kV transmission line are carried out in the Alternative Transients Program (ATP). The results show that the behavior of the work is swift and effective in order to locate the impact point, especially in situations where flash current values, inception angles, distances from the impact point to protection relays, direct and indirect lightning and other factors, are considered, since it is immune to flash currents and other features. Finally, the proposed work could be considered as an alternative routine for protection relay algorithms

1. Introduction

Electric Power Systems (EPS) constitute a crucial element for the development of a region. Transmission Lines (TLs) allow electric power supply to thousands of consumers such as hospitals, school, factories and others. Currently, EPS are modern, but must be more secure and reliable in order to guarantee adequate electric power service under outages caused by external or internal causes. TLs supply electric power to customers that generally are in an exterior environment. These elements are highly exposed to different conditions and phenomenon that can produce outages. Within this context, weather can cause damage to TL systems, producing service interruptions and possible outages, where system parameters such as voltage, current, frequency, must be regulated and controlled [1]. Thus, lightning strokes on TLs are manifested in two ways. First, when lightning hits directly on the transmission tower and the second when the lightning hits the ground and induces an overvoltage on the insulator strings. EPS are most vulnerable to

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weather conditions. In this context, it is highly desirable to improve the TL reliability. Thus, the device known as Protection Relay is crucial for the proper behavior of these devices. The main roles of relay are to induce the secure detection, classification, location of faults or disturbances produced by different causes.

Lightning strokes are the main cause of power line outages, imposing a crucial impact on the quality of the electric power supplied. Based on data analyzed from a regional worldwide bibliographical review, it allows authors to conclude that LS exert great influence on outages. For instance, from 1984 to 2006 in United States, more than 933 outages were reported, of which, lighting stroke represents the third major cause in outages produced [2]. See Fig. 1. Moreover, several countries have suffered serious consequences. One example is Austria, where by using a lightning location system (LLS), operators determined that lightning strokes directly affect overhead lines [3]. Analyzing the outages of 25 TLs of 220 kV and 440 kV, revealed that more than 205 outages were related to the lightning discharges [4]. Other cases demonstrating that electric power is susceptible to lightning phenomenon occurred in the southeastern Amazonia in the state of Pará, where frequent outages have been attributed to this phenomenon. Thus, different outages have been produced in the Brazilian network [5,6]. This zone has the highest flash peak current magnitude compared to anywhere else worldwide [7,8]. In addition, based on the report regarding the ten severest blackout events that affected the population, in Brazil, a lightning stroke on a substation in the state of Bauru–Sao Paulo caused several 440 kV circuits to trip. More than 65% of population suffers effects of this blackout [9].

On the contrary, atmospheric discharges were the most important cause in the blackout produced in New York City and Ontario in July 1997 and June 1998, respectively [10]. Several cases of outages where the lightning stroke have been the cause are presented in Refs. [11–18]. Corresponding to protection relays, one of the ten most severe blackout events was produced in Brazil in 02-April-2011. The cause was a failure in an element corresponding to part of protection system, affecting approximately fifty-three million people [19].

Therefore, lightning is clearly a significant influence on EPS behavior, which has been seriously considered by different countries in order to search for strategies and ideas that could incorporate smart grids, automatization and other measures that allow for increasing the reliability and reducing the outages of EPSs caused by hazardous weather [20]. In this context, international suggestions have been directional for reducing weather-related outages such as Tree-Trimming Schedules [21], Undergrounding of Distribution/Transmission Lines [22], Implementing Smart Grid Improvements [23,24] among others.

In addition, studies have estimated that weather effects have a big cost on the EPS, being cost around of billion dollars. Thus, it is crucial develop or propose new policies, plans, actions and others for reducing the impact of this phenomenon. On the other hand, it is important to make plans, methodologies and other measures in order to strengthen and improve everything related to the electrical system. Therefore, increase power flow capacity and provide the best control over power system could increase the performance of EPS, providing the first step to increase the system flexibility and robustness, which can reduce the risk of outages. In this context, energy management system researches in order to control monitor and conserving energy has been proposed, which are crucial to reduce line power wastage and improve the reliability of electric power [25–32].

An EPS operates in steady-state when the variables describing voltages, currents, and others are periodical functions of time. However, it can be in a transient-state when the variables are suddenly changed by any disturbance. It changes from one steady-state to another [33]. Usually, the transient process in TL is produced by lightning, switching operation, and other variables. After transient disturbances on TL are produced, these changes are followed by traveling waves, which at first approximation can be treated as step front waves. For instance, when a LS hits a TL wire conductor, the induced overvoltage wave tends to divide into two halves, each going in opposite directions. When a voltage wave arrives at any element, such as an insulator string, it can cause a stress distribution, which is not uniform and may lead to the breakdown of the insulator [34]. Thus, LSs can cause permanent or temporary faults on TLs, independently if it is direct or induced LS. Currently, the TL isolation level is highly affected by atmospheric discharges, where localizing the impact point of this phenomena is crucial to the proper behavior of EPS. This argument alone would caveat the importance of developing methodologies related to LS impact point location.

Based on research review, traditional protection schemes and also those based on travelling waves, have usually been proposed to determine the common fault direction, omitting LS signals, which are crucial to the performance of EPS. Additionally, due to advances of ultra-high frequency bandwidth equipment, microprocessors and other technology, research has led to proposing schemes based on traveling waves.

In the instances when a lightning bolt hits on a TL or the ground, the protection relay must localize the impact point of this phenomenon. However, at the moment those techniques could suffer from drawbacks due to lightning strokes, which are indicated as follows:

The basic principle of the protection relays is based on Fourier, which uses the movement of a sampling window to analyze and extract information of input signals. However, it is well known, that operation time of Fourier filters is dependent on the length of the sampling window. Its operation time is usually 1 cycle. Moreover, when high frequency transient signals caused by lightning strokes are present; sampling windows longer than 1 cycle could be necessary to remove those unwanted components. However, longer sampling windows delay the operation time of protection relays. Therefore, transmission line protection relays based on phasor estimation, such as the distance protection, cannot always operate correctly due to lightning stroke effects on transmission lines. At the moment, the operating time of these relays often reaches 50–70 ms for lightning strokes impact point location. Conversely, in order effect proper behavior of this relay like speed, security and other variables, adequate settings must be established.

The impedance protective relay determines the distance from the lightning impact point to location of installation of protection relay based on the calculated impedance. Of course, these devices must fix settings based on the recommendations by the manufacturer of protective devices.

In Ref. [35], an analysis of lightning location on real transmission lines belonging to the CEMIG (Brazilian Energy Utility), using distance protection relays is presented. The analysis was done by using Real Time Digital Simulations (RTDS^{TM}) at SIEMENS AG's facilities (Erlangen–Germany). In this analysis, different lightning stroke cases were used to analyze the behavior of the protection relays, specifically its operation time. In this context, the protection relay behavior regarding the operation time and location error is one on one short line (23.9 km) and one long line (148.6 km), constructed around the city of Belo Horizonte. 134 simulations of lightning strokes with different conditions were realized and testing with the RTDS. Table 1 presents some results of simulations on work presented in Ref. [35].

Based on the 134 simulation, it can be determined that the operation time range of protection relay in order to localize the lightning stroke is about 13.8 ms–45.7 ms, respectively.

Based on the work presented in Ref. [35], it is clear that operation time of distance protection relays in order to analyze and localize

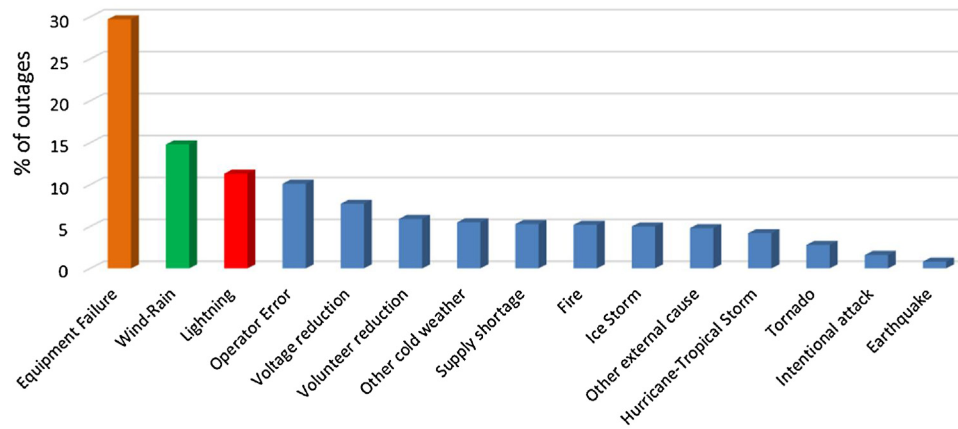


Fig. 1. Statistics of outages-causes in the United States of America [2].

Table 1
Distance protection relay behavior under lighting stroke.

Real position (km)	Determined position (km)	Trip time	Location error (km)
23.9	24.8	38.5 ms	0.9
11.95	12.9	16.6 ms	0.95
0	0	15.8 ms	0
148.6	149	41.1 ms	0.4
74.3	75.1	16.5 ms	0.8

lightning stroke is about 1 cycle, and some cases is approximately 3 cycles. On the contrary, the proposed research lightning stroke location reference is presented in Section 2.

Despite being aware of possible effects of lightning strokes on TLs, quick, accurate location of lightning stroke transient signals on TLs is extremely important for protection schemes. Accordingly, in order to develop a new protection methodology based on data mining and travelling waves, the main objective of this paper is to develop a novel protection methodology for lightning stroke on overhead TLs. Results show that the proposed work is capable of locating the impact point of lightning along the TL, providing adequate response of the protection relay, identifying the distance from ends to the impact point.

2. Bibliographic review on lightning stroke location

Because lightning stroke is one of the most damaging causes on TLs, development of methodologies, protection relay algorithms that on-line monitoring the transmission line could be an efficient way to prevent drawbacks. In this context, regarding the state of the art at the moment, the progress and development of new components, new communications or automatized systems can be used in order to modernize the protection relay algorithms, which can incorporate the information processing capabilities by using Signal Processing Techniques.

The main method widely implemented to distance relays uses the Fourier transform, while others are based on the correlation between the lightning location system-protection relay pick-up times. In addition, in recent decades, research, analyzing currents and voltage signals and applying machine learning have proposed new work in order to determine the lightning stroke location. It is necessary to note that, despite the significance papers on lightning stroke location, few articles were found that assessed or referenced estimates of the location of such. While several studies have proposed the methodologies for fault direction based on travelling waves, minimal research was found on the lightning impact point location. On the other hand, numerous features of lightning stroke have not been considered in previous research, which are crucial in order to analyze this phenomenon as real as possible.

At the beginning, Rockefeller was the pioneer who proposed the Digital Protection (DP), which had its origins not only in different papers proffered by Rockefeller, Mann and Morrison, but also with different field experiments [36–39]. Hence, Rockefeller proposed a protection relay in a substation. Nevertheless, since computers were very expensive then, Rockefeller used a very single, slow mini-computer to develop multiple protection relaying in the substation. However, in later years, computers became smaller, faster, and cheaper. Thus, smart Signal Processing Techniques (SPTs), especially focused on the signals analysis together with digital signal processors, data storage broad, fast communication, and others, new methodologies could be proposed. In this context, several research projects, not only assuming the disturbance signal to be sinusoidal [40,41] but also proposed protection algorithms based on the detection of signal peak values were proposed. However, this assumption is not always true, especially if one considers distortion due to transient signals especially to lightning strokes.

Instead, to solve those previous drawbacks, researchers took into account the signal non-sinusoidal nature and started to extract the fundamental component from fault signals [42,43]. Having stated the previous, currently, the most widely used protection relay for the lightning stroke location on transmission lines is the distance relay, which is based on the periodicity of the signals. It uses the movement of a sampling window to calculate the distance from the impact point of lightning to the end where protection devices are located. Its operation time is dependent on the length of the sampling window, which cannot be less than 1 cycle [35]. Still, that operation time has usually been used for disturbances whose frequency content is not very high, such as switching operations, common faults and others. On the other hand, since lightning stokes produce very high frequency components, sampling windows wider than 1 cycle could be necessary [35]. However, it is clear that the main aim of the protection relay is to detect, classify and localize the disturbance and initiate adequate action as quickly, as possible. Based on the aforementioned, it is possible to see that the traditional distance protection could have drawbacks in order to analyze lightning stroke signal related to the operation time and data windows.

Contrarily, researchers have proposed the use of the distance protection of the relay pick-up time, and the times of lightning stroke measured by lightning location system (LLS) in order to determine the lightning stroke location [44]. Thus, after lightning hits on the transmission line by using its pick-up disturbance detection time is determined. Then, a correlation between both times is calculated by using the LLS detection time around the TL, after lightning hits. However, as stated previously, the operation time of the traditional relays is in the 1 cycle range. In addition, results have shown that the average pick-up time of relays is 17 ms, approximately after the signal generation point, which could increase the operation time. An example of this correlation was applied to 110 kV transmission line, where distance protection relays registered pick-ups at 06:35:12.763 and 06:35:12.769 local time, and the LLS registered a lightning stroke at 06:35:12.754 local time. Thus, differences of time of LLS and protection relays were determined like 9 and 15 ms, respectively. Where, a location error of 900 m was determined.

Moreover, by using this procedure, the protection relays detect faults with time difference more than 25 ms after a lightning stroke. Also, average value between the lightning location and the lightning stroke location is more than 1.2% of total transmission line length, which affect the accuracy of the lightning locator.

In addition, these protection relays use basic or mother functions sine and cosine, which are precise to periodic, stationary and sinusoidal signal. However, lightning stroke signals could be widely transients, and these functions can be inadequate for accurate location of lightning stroke impact point.

On the contrary, based on the bibliographic review, protection schemes based on travelling waves, have usually been proposed to determine the common fault direction and other phenomena different to lightning stroke location. However, the impact point of the LS on TLs has not been considered. The LS can hit either on TL directly called direct LS or on the ground called induced LS. Independently if a direct or induced LS hits on the TL, these generate travelling waves that propagate from the impact point to both ends of the TL, where protection relays are located. In this context, in order to localize the impact point of the LS on TLs, very few approaches have been reported, applied usually to direct LSs, omitting induced LSs (LSs that hit on the ground).

In this context, Travelling-Wave Distance Protection (TWDP) first became possible with the development of digital protection algorithm and the advances in SPT. Hence, in Ref. [45], a distance protection algorithm based on single-ended travelling waves, which recognizes the wave returning from the transient signal point, was presented. The distance to the impact point is estimated by measuring the time it takes the initial wave to travel from the relay to the impact point and back. However, due to some parameters such as distortion and attenuation, multiple reflections at the branching points of the transmission lines, which are not defined, affect its performance. In this context, the work proposed in Ref. [46], is only effective to closed fault signals. Moreover, that methodology is applied to signals corresponding to common faults. Furthermore, in Ref. [47] an algorithm based on the increments in voltage and current signals given by wave reflection after a flash impact, is presented in order to determine the apparent resistance corresponding to the lightning signal. A characteristic of this algorithm is that in order to avoid remote reflections, subsequent estimations of resistance are calculated. Later on, in Ref. [48], the maximum likelihood estimation of the arrival times of reflected travelling waves produced by LSs was proposed as a novel single-ended algorithm. In Ref. [49], by using the correlation function method with the technique called k-nearest neighbors (K-NN) another algorithm was proposed. However, problems might occur in those previous algorithms when close-in lightning strokes that generate faults are analyzed.

Nevertheless, Signal Processing Techniques and Machine Learning have been used in order to localize the lightning stroke impact point. In Ref. [50], a hybrid method by using travelling waves and Continuous Wavelet Transform (CWT), a fault location system is proposed, which is effective only for specific faults, being widely affected for long transmission lines. In Ref. [51], by employing the Wavelet Transform on travelling waves, which uses time delays between modal components. However, its behavior is based on the sampling rate used. Unlike the previous research, in Ref. [52] an approach to lightning stroke location based on sensors located along the transmission lines, placed on the top of the towers, is proposed. This technique uses measurements from the sensors, which are placed in each transmission tower. By using the highest measured current value and its transmission tower number, the lightning stroke location is determined employing these previous values. However, it is necessary to place sensors at every tower, which depending of the transmission line length, can require hundreds of sensors.

In Ref. [53], by using Wavelet Multiresolution-Based Analysis, a function to lightning stroke location is proposed. The main characteristic of that work is the decomposition of the lightning stroke signal to the tenth level output generated by daubechies eight like the mother wavelet in the MRA. This uses data windows of 5 ms approximately, which is less than the distance protection relay one. However, in that work, the original signals are decomposed from the first to tenth level. Then, by using these levels empirically, the results were obtained. Nevertheless, in order to get the best performance, it is necessary to make test-error cases varying not only the decomposition level but also the mother wavelet.

In Ref. [54], by using data mining (Principal Component Analysis), direct lightning strokes are processed and their main features are extracted using that technique. That work uses lightning voltage and current signals of ¼ cycles registered by protection relays. From these signals, its eigenvalues and eigenvector are calculated, and then, the original signals are transformed to new axis corresponding to principal components, where a new impedance value is calculated. After all signals are projected to the new axes, it was possible to observe a correlation between these new impedance values and lightning stroke impact point. Thus, two functions applied to localize the impact point are determined. However, this methodology uses data windows less than traditional protection relays but higher than the travelling wave.

Based on the previous information, in order to localize impact point of lightning strokes on transmission lines, several approaches have been reported by researchers. Some of them achieved their practical implementation long ago; such as the distance protection relay and travelling wave, whereas others have been presented as well-funded research proposals based on alternative processing signals and machine learning, which could be considered as basic research.

In addition, the lightning stroke is a random phenomenon, which must be analyzed and studied considering the wide gamma of parameters like flash peak current magnitudes, positive and negative polarity, tower footing resistances (TFR), lightning stroke on transmission tower or on ground, and others [55,56]. Nonetheless, from bibliographic review it is possible to observe that previous researches omitted several parameters like the high flash currents range (10–200 kA), the footing resistance value and one polarity (10 Ω/positive are usually used). In addition, the lightning may hits on ground and induce transients on TL, which are necessary to detect and localize in order to avoid later effects.

3. Mathematical model

When a LS hits directly on a TL or on the ground and induces overvoltage, travelling waves tend to divide into two halves, which travel in opposite directions and are registered by the relays R_M and R_N placed at the TL, respectively [57]. See Fig. 2. In this context, it is imperative to detect the first instance after that lighting hit on a TL or it hits on ground and induces an overvoltage on insulator string.

Traditional protection relays calculate the impedance value using a convolution process. The analyzed signal is convolved

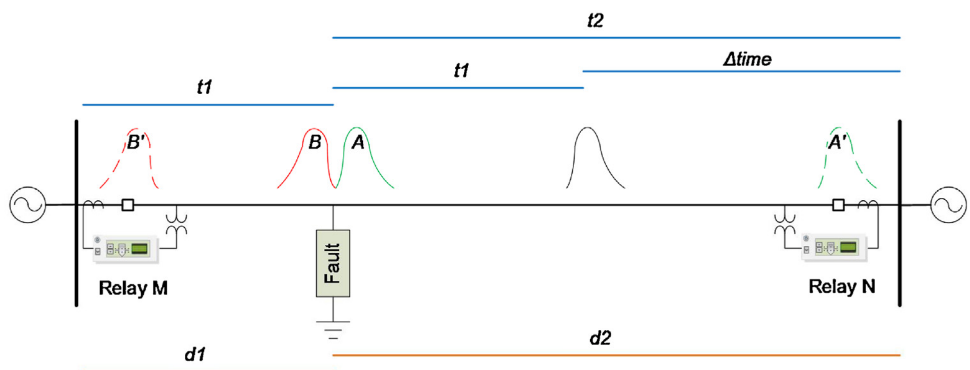
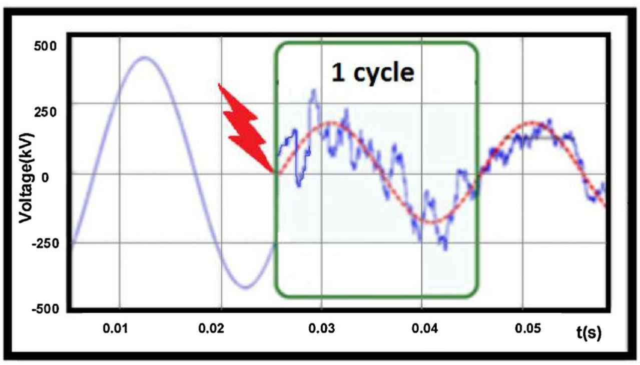
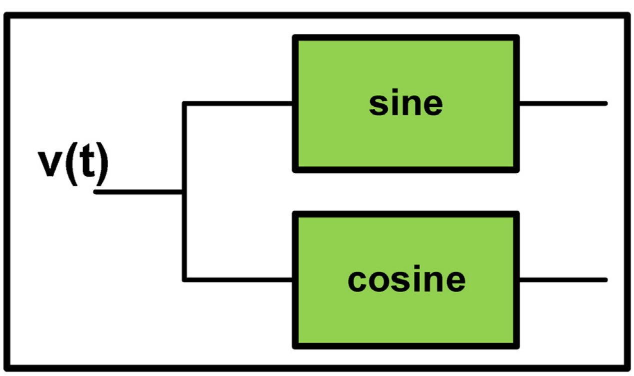


Fig. 2. Electric power system.



(a)



(b)

Fig. 3. (a) Lightning signal and convolution with mother function (sine), (b) convolution process. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

through a mother function (sine and cosine) and the phasor is calculated. Eqs. (1)–(3) present this issue.

$$v(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos(nw_0 t) + \sum_{n=1}^{\infty} b_n \sin(nw_0 t) \tag{1}$$

$$a_n = \frac{2}{T} \int_{t_0}^{t_0+T} v(t)\cos(nw_0 t)dt,\ n = 0, 1, \ldots \tag{2}$$

$$b_n = \frac{2}{T} \int_{t_0}^{t_0+T} v(t)\sin(nw_0 t)dt,\ n = 1, 2.\ldots \tag{3}$$

where $v(t)$ is the analyzed signal and $\cos(nw_o t)$ and $\sin(nw_o t)$ represent the discrete points of the mother function. Fig. 3 shows this issue. In Fig. 3a shows the lightning signal (blue color) and the mother function (red color). In order to make the convolution, these two signals must have similar size. Thus, the mother function usually is discretized in 16–32 samples per cycle and therefore the lightning signal must be also sampled to 16–32 samples per cycle.

Unlike the traditional schemes, by using a methodology previously presented [58], which is based on the ellipsoidal pattern determined through the data mining, it is possible to determine when a transient signal produced by lightning stroke in first instance hits a TL.

Atmospheric discharges transient signal data windows of 25us are used. Thus, these signals represented by a vector of $x(p) = 1 \times 25$ are processed through the eigenvectors. The signal calculation is represented as a new vector of $z(p) = 1 \times 25$, which is projected on a new axis. In matrix form, the proposed detection algorithm undergoes a similar convolution process to the Fourier method, between the lightning signal and the mother function, which corresponds to the eigenvectors extracted through Principal Component Analysis. The equation to elicit the convolution is as follows:

$$PC = UV \tag{4}$$

where ***V*** represents the lightning signal, ***U*** represents the eigenvectors and ***PC*** are the principal component values. Fig. 4 shows the procedure.

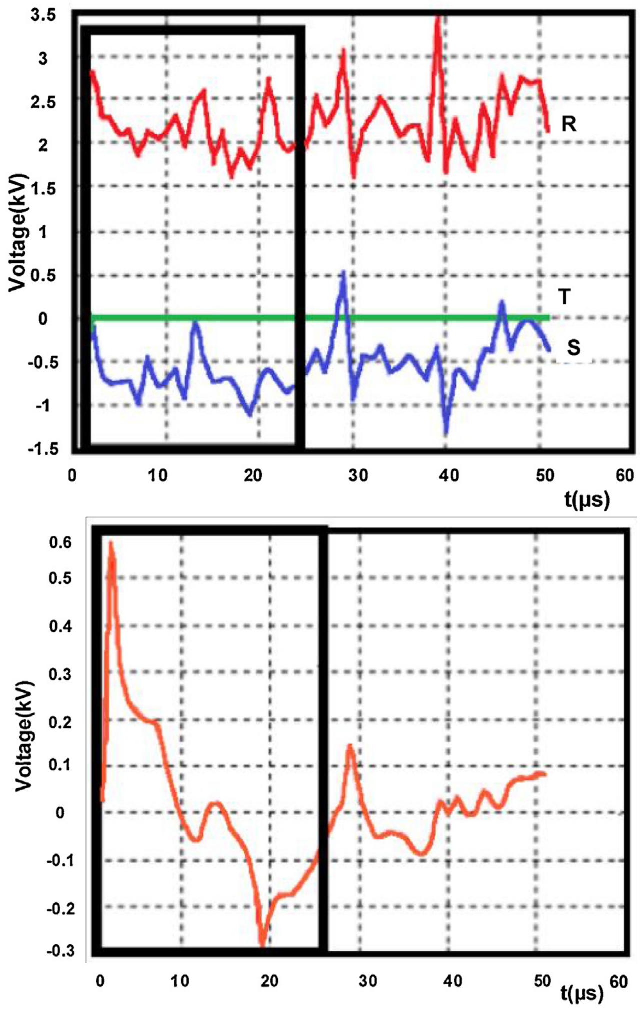
A convolution processes is also developed, where transient signals and mother function of 25us are used. By using the mathematical procedure stated above, when a transient different signal from the normal operation is presented, a trajectory that is outside of the ellipsoidal pattern is founded. Therefore, while new signals are continuously projected on that EP, and if any moment that projection is outside of the border of this pattern, a transient signal is detected.

Supposing that new signals corresponding to a lightning stroke, are registered by both protection relays, and the ellipse equation values are determined. Thus, if the equation of the ellipse value calculated of these signals is different to 1, a transient signal corresponding to lightning strokes, is detected. These values are calculated as follows:

$$EE = \frac{{PC_{1r}}^2}{{PC_{1\max}}^2} + \frac{{PC_{2r}}^2}{{PC_{2\max}}^2} \approx 1 \tag{5}$$

where PC_{1r} and PC_{2r} are calculated by using the data mining based on Multivariable Analysis, representing the first two PCs and EE represents the calculated value of the equation of the ellipse. A more detailed description is presented in Ref. [58].

After that first instance of lightning stroke is detected. Based on the traveling-wave property on TLs, the behavior of travelling waves are analyzed considering some particular points on the wave and checking it for different instances of time. At this point, the velocity of the voltage wave propagation is the light velocity c, and that if t increases, x increases too, so $\Delta x = c\Delta t$ and the first halve



(b)

Fig. 4. (a) Lightning signal, (b) mother function.

step front waves denoted by A moves a distance of Δx, as is shown in Fig. 2. Therefore, the voltage-travelling wave vtr is a function of x distance for consecutive values of t time (broken line), which moves along the positive direction (broken line). Hence, vtr correspond to the forward-travelling wave.

In the second halve step front wave denoted by B, x to decrease as t increases i.e $\Delta x = -c\Delta t$, which indicate that vtl moves along the negative direction (red line). Therefore, vtl represent the backward-travelling wave. Along the TL, both voltage-travelling waves propagate to the speed of light until that, halves step front waves arrive at the protection relays. For example, the protection relay connected at point M will recover the voltage wave (backward-travelling wave) as a function of time as is shown in Fig. 5 (bold line). Similarly, the protection relay connected at point N will recover the curve corresponding to the forward-travelling wave (broken line).

Depending on the section of TL where a LS hits, measurement devices recover these signals, but with a time delay such as $\Delta_{time} = t_2 - t_1$, where t_2 and t_1 represent times that travelling waves take to travel from the point of impact to the protection relays M an N, respectively. See Fig. 2.

Based on Fig. 2, it is possible to determine two equations.

$$t_1 = t_2 - \Delta time \tag{6}$$

$$t_{total} = t_1 + t_2 \tag{7}$$

where t_{total} is the time that a travelling wave takes to travel from an end to other, d_{total} of the TL.

From Eqs. (6) and (7), two equations useful to determine the times, t_1 and t_2 are obtained as follows:

$$t_1 = \frac{t_{total} - \Delta time}{2} \tag{8}$$

$$t_2 = \frac{t_{total} + \Delta time}{2} \tag{9}$$

Based on Eqs. (8) and (9), t_1 and t_2 are functions of t_{total} and Δ_{time}. t_{total} is a constant value and depends on the length of TL used (see Section 4). However, Δ_{time} depends on the point where a LS hits. In this paper, to determine Δ_{time}, a count scheme and the sampling rate between samples denoted by $srbs$ are used.

After LSs hits on TL, it is necessary to detect the presence of travelling waves on any of the ends of TL. In this instance, it is possible to determine in which sample (s_m) the first half travelling wave arrives at relay M (see Fig. 5). Then, the count scheme starts in order to determine in which sample (s_n) the second half travelling wave arrives at relay N. By using s_m and s_n, the difference between samples can be determined. Next, using a sampling rate between samples denoted by $srbs$, Δ_{time}, can be calculated as follows:

$$\Delta time = srbs \times (sm - sn) \tag{10}$$

Finally, the distance from the point where the LS hits on TL to the protection relays denoted by d_1 and d_2 are calculated multiplying Eqs. (8) and (9), by the propagation velocity c.

The previous methodology is applied to conditions where $s_m < s_n$ i.e. distance $d_1 <$ distance d_2. However, if a LS hits on the TL or ground then: $s_m > s_n$ or $d_1 > d_2$. Equations to calculate t_1 and t_2 are similar to these Eqs. (8) and (9), only the signs changed as follows:

$$t_1 = \frac{t_{total} + \Delta time}{2} \tag{11}$$

$$t_2 = \frac{t_{total} - \Delta time}{2} \tag{12}$$

4. Power system used

By using the Alternative Transients Program (ATP) [59], a 220 kV EPS is simulated, which has a TL of 31 km. Spans between transmission towers of 400 m are simulated. Two transmission towers on each side of the point of impact of the LS is simulated. Two protection relays denoted by M and N are collected at the ends of the three phases TL, which recover the overvoltage signals to a sampling rate between samples $srbs$ = 1E − 8s. The TL is simulated by using the JMarti, model. Besides that, elements of LS studies such as tower model, ground resistance, insulator string and others, have been simulated using international references [60]. Thus, in order to analyze and study transmission line protection relays performance against atmospheric discharges, different parts of an overhead transmission line such as shield wires and phase conductors, towers, grounding, insulator strings among others [61,62] must be included in an adequate model.

The most important factor in lightning surge simulations is related to their magnitude. However, it is widely accepted that when a lightning bolt a TL, it injects current into the power system. In this context, the Heidler model was used to represent that current.

By using untransposed distributed parameter line models, shield wires and live wires of transmission lines were modeled by two or three spans at each side of the point of impact. Respecting the transmission tower, there are two possibilities to simulate this element: the first consists of using inductances-resistances, and the second consists of using distributed parameter impedances. The

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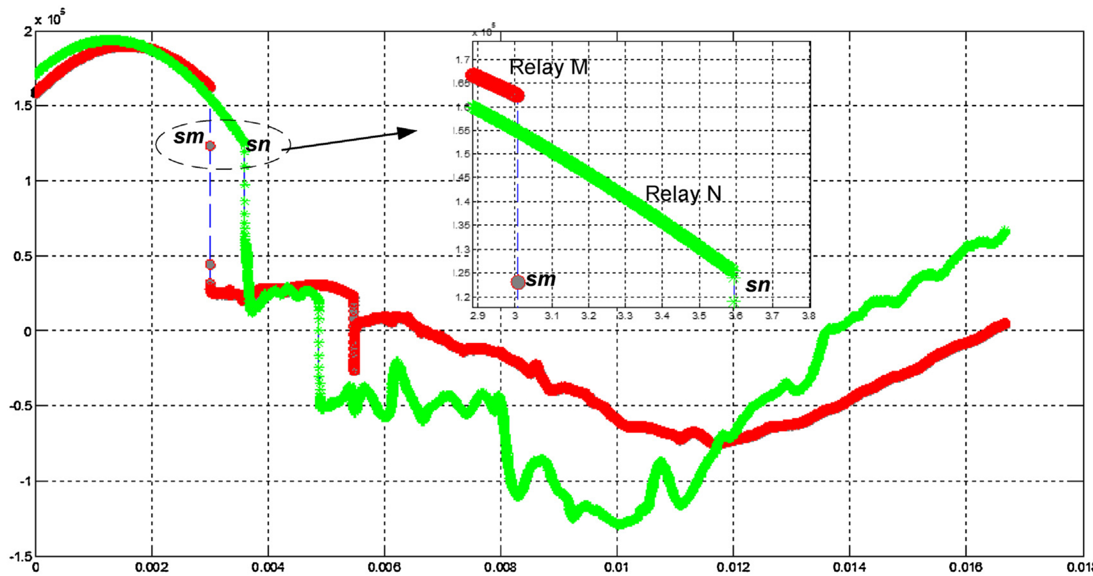

Fig. 5. Initial voltage travelling waves recovered by protection relays.

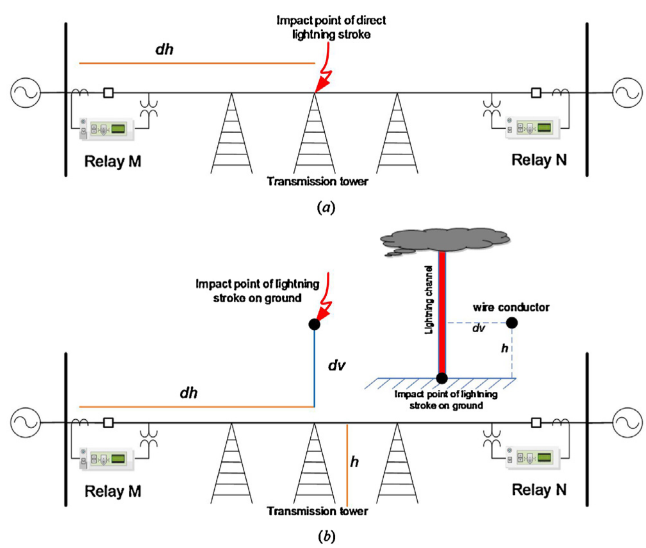

Fig. 6. Analyzed study cases (a) direct lightning, (b) induced lightning.

later considers voltage reflections from adjacent towers and from cross arms. Thus, in this paper the tower is represented as a loss-less distribute-parameter transmission line, characterized by its impedance and travel time. Insulators were simulated by a voltage-dependent flashover switch and a voltage-time characteristic. The footing tower resistance (FTR) is simulated by using a resistance.

In this context, regarding direct LS, different parameters were varied such as: Flash Peak Current Magnitude (FPCM) = 5 kA, 10 kA, 20 kA, 31 kA, 40 kA. The point of impact of LS on TL is directly on the wire conductor. For each FPCM, the LS impact point varying the horizontal distance d_h from 2 to 31 km with 2 km step was run. Furthermore, the inception angle was varied by using the time controlled switch in ATP, these time instances are: 2.5 ms, 1.2 ms, 0.7 ms, 4.16 ms and 6.25 ms, respectively (Fig. 6a).

Regarding the LS that hit the ground, FPCM = −25 kA, −31 kA, −70 kA, −90 kA, 15 kA, 30 kA, 50 kA, 90 kA, 130 kA, 160 kA and 210 kA were simulated. Unlike direct LSs, in induced LSs, two distances denoted by d_h and d_v are varied, respectively (Fig. 6b). Hence, for each induced LS, the impact point varied such as d_v = 50 m and 150 m, respectively. Regarding to d_h, it is similar to the study cases corresponding to direct LSs. It is necessary to note that those FPCM values were run, varied the d_v and d_h distances, and the inception angle, depending on the case under study.

Induced LS overvoltages are simulated in ATP by using the Rusckís equation [63]. The phase conductor is located at perpendicular distance d_v meters from the LS impact point to the ground, having a mean height above ground of h meters. The Rusckís equation is as follows:

$$V_{(t)} = 2Z_o I_o h \frac{vt}{D^2 + (vt)^2} \left[1 + \frac{\beta vt}{\sqrt{(vt)^2 + D^2(1-\beta^2)}} \right] \tag{13}$$

where $V(t)$ represents the induced voltage on the wire conductor, t is the time in seconds, c is the velocity of light in free space, I is the return-peak current value, h is the average height of the transmission line and Z_o is the surge impedance of discharge channel, approximately 30 Ω.

In this paper, the signals used were simulated by using the ATP. Thus, real oscilograms that represent lightning stroke on TL were not found. It could be that at the moment there are no real signals recovered for any protection relay. Therefore, the authors have considered that the use of real lighting stroke signals recovered from high samples exceed the scope of this paper.

5. Methodology evaluation

The distance from the impact point of two protection relays denoted by d_1 and d_2 are calculated by determining firstly s_m and s_n. Then, Δ_{time} can be determined and finally the times and distances are calculated.

The methodology uses the first voltage traveling waves that arrive to the protection relays. These voltage samples are processed through methodology presented in Section 3. Results show that the both distances from the impact point of the LS to protection relays are acceptably determined, which are detailed below.

5.1. Methodology applied to direct lightning stroke

Direct LSs on TL presented in Section 2 are tested. After the LS has been detected i.e the first instance after that LS hits on TL, the distances d_1 and d_2 can be computed. For example, in Fig. 7a, the voltage signals measured by the protection relays M and N pro-

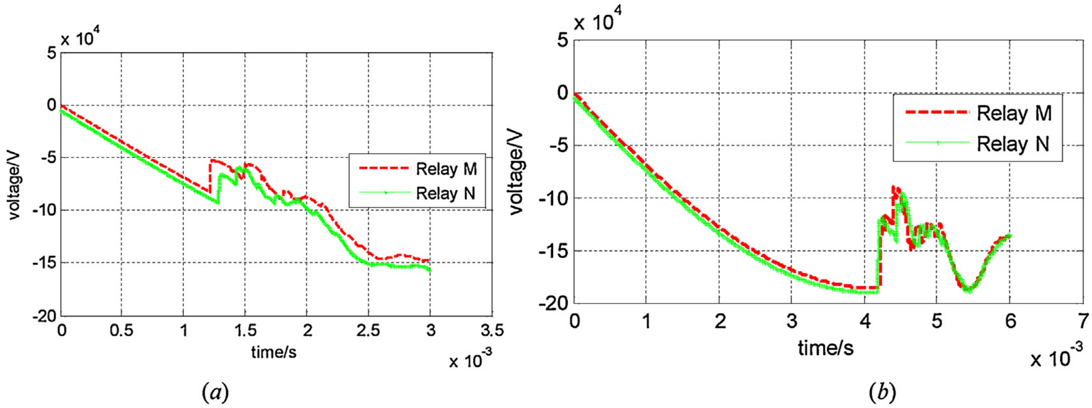

Fig. 7. Direct LS testing signals. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

duced by a direct LS of 10 kA, which hit in a stretch of the TL of $d_h = 6$ km from the M relay with a time instance of 1.2 ms, is presented (in Fig. 7a the red and green color lines are the voltage wave measurement by the relay M and N, respectively). On the other hand, in Fig. 7b another example is presented. In this fig. a direct LS of 31 kA, which hits in a stretch of the TL of $d_h = 22$ km from the M relay with a time instance of 4.16 ms, is run.

According to Fig. 7a, after the LS hits on the TL, the travelling wave that reaches to the ends to the TL have a gap between them, which using the equations previously introduced, $s_m = 122{,}016$, $s_n = 128{,}403$ and $srbs = 1E-8$s, $\Delta_{time} = 6.3870E-05$ s are determined. Later on, $t_1 = 1.9732E-05$s, and $t_2 = 8.3602E-05$ s are calculated. Finally, distances $d_1 = 5{,}9195$ km and $d_2 = 25{,}0805$ km, are calculated. Regarding Fig. 7b, in this study case, applying previous equations, $d_1 = 22{,}052$ km and $d_2 = 8{,}948$ km, are determined, respectively. In both cases, the LS impact point distances are close to the real value of $d_1 = 6$ km, $d_2 = 25$ km, $d_1 = 22$ km and $d_2 = 9$ km, respectively. A summary of calculated distances using the methodology is presented in Table 2.

From Table 2, it is observable that the calculated distances corresponding to LSs are well-determined. According to that table, the stretches calculated are very close to those real stretches. Finally, the time instance influence or inception angle does not affect the behavior of the work presented. Thus, evaluated distances are also close to the real distances.

5.2. Methodology applied to induced lightning stroke

LSs that hit on the ground and induce overvoltage on TL presented in Section 4 are tested by using the presented methodology. Unlike direct LS, in this case, induced LSs varying the horizontal and vertical distances d_h and d_v were run, respectively. For example, Fig. 8a shows the voltage signals measured by the protection relays M and N produced by an induced LS of −70 kA, which hit at a vertical distance from the TL $d_v = 50$ m and in a stretch of the TL $d_h = 24$ km from the M relay (in Fig. 8a, the red color line is the voltage wave measurement by the relay M, and the green color line is the voltage wave recovery by the relay N, respectively).

According to Fig. 8a, after the LS hits on the ground, the travelling wave that arrives to the ends of the TL has a gap between them, which using the equations previously presented, $s_m = 258{,}065$, $s_n = 252{,}354$ and $srbs = 1E-8$s, $\Delta_{time} = 5.7110E-05$ s are determined. Later on, $t_1 = 8.0222E-05$s, and $t_2 = 2.3112E-05$ s are calculated. Finally, distances $d_1 = 24.0665$ km and $d_2 = 6{,}9335$ km, are calculated.

It is evident that the value d_1 is very close to the real value of $d_h = 24$ km. It is important to note that for induced LSs, the work presented in this paper determines the distances or stretches from the induced LS impact point to the ends of TLs denoted by d_h (see Fig. 6b). However, the perpendicular distance from the impact point to the conductors denoted by d_v is out of the scope of this research (see Fig. 6b).

Another case is presented in Fig. 8b, where initial voltage signals measured by the protection relays M and N produced by an induced LS of 210 kA, which hits at a distance $d_v = 150$ m and in a stretch of the TL $d_h = 16$ km from the M relay, is considered.

In Tables 3 and 4, distances d_1 and d_2 of induced LSs presented in Section 4, are summarized. According to these tables, the stretches calculated are very close to the real data.

Moreover, in order to verify the behavior of the proposed work, in Fig. 9, a summary of average error between real and determined distances for direct and induced LSs, is presented. Regarding to direct LS, it is possible to determine that the calculated distance maximum error is present when a direct LS of 20 kA hits to 2 km from the protection relay M, respectively. In this case, an error corresponding to 118.5 m is determined. On the contrary, regarding to induced LS, it is possible to determine that the calculated distance maximum error is presented when an atmospheric discharge of −70 kA or −90 kA hit the ground 2 km from the protection relay M, respectively. In this case, an error corresponding to 117 m is determined.

5.3. Effects of flash currents, inception angle and section of the TL

The most crucial parameters of LS phenomena is its magnitude where it is random, and when a LS hits on the TL, the induced voltage depends on the flash value. However, the work presented in this research, could detect the signals produced by direct and induced LS, and thus the impact point of the LS is determined. Five inception angles were varied in order to demonstrate the viability of the research. From the results, it is possible to see that this parameter does not influence in determining the distance. Besides that, several spans of 2 km were varied along the TL in order to verify the behavior of the work. Based on Fig. 9, it is clear that the major error is produced in the surroundings of protection relays. For a distance of 2 km and 28 km the maximum error is 110 m and 220 m for direct and induced LSs, respectively. Additionally, while the impact point tends to the center of the line, the error decreases linearly to approximately zero. Finally, to induced LSs, the vertical distance from the impact point of the LS to the TL were varied. Therefore, based on results, the work determined the impact point, independently of this distance.

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Table 2
Calculated impact points of direct LS on TL.

Real distnace (km)		Flash peak current magnitude									
		5 kA		10 kA		20 kA		31 kA		40 kA	
		Estimated distance (km)		Estimated distance (km)		Estimated distance (km)		Estimated distance (km)		Estimated distance (km)	
d1	d2	d1	d2	d1	d2	d1	d2	d1	d2	d1	d2
2	29	1.883	29.117	1.883	29.117	1.8815	29.119	1.8845	29.116	1.8845	29.116
4	27	3.902	27.098	3.902	27.098	3.9005	27.1	3.9035	27.097	3.9035	27.097
6	25	5.9195	25.081	5.9195	25.081	5.9195	25.081	5.921	25.079	5.921	25.079
8	23	7.9355	23.065	7.9355	23.065	7.937	23.063	7.937	23.063	7.937	23.063
10	21	9.95	21.05	9.95	21.05	9.9485	21.052	9.95	21.05	9.9515	21.049
12	19	11.963	19.037	11.963	19.037	11.965	19.036	11.965	19.036	11.965	19.036
14	17	13.987	17.014	13.987	17.014	13.987	17.014	13.985	17.015	13.987	17.014
16	15	16.001	14.999	16.001	14.999	16	15.001	16.001	14.999	16.003	14.998
18	13	18.022	12.979	18.022	12.979	18.022	12.979	18.023	12.977	18.022	12.979
20	11	20.039	10.961	20.039	10.961	20.039	10.961	20.038	10.963	20.039	10.961
22	9	22.051	8.9495	22.051	8.9495	22.051	8.9495	22.052	8.948	22.051	8.9495
24	7	24.068	6.932	24.068	6.932	24.067	6.9335	24.067	6.9335	24.067	6.9335
26	5	26.086	4.9145	26.086	4.9145	26.086	4.9145	26.087	4.913	26.087	4.913
28	3	28.105	2.8955	28.105	2.8955	28.105	2.8955	28.103	2.897	28.103	2.897

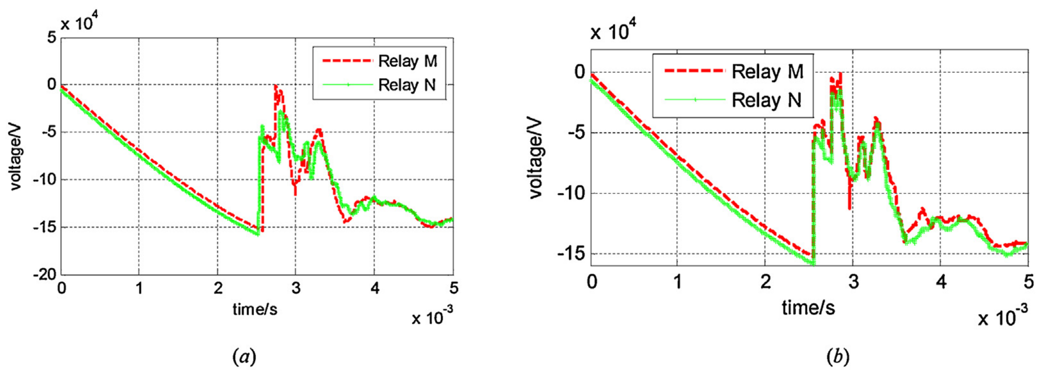

Fig. 8. Induced LS testing signals. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

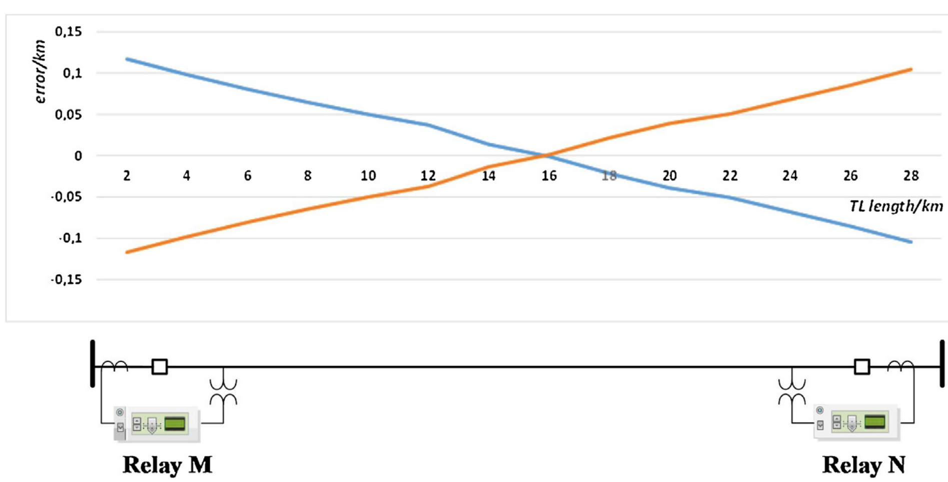

Fig. 9. Average error percentage of real and calculated distances for indirect and induced LSs.

6. Flow chart

Fig. 10 presents the flow chart to determine the impact point of direct and induced LSs on TL. The voltage samples corresponding to travelling waves that are generated after the LS hits on either TL or on the ground, and propagates along the TL, are registered by the protection relays at both ends of the TL. Later on, when an initial travelling wave arrives to one of the ends of the TL, a subscript set of the sample in which the travelling wave reaches the protection relay, is determined. Then, the other subscript set is continuously updated by the relay until the other travelling wave arrives at the other end of the TL. The Δ_{time} time difference between both travelling waves is carried out by remaining both subscript sets. Besides that, depending if the subscript set of s_m is higher than s_n or vice versa, the times t_1 and t_2 are calculated, respectively. Finally, the distances d_1 and d_2 are calculated.

Table 3
Calculated impact points of induced LS on TL: part 1.

Vertical distance (m)	Real distance (km)		Flash peak current magnitude									
			(−25 kA)		(−31 kA)		(−70 kA)		(−90 kA)		15 kA	
			Estimated distance (km)		Estimated distance (km)		Estimated distance (km)		Estimated distance (km)		Estimated distance (km)	
dv	d1	d2	d1	d2	d1	d2	d1	d2	d1	d2	d1	d2
50	2	29	1.9	29.1	1.9	29.1	1.9	29.1	1.9	29.1	1.9	29.1
	4	27	3.9	27.1	3.9	27.1	3.9	27.1	3.9	27.1	3.9	27.1
	6	25	5.9	25.1	5.9	25.1	5.9	25.1	5.9	25.1	5.9	25.1
	8	23	7.9	23.1	7.9	23.1	7.9	23.1	7.9	23.1	7.9	23.1
	10	21	10.0	21.1	10.0	21.1	10.0	21.1	10.0	21.1	10.0	21.1
	12	19	12.0	19.0	12.0	19.0	12.0	19.0	12.0	19.0	12.0	19.0
	14	17	14.0	17.0	14.0	17.0	14.0	17.0	14.0	17.0	14.0	17.0
	16	15	16.0	15.0	16.0	15.0	16.0	15.0	16.0	15.0	16.0	15.0
	18	13	18.0	13.0	18.0	13.0	18.0	13.0	18.0	13.0	18.0	13.0
	20	11	20.0	11.0	20.0	11.0	20.0	11.0	20.0	11.0	20.0	11.0
	22	9	22.1	8.9	22.1	8.9	22.1	8.9	22.1	8.9	22.1	8.9
	24	7	24.1	6.9	24.1	6.9	24.1	6.9	24.1	6.9	24.1	6.9
	26	5	26.1	4.9	26.1	4.9	26.1	4.9	26.1	4.9	26.1	4.9
	28	3	28.1	2.9	28.1	2.9	28.1	2.9	28.1	2.9	28.1	2.9
150	2	29	1.9	29.1	1.9	29.1	1.9	29.1	1.9	29.1	1.9	29.1
	4	27	3.9	27.1	3.9	27.1	3.9	27.1	3.9	27.1	3.9	27.1
	6	25	5.9	25.1	5.9	25.1	5.9	25.1	5.9	25.1	5.9	25.1
	8	23	7.9	23.1	7.9	23.1	7.9	23.1	7.9	23.1	7.9	23.1
	10	21	10.0	21.0	10.0	21.0	10.0	21.0	10.0	21.0	10.0	21.0
	12	19	12.0	19.0	12.0	19.0	12.0	19.0	12.0	19.0	12.0	19.0
	14	17	14.0	17.0	14.0	17.0	14.0	17.0	14.0	17.0	14.0	17.0
	16	15	16.0	15.0	16.0	15.0	16.0	15.0	16.0	15.0	16.0	15.0
	18	13	18.0	13.0	18.0	13.0	18.0	13.0	18.0	13.0	18.0	13.0
	20	11	20.0	11.0	20.0	11.0	20.0	11.0	20.0	11.0	20.0	11.0
	22	9	22.1	8.9	22.1	8.9	22.1	8.9	22.1	8.9	22.1	8.9
	24	7	24.1	6.9	24.1	6.9	24.1	6.9	24.1	6.9	24.1	6.9
	26	5	26.1	4.9	26.1	4.9	26.1	4.9	26.1	4.9	26.1	4.9
	28	3	28.1	2.9	28.1	2.9	28.1	2.9	28.1	2.9	28.1	2.9

Table 4
Calculated impact points of induced LS on TL: part 2.

Vertical distance (m)	Real distance (km)		Flash peak current magnitude											
			30 kA		50 kA		90 kA		130 kA		160 kA		210 kA	
			Estimated distance (km)		Estimated distance (km)		Estimated distance (km)		Estimated distance (km)		Estimated distance (km)		Estimated distance (km)	
dv	d1	d2	d1	d2	d1	d2	d1	d2	d1	d2	d1	d2	d1	d2
50	2	29	1.9	29.1	1.9	29.1	1.9	29.1	1.9	29.1	1.9	29.1	1.9	29.1
	4	27	3.9	27.1	3.9	27.1	3.9	27.1	3.9	27.1	3.9	27.1	3.9	27.1
	6	25	5.9	25.1	5.9	25.1	5.9	25.1	5.9	25.1	5.9	25.1	5.9	25.1
	8	23	7.9	23.1	7.9	23.1	7.9	23.1	7.9	23.1	7.9	23.1	7.9	23.1
	10	21	10.0	21.1	10.0	21.1	10.0	21.1	10.0	21.1	10.0	21.1	10.0	21.1
	12	19	12.0	19.0	12.0	19.0	12.0	19.0	12.0	19.0	12.0	19.0	12.0	19.0
	14	17	14.0	17.0	14.0	17.0	14.0	17.0	14.0	17.0	14.0	17.0	14.0	17.0
	16	15	16.0	15.0	16.0	15.0	16.0	15.0	16.0	15.0	16.0	15.0	16.0	15.0
	18	13	18.0	13.0	18.0	13.0	18.0	13.0	18.0	13.0	18.0	13.0	18.0	13.0
	20	11	20.0	11.0	20.0	11.0	20.0	11.0	20.0	11.0	20.0	11.0	20.0	11.0
	22	9	22.1	8.9	22.1	8.9	22.1	8.9	22.1	8.9	22.1	8.9	22.1	8.9
	24	7	24.1	6.9	24.1	6.9	24.1	6.9	24.1	6.9	24.1	6.9	24.1	6.9
	26	5	26.1	4.9	26.1	4.9	26.1	4.9	26.1	4.9	26.1	4.9	26.1	4.9
	28	3	28.1	2.9	28.1	2.9	28.1	2.9	28.1	2.9	28.1	2.9	28.1	2.9
150	2	29	1.9	29.1	1.9	29.1	1.9	29.1	1.9	29.1	1.9	29.1	1.9	29.1
	4	27	3.9	27.1	3.9	27.1	3.9	27.1	3.9	27.1	3.9	27.1	3.9	27.1
	6	25	5.9	25.1	5.9	25.1	5.9	25.1	5.9	25.1	5.9	25.1	5.9	25.1
	8	23	7.9	23.1	7.9	23.1	7.9	23.1	7.9	23.1	7.9	23.1	7.9	23.1
	10	21	10.0	21.0	10.0	21.0	10.0	21.0	8.9	22.1	10.0	21.0	10.0	21.0
	12	19	12.0	19.0	12.0	19.0	12.0	19.0	12.0	19.0	12.0	19.0	12.0	19.0
	14	17	14.0	17.0	14.0	17.0	14.0	17.0	14.0	17.0	14.0	17.0	14.0	17.0
	16	15	16.0	15.0	16.0	15.0	16.0	15.0	16.0	15.0	16.0	15.0	16.0	15.0
	18	13	18.0	13.0	18.0	13.0	18.0	13.0	18.0	13.0	18.0	13.0	18.0	13.0
	20	11	20.0	11.0	20.0	11.0	19.0	12.0	20.0	11.0	20.0	11.0	20.0	11.0
	22	9	22.1	8.9	22.1	8.9	22.1	8.9	22.1	8.9	22.1	8.9	22.1	8.9
	24	7	24.1	6.9	24.1	6.9	24.1	6.9	24.1	6.9	24.1	6.9	24.1	6.9
	26	5	26.1	4.9	26.1	4.9	26.1	4.9	26.1	4.9	26.1	4.9	26.1	4.9
	28	3	28.1	2.9	28.1	2.9	28.1	2.9	28.1	2.9	28.1	2.9	28.1	2.9

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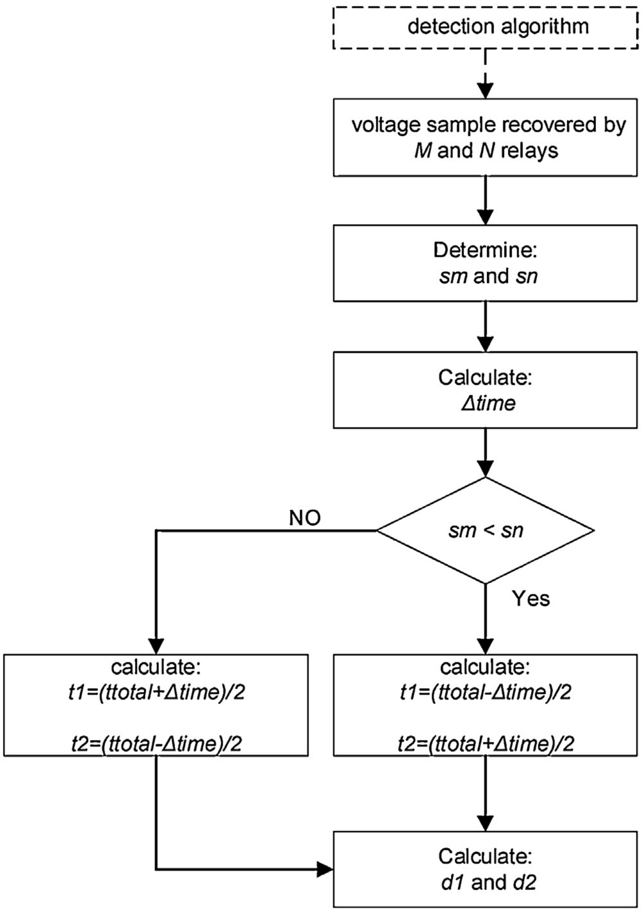

Fig. 10. Flow chart.

7. Conclusions

The main contribution of this paper is to determine whether the travelling waves and data mining can be used for the lighting stroke location on TL as well on ground. The first step of the work is the use of the ellipsoidal pattern in order to detect the first instance after lightning hits on transmission line or on ground. The second step of the proposed research consists of developing a methodology based on synchronized travelling waves registered at both ends of transmission lines to compute the distance from the lighting stroke to the protection relays. For signal processing and transient signal detection, a pattern ellipsoidal is used.

Synchronized Travelling waves at both ends of transmission lines have been used. The proposed methodology was applied to a transmission line taking into account the influence of main parameter of atmospheric discharges such as flash current, polarity, direct and induced lighting stroke, distance along the transmission line, inception angle among others. In this context, the proposed methodology is robust against the most important parameter of lighting strokes. Thus, under several conditions of lightning stroke such as small and high flash current, the research presented could localize the impact point in very short time. The results show that the distance error is smaller than 100 m on all the 200 simulation cases.

Finally, based on results, the proposed methodology is particularly simple and, accurate. Unlike the distance protection relay and wavelet based methodologies, the proposed work not only eliminates requiring data windows of 1 cycle but is also independent of the mother wavelet such as Fourier transform, multiresolution analysis and mathematical morphologic, which depend on the sine, cosine, mother wavelet and structuring element, respectively.

In summary the presented scheme could be used as an alternative one in protection relay algorithms, which work in combination with other protection schemes such as classification of lightning strokes, switching operation blocking and others.

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