Forecast of the Effects of Lightning IN Electrical Systems (FELINES)

Simulations of a Large Set of Events

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1. Context

Project: FELINES

PRIN 2022, grant number 20224CL7HM, Italian Ministry for Education, University, and Research and the European Union-Next Generation EU. The research project Forecast of the Effects of Lightning IN Electrical Systems (FELINES) aims at designing a protection system capable of sensing phenomena that preliminary to a lightning event, and consequently disconnect part (or all) of the electric infrastructure under its protection. These phenomena are associated with the so-called Preliminary Breakdown (PB) pulses, localized events taking place during the first phases of the lightning inception.

Work Package 2: Modeling of PB pulses and sensors network
Responsible Research Unit: UniGe
Task 2.3: Simulations of a large set of events

The goal of this step is to create a large database useful for the following tasks, in which the detection system characteristics will be defined. The numerical models of the PB pulses and of the sensor equipment developed in T2.2 (Definition and modeling of the sensors network) will be used in this task to generate one or more large sets of (simulated) signals, corresponding to precursors of a Return Stroke (RS).

2. Introduction

Lightning represents a major issue to power systems, causing damage to equipment, faults in transmission and distribution networks, and disruptions in service continuity [1]. Flashovers on overhead lines may originate from direct strikes, typically modeled as injected current sources, or from indirect strikes, which induce overvoltages through electromagnetic coupling. Although generally less severe, indirect events are more frequent and can still exceed the insulation Critical FlashOver voltage (CFO), making them a significant source of outages [2].

Protection of overhead distribution lines commonly relies on shield wires and surge arresters. Shield wires mainly mitigate the impact of direct strikes [3, 4], while surge arresters limit transient overvoltages by diverting excess energy to ground, with several studies addressing their optimal deployment [5, 6, 7].

A complementary approach consists in predictive protection based on Preliminary Breakdown (PB) pulses, i.e., phenomena characterizing the initial stages of lightning, usually much weaker than the Return Stroke (RS). Detecting PB activity may enable short-term estimation of RS severity and the activation of preventive actions. PB pulses are among the most complex phases of the lightning process and provide insight into the mechanisms leading to RS initiation [8, 9, 10, 11]. The typical PB–RS delay, on the order of tens of milliseconds, is compatible with modern control systems [12].

This report presents an initial step toward the development of a PB-based predictive protection tool, which is the objective of the FELINES project. Synthetic PB- and RS-induced voltages measured on a medium-voltage overhead line are generated by means of a dedicated simulation tool [13]. These PB-induced waveforms will serve as input to train a Deep Learning model aimed at estimating the RS peak voltage and identifying potentially critical flashover conditions.

Each event of the dataset is modeled as the combination of a PB pulse and a RS, producing two independent induced-voltage waveforms. This assumption is supported by the large difference in time scales: PB pulses last two to three orders of magnitude less than the PB–RS interval, so the PB-induced waveform has typically vanished by the time the RS-induced response begins (e.g., [14]).

3. Lightning-Induced Voltage Simulator

Lightning-induced voltages are computed using LIGHT-PESTO, a MATLAB-Simulink–based simulation tool derived from the methodology in [15], originally implemented in PSCAD-EMTDC. The platform enables detailed modeling of power networks with realistic layouts and advanced lightning representations, including automatic classification of direct and indirect strikes. Its validation against reduced-scale experimental measurements [16, 17] supports its use as a reliable surrogate for field data.

The simulation procedure consists of two main steps:

1. Calculation of lightning-radiated electromagnetic fields in free space using semi-analytical formulations for both perfectly conducting ground [18] and lossy ground [19] conditions.
2. Solution of the field-to-line coupling through a second-order FDTD implementation based on the Agrawal model [20].

While originally conceived for RS-induced voltage analysis, the tool has been extended in this study to simulate PB-induced voltages by incorporating a transmission-line–type current model for PB pulses [21].

4. Power System Layouts

Two power-system configurations and soil models are analyzed. Scenario A is intended as a simplified benchmark, whereas Scenario B represents more realistic operating conditions. Figure 1 illustrates both setups.

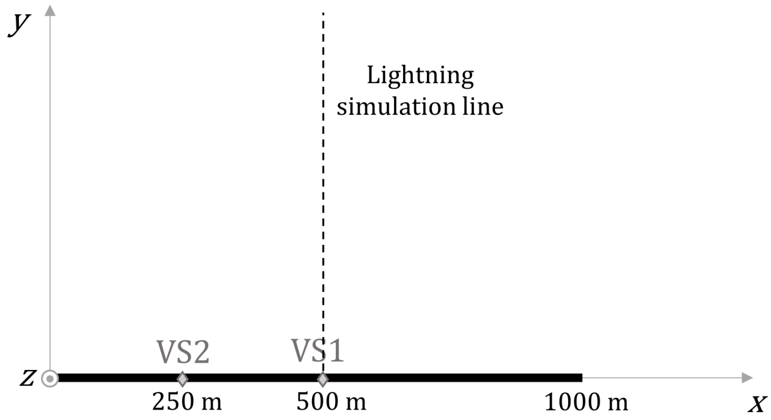

Figure 1: Top view of the modeled network layout. In both scenarios, the phase conductor runs along the plane $y = 0$ at an height of $z = 10$ m, with the voltage sensors VS1 and VS2 mounted at positions $x = 500$ m and $x = 250$ m. In Scenario B, an additional neutral conductor is present on the same vertical plane, located at $z = 8$ m.

4.1. Scenario A

A single-phase overhead distribution line is considered, with a CFO of 50 kV. An indirect lightning event is classified as critical when the induced voltage exceeds CFO by 50%, following [2]. The line is 1 km long, with conductor height of 10 m and radius of 1 cm, and is terminated with matching impedances to suppress reflections. A perfectly electric conducting (PEC) ground is assumed.

Two voltage sensors (VS1 at $x = 500$ m and VS2 at $x = 250$ m) are installed across line insulators, which are represented by a parasitic capacitance of 1 pF [22].

4.2. Scenario B

A more realistic configuration with phase and neutral conductors is examined. The CFO, conductor dimensions, terminations, and insulator model are the same as in Scenario A. The phase conductor is located at 10 m height, while the neutral is positioned 2 m below and is grounded every 125 m through a 30 Ω resistor.

The soil is modeled with conductivity of 1 mS/m and relative permittivity equal to 10. Voltage sensors VS1 and VS2 are placed on the phase conductor at $x = 500$ m and $x = 250$ m, respectively, as in Scenario A. conductor at $x = 500$ m and $x = 250$ m, respectively.

5. Lightning Modeling

Each simulated lightning event is represented by two consecutive phases, namely the PB and the RS, which are described using separate modeling frameworks.

5.1. Preliminary Breakdown Model

The PB current is simulated using the formulation proposed by Karunarathne et al. [21], referred to as the MTLK model. This approach shares the same physical rationale as classical transmission-line–type models commonly adopted for RS currents [23, 24, 25].

In this representation, the PB channel is modeled as a vertical transmission line extending between altitudes H_1 and H_2. The current distribution along the channel is expressed as

$$i_{PB}(z,t) = f(z)\, i_{PB,H_1}\left(t - \frac{z - H_1}{v_{PB}}\right), \qquad H_1 \le z \le H_2 \tag{1}$$

where i_{PB,H_1} is the injected current at the lower boundary propagating upward with velocity v_{PB}, and $f(z)$ describes the variation of current amplitude with height.

The vertical profile is shaped so that the current starts from zero at H_1, reaches a maximum at the height H_m, and vanishes at H_2. This behavior is reproduced using the model proposed in [26], leading to

$$f(z) = \left(\frac{z - H_1}{H_2 - H_1}\right)^{a-1} \left[1 - \left(\frac{z - H_1}{H_2 - H_1}\right)^{a}\right]^{b-1}. \tag{2}$$

where a and b are shape parameters. The source current i_{PB,H_1} applied at $z = H_1$ is described by the asymmetric Gaussian formulation introduced in [27] and adopted in [21]. It is expressed as

$$i_{PB,H_1} = \begin{cases} A\, e^{-\left[\frac{\alpha_{ind}}{t_2}(t-t_1)\right]^2}, & t \le t_1 \\ A\, e^{-\left[\frac{\alpha_{ind}}{t_2}\frac{(t-t_1)t_1}{(t_2-t_1)}\right]^2}, & t > t_1 \end{cases} \tag{3}$$

where A defines the peak value of the current, t_1 controls the rise time, and t_2 sets the pulse duration. The parameter α_{ind} is a dimensionless factor that regulates the waveform asymmetry.

A subset of the MTLK parameters is kept fixed (Table 1), specifically those related to channel geometry and waveform shape, with values selected in accordance with [21].

5.2. Return Stroke Model

The RS is modeled using a classical transmission-line–based engineering approach, in which the lightning channel is treated as a vertical thin-wire radiator excited by a base current source [23, 24, 25]. For a channel of height H, the current distribution is

$$i_{RS}(z,t) = p(z)\, i_{RS,0}\left(t - \frac{z}{v_{RS}}\right), \qquad 0 \le z \le H. \tag{4}$$

Current attenuation with height is described using the Modified Transmission Line with Exponential decay (MTLE) formulation [25], i.e., $p(z) = e^{-z/\lambda}$, where λ is the decay constant. The channel-base current $i_{RS,0}$ is represented by the Heidler function [28].

Parameter assumptions are reported in Table 1. In this study, the RS channel is assumed to extend to a height of $H = 8$ km. The RS propagates upward at a constant speed of $v_{RS} = 0.5\, c_0$, where $c_0 = 3 \cdot 10^8$ m/s is the speed of light in vacuum. The Heidler function is tuned with standard parameters for the first negative RS

Table 1: Assumption of constant parameters of preliminary breakdown model and return stroke model

Model	Parameter	Value
PB	H_1 (km)	5.5
PB	H_2 (km)	6.4
PB	v_{PB} ($\times 10^8$ m/s)	1.15
PB	a	1.35
PB	b	2.90
RS	H (km)	8.0
RS	v_{RS} ($\times 10^8$ m/s)	1.50
RS	τ_1 (μs)	1.80
RS	λ (km)	2.0

[29], including a fixed front time of $\tau_1 = 1.8$ μs; the peak current is taken to scale with the PB peak current. The MTLE attenuation parameter is set to $\lambda = 2$ km.

6. Procedure for the Simulation of Random Lightning

The creation of a single event in the dataset follows the flowchart in Figure 2, with the generation of random PB pulse and RS summarized in the points below.

1. **Strike location selection.** The PB and RS strike positions (x, y) are assumed coincident, in line with the PB current model characterization [30]. For both Scenario A and Scenario B, the x-coordinate is fixed at 500 m, placing the strike in front of VS1. The y-coordinate is randomly sampled from a uniform distribution between 1 m and 400 m. The upper bound is chosen to ensure a balanced dataset, since increasing the distance from the line reduces the incidence of dangerous events.
2. **PB pulse generation.** The MTLK parameters not fixed in Table 1—namely t_1, t_2, α_{ind}, and A—are randomly sampled from the statistical distributions reported in [30] (Table 2). These distributions were obtained by fitting experimental electric field measurements from over 3000 high-intensity negative Cloud-to-Ground lightning flashes in Florida, U.S.A. [14]. Correlations among the parameters are also accounted for (Table 3).
3. **RS generation.** The sole free parameter for the RS model is the channel-base peak current, which is sampled based on the PB peak current $(A \cdot f(H_m))$ using the PB/RS peak current ratio distribution from [30]. This distribution has arithmetic mean 0.27, geometric mean 0.19, median 0.20, and standard deviation 0.25.

7. Simulation Parameters

The simulations use a time step of $\Delta t = 50$ ns. For both scenarios, the PB time window is $T_{PB} = 100$ μs $+r/c_0$, where r is the distance from the strike location to VS1. The RS time window is set to $T_{RS} = 10$ μs $+r/c_0$ for Scenario A and

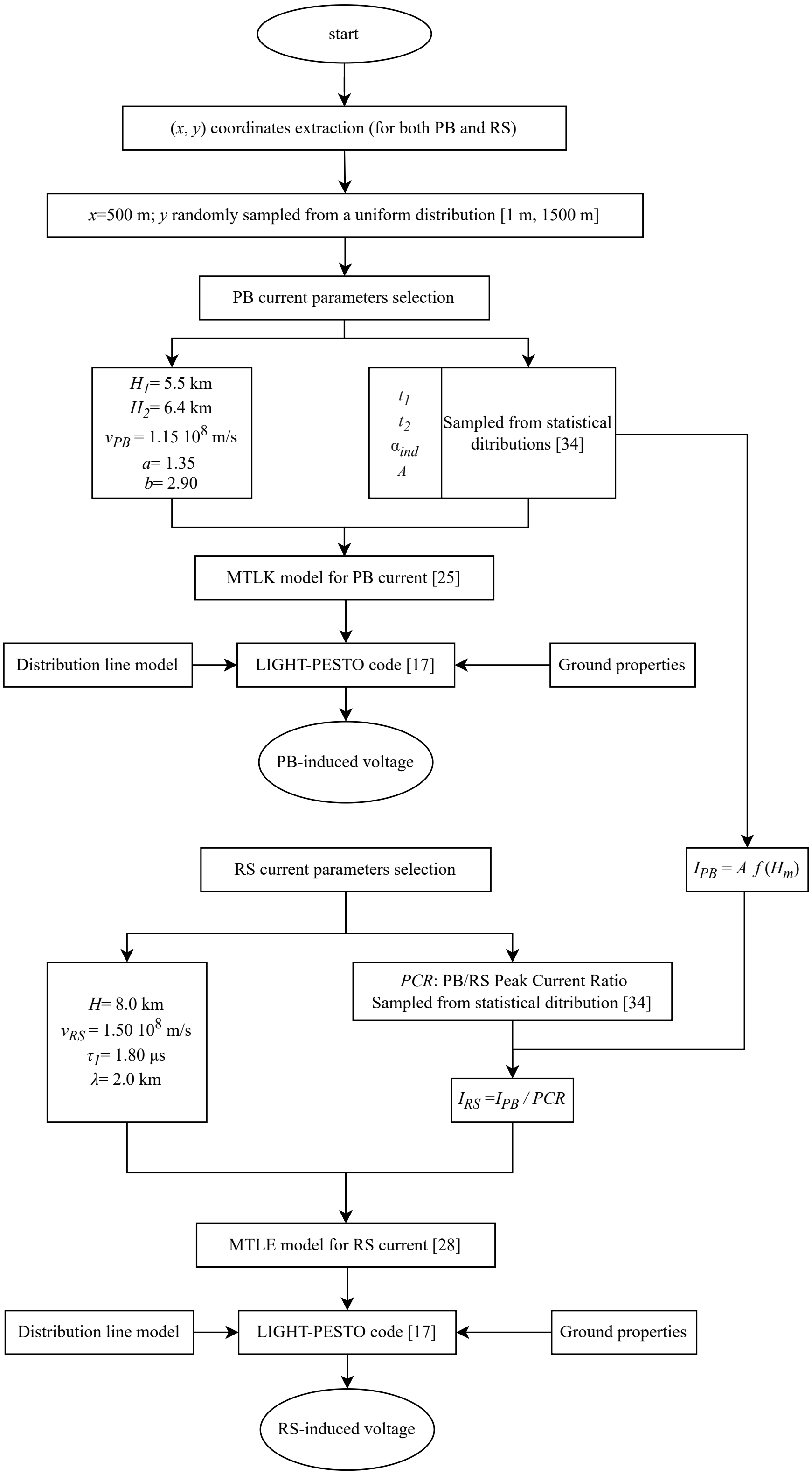

Figure 2: Simulation of voltage waveforms induced by the PB and RS phases of an individual lightning event.

Table 2: Statistical descriptors of the MTLK model parameters obtained from the dataset in [14]. AM and GM denote the arithmetic and geometric means, respectively. Data reproduced from [30].

Parameter	AM	GM	Median	Standard Deviation
t_1 (μs)	9.58	8.61	9.23	4.12
t_2 (μs)	49.05	43.40	45.41	23.78
α_{ind} ()	18.20	15.38	16.70	9.54
A (kA)	56.55	37.69	41.15	51.07

Table 3: Correlation matrix of the random MTLK model parameters. Adapted from [30].

	t_1	t_2	A	α_{ind}
t_1	1	0.60	0.37	-0.49
t_2		1	0.32	-0.33
A			1	-0.39
α_{ind}				1

$T_{RS} = 25$ μs $+r/c_0$ for Scenario B. The PB waveform evolves more slowly, resulting in a longer duration compared to the faster and shorter RS waveform. Accordingly, each PB- and RS-induced voltage signal contains $n_{PB} = 1 + T_{PB}/\Delta t$ and $n_{RS} = 1 + T_{RS}/\Delta t$ samples, respectively.

The spatial discretization is determined using Courant's stability criterion combined with the method of characteristics [31], giving $\Delta x = 3\, c_0\, \Delta t = 45$ m. On a Windows 10 workstation with 64 GB RAM and an Intel Core i9-14900KF CPU (5 GHz), the computation time for simulating a single PB pulse or RS and computing the corresponding voltages is approximately 1.8 s and 0.5 s, respectively [13].

8. Induced Voltage Datasets

Each LIGHT-PESTO simulation generates two voltage waveforms per sensor, corresponding to the PB and RS contributions. Flashes resulting in direct RS strikes are identified using the electro-geometric criterion [32] and excluded from the dataset, as these events induce voltage pulses on overhead conductors that are fundamentally different from those caused by electromagnetic coupling, requiring a distinct modeling approach in future studies.

For Scenario A (B), out of 16,972 (13,095) RS events producing an indirect flashover, 4,156 (6,925) are classified as dangerous, providing a measure of dataset balance. Representative segments of the induced voltage datasets are shown in Figure 3.

9. Conclusions

This report presented the first operational stage of the FELINES project, focusing on the generation of a comprehensive dataset of lightning-induced voltages on overhead distribution lines. Using the LIGHT-PESTO simulator, both Preliminary Breakdown (PB) and Return Stroke (RS) contributions were modeled for two

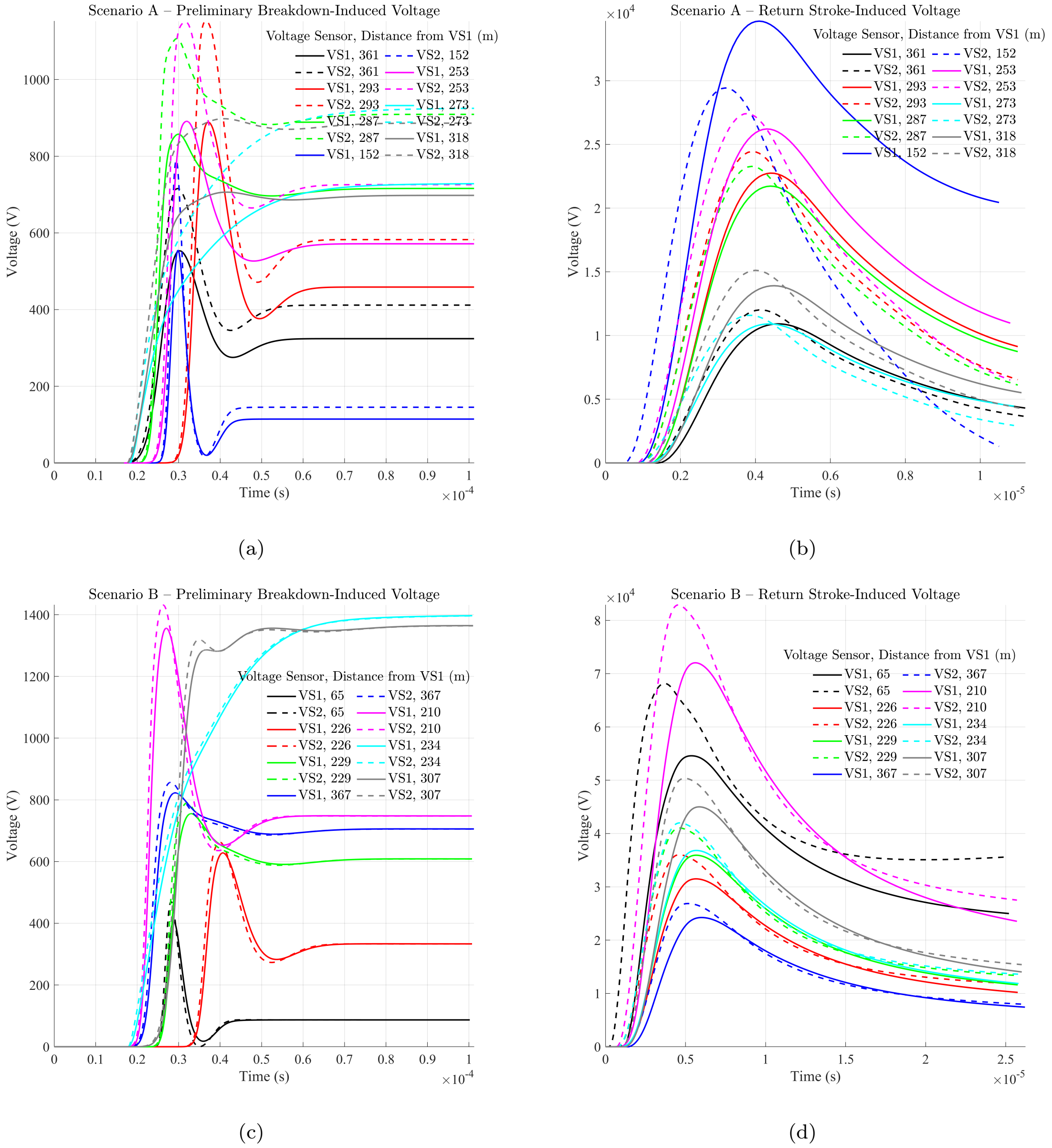

Figure 3: Sample voltage waveforms from the dataset. (a) PB-induced voltages for Scenario A measured at VS1 ($x = 500$ m) and VS2 ($x = 250$ m). (b) RS-induced voltages for Scenario A at VS1 and VS2. (c) PB-induced voltages for Scenario B at VS1 and VS2. (d) RS-induced voltages for Scenario B at VS1 and VS2.

different power systems and ground conditions. Both PB pulses and RS were simulated with a transmission-line–based approach. Randomization of key parameters and strike locations allowed for the creation of a large, balanced dataset suitable for training predictive algorithms. Direct strike events were excluded, ensuring the focus on indirect flashovers. These datasets provide the foundation for the next steps, where Deep Learning models will leverage PB-induced voltages to estimate RS peak amplitudes and identify potentially critical flashover events, supporting the development of a predictive lightning protection system.

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