

Progetto PRIN 2022 n° 20224CL7HM

FELINES

Forecast of the Effects of Lightning IN Electrical Systems

Deliverable I: State of the art

Compiled by A. Formisano with the cooperation of E. Akbarisekehravani, S. Barmada, D. Mestriner, R. Procopio, and the support of M. Brignone, M. Nicora.

V. 1.1 – Feb. 7th, 2024

Executive Summary

This document describes the bibliographic recognition performed as a first step in the frame of the research project FELINES (Forecast of the Effects of Lightning IN Electrical Systems) about different aspects of lightning events and their impact on electromagnetic devices and systems. It represents the first deliverable of the research project, financed by the Italian Ministry of Research under the PRIN 2022 call.

FELINES aims at designing a protection system capable of sensing electromagnetic fields that are preliminary to a lightning event, and consequently disconnect part (or all) of the electric infrastructure under its protection. These fields are generated by the so-called *Preliminary Breakdown Pulses* (PBP), localized events taking place during the first phases of the lightning inception.

Few studies in the literature exist about the modelling and measurements of such phenomena, and one of the key points of the project is to use them (or develop new ones) to perform a thorough study about the electromagnetic quantities that characterize the phenomenon itself, which can be measured and exploited for the protection system.

As a first step, a thorough literature analysis about Preliminary Breakdown Pulses (PBP) was performed to:

- find the available PBP mathematical models and assess their limits of applicability, strengths, and weaknesses;
- collect data available in the literature, and search for available data from other international research groups;
- define the most sensitive systems with respect to the effects of direct and especially indirect lightning.

The considered databases are mostly journals archives, such as *IEEE Explore* (ieeexplore.org), *Elsevier* (www.sciencedirect.com), *Wiley Online Library on Earth and Space sciences* (agupubs.onlinelibrary.wiley.com/), or *MDPI* (www.mdpi.com). The outcome of the bibliographic search is described in the following: Sect.1 shortly describes the FELINES project and its aims; Sect. 2 reports a description of papers and articles about the PBP models; Sect. 3 reports an overview of papers on available experimental data, and finally Sect. 4 presents a non-exhaustive list of potentially sensitive devices.

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1. Introduction

In this introduction we report a description of the main lines of the *FELINES* project, supported by the bibliography used during the preparation of research project (reported here for the sake of readability). The outcomes of the bibliographic research to define the state of the art on the different aspects of *FELINES* at its start (Fall 2023) will be given and discussed in the following sections, and are not listed in the bibliography, but rather examined with some details in the different sections.

The phenomena associated with Lightning Events (LE) represent a critical issue for the Electrical Infrastructures (EI). Among them, LE mostly impact the Transmission and Distribution Systems (TS & DS), but also Renewable Energy Sources (RES) and electronic devices are sensible to such damages.

The natural lightning can be categorized into four main types:

- *Intracloud lightning*, which is the most common type and solely occurs between two clouds.
- ***Negative cloud-to-ground (NC2G) lightning, starting from cloud to ground.***
- *Positive cloud-to-ground lightning*. It is similar to the second type, but much less common.
- *Upward lightning*, which rarely occurs and only happens by helping mountains or tall buildings.

The most common is the second one, and in this study, we are concerned with the possible early detection of such type of event.

In order to better understand the following discussion, let's briefly introduce some terms and notions about lighting discharges. Lightning is a large-scale natural spark discharge that occurs within the atmosphere or between the atmosphere and the Earth's surface. In an initial phase, within the atmosphere, positive and negative electric charges form due to processes like ionization of air molecules by some high-energy phenomenon (e.g. cosmic rays). In a thundercloud, water droplets and ice crystals move rapidly upward and downward, separating and concentrating these charges. Negative charges accumulate at the cloud's base, while positive charges gather toward the top.

The separation of positive and negative charges creates an intense electric field. As the area of negative charge at the base of the thundercloud builds up, it induces a region of positive charge on the ground below. This creates a voltage across the cloud-to-ground gap. When the voltage reaches a critical strength, the air between the cloud base and the ground becomes electrically conductive.

Mostly, the NC2G lighting begins with a negatively-charged downward-moving stepped leader. When the leader channel approaches the ground, immediately a strong electrical attraction develops between negative charge in the leader channel and positive charge on the surface of the ground. Several positively charged sparks develop and move upward toward the stepped leader.

One of these will intercept the stepped leader and close the connection between negative charge in the cloud and positive charge on the ground. A downward *dart leader* will then travel from the cloud to the ground. The dart leader does not step but travels smoothly and follows the channel created by the stepped leader (avoiding the branches). It is followed by a subsequent return stroke that travels back up the channel to the cloud. This second stroke might be followed by a third, a fourth, and so on. The subsequent return stroke channel usually does not have branches.

The earlier steps of this sequence have a distinct electromagnetic signature, that the *FELINES* project aims to detect through suited measurement systems and to use as a warning signal.

Different works [16]–[18] studied the modeling of the initial phases of LE (i.e., the so called Preliminary Breakdown Pulses - PBP) in terms of measured ElectroMagnetic Fields (EMF) and in terms of induced voltages on DS, showing that the electric field generated by dart leader has a significant impact on the amplitude and shape of the induced voltages in the time instants preceding the return stroke [18]. The authors of [16] investigated the

possible relationship between the electric field pulses and the preliminary phases of lightning discharge, while in [18] it is shown that in some cases the leader-induced voltages can be large enough to trigger protection devices.

As mentioned earlier, the most common lightning events begin with an upward discharge that starts at the ground, but are quite difficult to characterize, as their location cannot be known in advance, and measurements can only be done remotely (e.g. using high speed cameras or broad range electromagnetic field probes). On the other hand, a full-scale lightning discharge between a natural thundercloud and a designated point on the ground can be artificially initiated using the so-called rocket-and-wire technique. This technique involves to trigger lightning by firing/launching a small rocket extending a thin wire toward the charged clouds overhead. The wire spool can be either grounded or ungrounded. When the rocket arrives at a distance above the ground an upward streamer will develop off the top of the wire. Once the streamer reaches the cloud it can initiate a normal series of downward dart leaders and upward subsequent return strokes. After the upward, the positively charged leader reaches the negative charge center in the thundercloud. Then, a normal sequence of downward dart leaders and subsequent strokes usually follows. The current flow in triggered lightning discharges is through the wire, so it is possible to measure it. The effect of this current may cause the wire explosion. Note that this type can be classified as an artificial upward lightning.

Very few models of the initial phases of the lightning have been proposed. The first one was due to Loeb in 1966, later improved and formalized in 1976 by Griffiths and Phelps. A further one was presented by Karunarathne and coworkers in 2014, proposing a comparison among 3 different model based on the transmission line model. The shortcoming of this study is that the results were assessed on just 6 events. Later on (2008) Petersen and colleagues presented a review, but essentially the most diffused model to date refers to Griffiths and Phelps. The papers are discussed in Sect. 2.

The purposes of rocket-and-wire triggered lightning experiments are to better understand the physics of lightning discharge; to improve the lightning protection schemes; evaluate the performance of lightning locating systems can be evaluated; to test the validity of the lightning models. A schematic view of the lightning initiation due to the rocket and wire presence is reported in Fig. 1

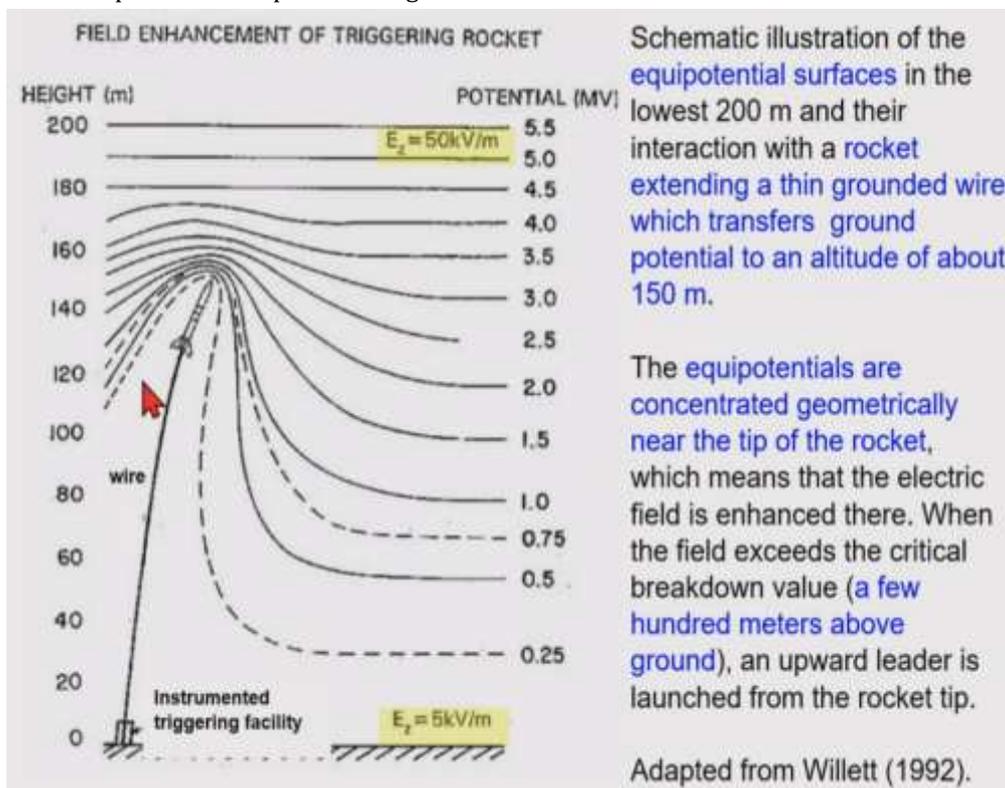


Fig. 1 - The scheme of rocket-and-wire technique (from Willett, 1992).

In most respects the triggered lightning is a controllable analog of the natural lightning. In fact, the first triggering was done in the U.S. in the 1960s over salt water. The figure below represents a photograph of the rocket-and-wire technique carried out in Florida in 1966.

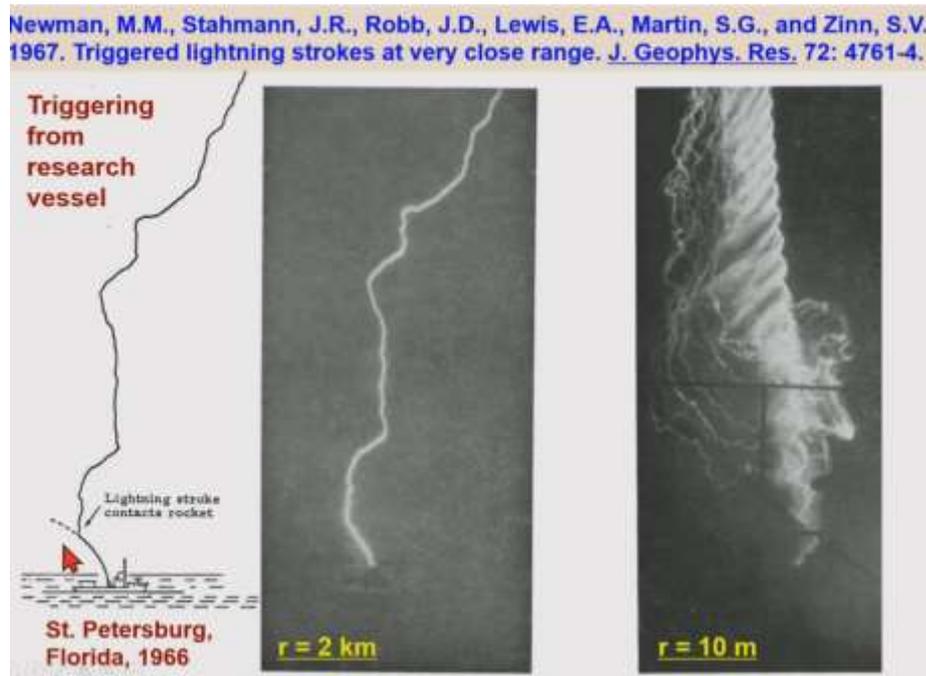


Fig. 2 – Pictures of the first rocket and wire triggered lightning strikes.

Successful rocket-and-wire lightning triggering were conducted in China by the Chinese Academy of Sciences (CAS). More than 300 flashes were triggered in seven different areas since 1977. Two sites are presently operated by CAS and Chinese Meteorological Administration (CMA).

A list of papers reporting rocket-triggered experiments is reported on Sect. 3.

Since 2012, a few experiments dedicated to measure the preliminary electromagnetic activity to the real lightning have been performed and discussed in the literature reported in Sect. 3

Finally, when dealing with damages due to LE, it is possible to distinguish between two categories: *direct strikes* and *indirect strikes* (the lightning hits the ground nearby the EI).

Electronic devices can suffer significant damage due to direct strikes. A few examples are:

Electrical Overloads: A direct lightning strike can introduce an enormous surge of electrical current into the power lines. This surge can overwhelm electronic devices, causing electrical overload. Components like circuit boards, transformers, and power supplies may fail due to excessive current.

Component Destruction: High-voltage surges can fry delicate components within devices. Integrated circuits, capacitors, and resistors may be irreparably damaged.

Fire Hazard: Intense heat from a lightning strike can ignite flammable materials. Damaged wiring, insulation, or electronic components can lead to electrical fires.

Communication Disruptions: Lightning-induced surges can affect communication lines (telephone, internet, etc.). Modems, routers, and network switches may fail or experience connectivity issues.

Antenna Damage: Lightning often strikes antennas, satellite dishes, or communication towers. Devices connected to these structures (TVs, radios, etc.) can suffer damage.

While direct hits are much more dangerous, indirect ones have a higher occurrence probability, which leads to a greater number of faults. A few examples are:

Effects of induced currents: The electromagnetic field generated by a nearby lightning strike can induce unwanted currents into nearby electrical wiring and devices. These induced currents can disrupt the normal operation of electronic equipment, causing malfunctions, data loss, and signal disturbances.

Data Loss: Indirect lightning strikes can corrupt data stored in electronic devices. Hard drives, solid-state drives, and memory cards are vulnerable, as sudden electromagnetic interference or power loss during a strike can lead to file system errors and data fragmentation.

Voltage Spikes: Lightning-induced voltage spikes can occur even if the strike doesn't hit directly. These spikes travel through power lines and can reach connected devices. Sensitive components (such as microchips and transistors) may get damaged by sudden voltage changes.

Typical examples of sensitive systems are overhead power lines of both TS and DS, Photovoltaic (PV) plants and Wind Turbine (WT) systems, all commonly positioned in large open spaces, hence more exposed to the lightning risk.

The evaluation of EMF coupling has been faced in several papers, analyzing the possible damages inferred to TS and DS [4], [9], [10] as well as on the RES (especially PV plants and WT) [11]–[14], leading to different models to evaluate the effectiveness of mitigation/protection systems. Due to the complexity of the EI, the most adopted models are the numerical ones, typically divided into *transmission-line* models and *full-wave* models. While the methods belonging to the first category usually require low computational effort, the second ones can model the complete electromagnetic coupling mechanism in soil or air with a higher level of detail.

Present lightning protection standards provide criteria for designing different kinds of Lightning Protection System (LPS), aimed at mitigating the risk associated with LE for the components of the EI. LPSs are based on the risk assessment, i.e., on the combination of:

- the number of LE affecting the considered EI (threat);
- the probability that a LE that affects the considered EI causes damage (vulnerability);
- the amount of the associated loss (consequence).

The protection of EI from LE [1] is based on the idea that hits are unavoidable due to the random nature of LE, and it is only possible to reduce damages. According to IEC EN 62305, four lightning protection levels can be introduced, and the possible protection measures depend on the infrastructure to be protected, but can be summarized as follows:

- Shielding wires (for DS and TS) [2];
- Earthing and Bonding measures [3];
- Surge protective devices [4];
- Cables shielding [5].

The choice of the protection system involves three main subsequent phases:

- a) the lightning current modeling [6];
- b) the Electro-Magnetic Fields (EMF) modeling [7]–[8];
- c) the modeling of the EMF coupling with the infrastructure to be protected, which provides the effective damage inferred to it.

The aim of the FELINES project is to investigate the possibility of measuring the PBP related fields and use these measurements as an early warning to trigger protection systems. As a first step of the project, thoughtful research of bibliography has been performed to identify possible models for the simulation of LE early phases, but also to

identify sources of measured data, as the experimental part is out of the scope of FELINES, which mainly relies on simulations of the PBP.

To easy categorizing the outcome of the bibliographic research, the results have been divided into three large groups, namely:

- State of the art about modeling – Results are reported and commented in Sect. 2;
- State of the art about experimental data - Results are reported and commented in Sect. 3;
- State of the art about sensitive devices - Results are reported and commented in Sect. 4.

A short discussion concludes this report.

The bibliographic research to define the state of the art about the PBP started from the pre-screened sources ([16]-18]), and was conducted essentially on the following journals/platforms:

- IEEE Explore (ieeexplore.org);
- Elsevier (www.sciencedirect.com);
- Wiley AGU journal (Advancing Earth and Space Sciences), mainly Geophysical Research Letters, Journal of Geophysical Research: Atmospheres, Radio Science (agupubs.onlinelibrary.wiley.com/);
- IOP Science (<https://iopscience.iop.org/journalList>), mainly Journal of Physics D: Applied Physics;
- MDPI (www.mdpi.com).

Results of the research is updated to December 2023, when this report was issued. For each of the relevant papers we report the publication date, the title, the list of authors, the journal, the link to the paper and the abstract. The most significant papers are reported in **bold font**.

2. State of the art about modeling

The most relevant papers found have been organized according to the research groups. We identified the following active groups:

1. Research group based at University of Florida (M. A. Uman) and at Kennedy Space Center (J. D. Hill).

The group worked on rocket-started lightning since 1966, but we report here contributions dating back only to 1998, in the frame of a cooperation with V. A. Rakov. The last contribution on this topic by the group, to the best knowledge of the writer, was in 2013.

Publ. year	Authors	Title	Journal	Link	Abstract
2013	T. Ngin, M. A. Uman, J. D. Hill, J. Pilkey, W. R. Gamerota, D. M. Jordan, R. C. Olsen III	Measurement and analysis of ground-level electric fields and wire-base current during the rocket-and-wire lightning triggering process	Atmospheres	agupubs.onlinelibrary.wiley.com/doi/full/10.1002/jgrd.50774	We present ground-level electric field intensity and trigger-wire-base current measurements in Florida during 33 successful rocket-and-wire triggered lightning attempts, those which initiated a sustained upward leader, and 20 unsuccessful attempts. The electric field changes during wire ascent were measured at eight stations between 35 m and 208 m from the launch site while the electric fields produced by precursor discharges at the ascending wire tip were measured at 120 m and 220 m. Both relatively steady trigger wire currents in the milliamperere-range and fast precursor currents in the ampere to hundred-ampere range were measured at the wire base. A total of 2196 individual precursors were measured in 45 launches with negative charge overhead, with 0 to 225 precursors per launch and each precursor depositing 1 μC to 157 μC of charge at the wire tip. With negative charge overhead, slowly varying currents measured during the wire ascent increased to a maximum value between 3 mA and 10 mA. Positive line charge densities on the trigger wire were inferred from both the wire-base current and the ground-level electric field reduction during wire ascent for 38 launches, ranging from 1 $\mu\text{C m}^{-1}$ near ground to about 100 $\mu\text{C m}^{-1}$ at 200 m to 300 m aloft. A comparison of successful launches and unsuccessful launches with negative charge overhead shows that successful launches tend to have larger trigger wire line charge densities and larger precursor charge magnitudes, implying larger electric fields aloft. Three unsuccessful triggering attempts were made with positive charge overhead.
2011	Christopher J. Biagi, M. A. Uman, J. D. Hill, D. M. Jordan	Observations of the initial, upward-propagating, positive leader steps in a rocket-and-wire triggered lightning discharge	Geophysical Research Letters	agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2011GL049944	We present high-speed video images (recorded at 300 kfps) of an upward positive leader developing stepwise from the top of a grounded triggering wire. The leader initiated from the wire top at a height of 123 m, and was imaged over a distance of 11 m in ten discrete steps. Unique current pulses were detected at the wire base corresponding to each optical step. Luminosity waves propagated downward from the leader tip. The step lengths ranged from 0.4 to 2.2 m; the interstep time intervals from 16.6 to 30.4 μs . The leader's upward development speed increased with height, from $5.5 \times 10^4 \text{ m s}^{-1}$ between heights of 123 m and 134 m, the bottom 11 m, to $2.1 \times 10^5 \text{ m s}^{-1}$ at a height of 350 m. The measured wire-base peak currents for the individual steps ranged from 17 to 153 A. After removing from the wire-base current measurements the effect of propagation on the triggering wire and the effect of reflection at the ground connection, we estimate that the peak currents at the wire top, the step current, ranged from 10 to 89 A. The charge lowered to ground following each step ranged from 22 to 107 μC . The leader channel contained, on average, 51 $\mu\text{C m}^{-1}$ of positive charge, a value that is similar to laboratory measurements of long positive polarity sparks.
2010	C. J. Biagi, M. A. Uman, J. D. Hill, D. M. Jordan, V. A. Rakov, J. Dwyer	Observations of stepping mechanisms in a rocket-and-wire triggered lightning flash	Atmospheres	agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2010JD014616	We present 10 high-speed video images that depict the bottom 150 m of a downward-negative, dart-stepped leader in a rocket-and-wire triggered flash, recorded at 240 kiloframes per second (4.17 μs frame integration time), along with correlated measurements of the X-ray emission at 50 m, electric field derivative (dE/dt) at 80 m, and the rocket-launch-tower current beneath the leader. We observed discrete segments of secondary channel that exhibited luminosity above that of the surrounding corona streamers and were distinctly separate and beneath the downward-extending leader channel. These segments appear similar to the space stems or space leaders that have been imaged in long negative laboratory sparks. Multiple simultaneous pulses in X-ray emission, dE/dt , and launch tower current were recorded during the time that the leader steps were imaged. The leader extended at an average downward speed between 2.7×10^6 and $3.4 \times 10^6 \text{ m s}^{-1}$.
2009	C. J. Biagi, D. M. Jordan, M. A. Uman, J. D. Hill, W. H. Beasley, J. Howard	High-speed video observations of rocket-and-wire initiated lightning	Geophysical Research Letters	agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2009GL038525	We present observations of a rocket-and-wire triggered lightning flash obtained with high-speed video cameras recording 5400 and 50000 frames per second (frame times 185 μs and 20 μs) with time-synchronized current and electric field measurements. Transient leader channels were observed with precursor current pulses occurring before the development of the sustained upward positive leader that initiated the initial continuous current. The sustained upward positive leader stepped with a constant speed of $5.6 \times 10^4 \text{ m s}^{-1}$ over its initial 100 m. The wire destruction occurred discontinuously over a time of 7 ms about 45 ms after sustained upward leader inception, with a small change in channel current. Downward leaders, upward connecting leaders, and filamentary streamers were imaged in the bottom 50 m of the channel. We present the first images of a negative step forming in lightning, apparently

					involving a space stem similar to steps in meter-length negative laboratory sparks.
1999	D. Wang, V. A. Rakov, M. A. Uman, M. I. Fernandez, K. J. Rambo, G. H. Schnetzer, R. J. Fisher	Characterization of the initial stage of negative rocket-triggered lightning	Atmospheres	agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/1998JD200087	We performed a statistical study on the initial stage (IS) of negative rocket-triggered lightning using 37 channel-base current recordings obtained during the summer of 1994 at Fort McClellan, Alabama, and during the summers of 1996 and 1997 at Camp Blanding, Florida. The IS can be viewed as composed of an upward positive leader (UPL) followed by an initial continuous current (ICC). The IS has a geometric mean (GM) duration of 279 ms and lowers a GM charge of 27 C to the ground. The average IS current in an individual lightning discharge varies from a minimum of 27 A to a maximum of 316 A with a GM value of 96 A for the entire sample of 37 discharges. We examined the current variation at the beginning of the IS in 24 flashes. In 22 out of 24 cases this initial current variation (ICV) includes a current drop, probably associated with the disintegration of the copper triggering wire and the subsequent current reestablishment. The GM time interval between the onset of the initial stage and the abrupt decrease in current is 8.6 ms, and the GM current level just prior to the current decrease is 312 A, a value about 3 times the GM value of average current for the whole IS, 96 A. Before this abrupt current decrease, a GM charge of 0.8 C has been lowered to ground with a corresponding GM action integral of 110 A2 s. The abrupt current decrease takes typically several hundred microseconds and is followed, immediately or after a time interval up to several hundred microseconds, by a pulse with a typical peak of about 1 kA and a typical risetime of less than 100 μs. The ICC usually includes impulsive processes that resemble the M processes observed during the continuing currents that follow return strokes in both natural and triggered lightning. We present statistics for the following parameters of current pulses superimposed on the ICC: magnitude, risetime, half-peak width, duration, charge transferred, preceding continuous current level, interpulse interval, and time interval between the onset of the IS and the first ICC pulse. The observed characteristics of ICC pulses varied significantly among the three data sets. For all data combined, the characteristics of the ICC pulses are similar to those of the M-component current pulses studied by Thottappillil et al [1995]. This latter finding suggests that ICC impulsive processes are of the same nature as M processes.
1998	P. Lalande, A. Bondiou-Clergerie, P. Laroche, A. Eybert-Berard, J.-P. Berlandis, B. Bador, A. Bonamy, M. A. Uman, V. A. Rakov	Leader properties determined with triggered lightning techniques	Atmospheres	agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/97JD02492	This paper presents current and electric field measurements from two triggered lightning flashes, 9519 and 9516, initiated by the "classical" and "altitude" technique, respectively, at Camp Blanding, Florida, in 1995. The current measurement for flash 9519 shows that the upward positive leader, initiated at the top of the grounded wire unreeled by the triggering rocket, propagates in a discontinuous pattern made of successive current pulses of tens to a few hundreds of amperes and separated by intervals of 20–25 μs. The downward negative leader in flash 9516, initiated from the electrically floating conductor, has a velocity greater than 1.3×10 ⁵ m s ⁻¹ , a stepping interval of 18 μs, and step length of about 3–5 m; the associated peak currents inferred from the electric field steps are at least 600 A.

The papers from the group highlighted differences between "laboratory" PBP and actual lightning precursors, yet some conclusions have been drawn. We report here just some excerpts from the various publications.

- The extent to which laboratory leaders resemble lightning leaders is unclear, since the scales of the two in length, voltage, current and time can be considerably different. **However, there are several reports of observations of stepped or dart-stepped leaders in lightning that resemble laboratory sparks.**
- The ground-level electric field is highly influenced by the space charge layer at ground, so the spatial variation of these electric fields might reveal something about the space charge layer.
- The upward positive leader is stepped, and initially it is like sparks

2. *Research group based at Chinese Academy of Science in Beijing and University of Science and Technology of China, Hefei.*

The group started working on the lightning initiation back in 1976, in the frame of a cooperation with Griffiths and Petersen. Then, since 2014, they started proposing a few models of the time evolution of the phenomenon.

Publ. year	Authors	Title	Journal	Link	Abstract
2021	X. Li, G. Lu, R. Jiang, H. Zhang, Y. Fan, T. Shi, X. Qie, Y. Zhang, H. Ren, C. Zhang, Y. Zhang	On the Transition from Precursors to the Initial Upward Positive Leader in Negative Rocket-Triggered Lightning	Atmospheres	agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020JD033926	Precursory current pulses (precursors) and initial upward leader pulses are examined to characterize the charge transfer of precursors and the sustained upward leader during the early stage of rocket-triggered lightning. According to the analysis of six negative triggered flashes, it is found that both precursors and the initial upward positive leader (iUPL) pulse are led by a small deflection that appears at about 25 μs prior to the major pulses. The characteristics of precursors and iUPL pulses are very similar except that the precursors generally transfer less electric charge (35.07 μC on average) than iUPL pulses do (64.73 μC on average). Some marginal differences in the parameters (e.g., rise time, duration) may be attributed to the modification of the current pulses caused by the different impedances of the leader channel and the steel wire. The ascending rocket causes the enhancement of electric field (E-field) in the close vicinity of the wire tip, and therefore the breakdown of the iUPL is initiated by a stronger E-field than that of the precursors. The step lengths of the precursors (defined as the extended length of the wire tip lifted by the rocket between two adjacent isolated precursors) are similar to that of iUPL pulses. Our analyses indicate that the

transition from precursors to the iUPL occurs when the E-field around the wire tip is strong enough, by the accumulation of more positive charge, to launch a meter-scale breakdown and the ensuing charge transfer to ground.

2020 S. Huang, W. Chen, Z. Pei, Z. Fu, L. Wang, T. He, Z. Li, J. Gu, K. Bian, N. Xiang, Y. Wang

The Discharge Preceding the Intense Reillumination in Positive Leader Steps Under the Slow Varying Ambient Electric Field

Geophysical Research Letters

agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019GL086183

Under the slow varying ambient electric field, positive leader propagation exhibits steps characterized by intense reilluminations and abrupt elongations. These steps are currently not well understood. In this work, we investigate these steps in laboratory atmospheric discharges, using a high-speed video camera and a synchronized electrical parameter measurement system. The discharge, emitting weak light and preceding the intense reillumination, is discovered. This finding suggests that the leader channel actually restarts and extends forward before the intense reillumination, which deepens our understanding of the dynamic process of the positive leader step. The discharge before the intense reillumination contributes to the corona inception from the electrode, leading to the intense reillumination of the leader channel and the emergence of an intense corona streamer burst from the leader tip.

2020 Y. Fan, G. Lu, Y. Zhang, W. Lyu, D. Zheng, X. Fan, X. Li, Y. Zhang

Characterizing Radio Frequency Magnetic Radiation of Initial Upward Leader Stepping in Triggered Lightning With Interferometric Lightning Mapping

Geophysical Research Letters

doi.org/10.1029/2020GL089392

In summer of 2019, the bandwidth of magnetic field sensor with relatively high sensitivity was extended to 1.2 MHz during the triggered lightning experiment of Field Experiment Base on Lightning Sciences, China Meteorological Administration (CMA-FEBLS) in Conghua, Guangdong Province. The measurements with the new magnetic fields reveal the presence of microsecond-scale magnetic pulses during the entire duration of upward positive leader (UPL), including the quiet stage when only few signals can be discerned in previous observations, which indicates that the UPL generally propagates in a stepwise manner during the initial stage of triggered lightning. Synchronous mapping observations from the broadband VHF interferometer shows that the VHF radiation corresponds to the onset of individual magnetic pulses, indicating that the VHF signals are radiated by the breakdown processes of individual stepping, and these breakdown events launch the meter-scale current pulses as the radiation source of individual magnetic pulses.

2020 Z. Chen, Y. Zhang, Y. Fan, J. Wang, D. Zheng, X. Fan, L. Xu, W. Lyu and Y. Zhang

Evolution Characteristics during Initial Stage of Triggered Lightning Based on Directly Measured Current

Atmosphere

www.mdpi.com/2073-4433/11/6/658

The initiation of a leader is an important lightning discharge process, but how an upward positive leader (UPL) initiates is still not fully understood. The evolution characteristics of a UPL during its initial stage was systematically studied based on directly measured current data of 14 triggered lightning events in 2019. It was found that the initial stage of triggered lightning can be divided into two types: a single initial process form and a multiple initial process form, with percentages of 64.29% and 35.71%, respectively. Compared with the former, the latter usually lasts longer, and the corresponding lightning is often triggered under a lower ground-level quasi-static electric field. In each initial process, precursor current pulses (PCPs), PCP clusters and initial precursor current pulse (IPCPs) are typical current waveforms, and the pulse durations and transferred charges of PCPs increase linearly with time. However, in the multiple initial process form, the pulse durations and transferred charges of PCPs will reduce significantly after each previous initial process and then continue to increase in the following initial process. In each initial process, when the pulse duration and transferred charge of a PCP increase to a certain extent, PCP clusters and IPCPs begin to appear. For the emergence of PCP clusters, the average values of the threshold are 3.48 μ s and 19.53 μ C, respectively. For the occurrence of IPCPs, the corresponding values are 4.69 μ s and 27.23 μ C, respectively. The average values of pulse durations and transferred charges of IPCPs are larger than those of PCP clusters. Compared with adjacent PCP clusters, IPCPs contain more pulses, with a critical range of 6–7. IPCPs also last longer, and have a critical range of 138–198 μ s.

2019 Y. Fan, G. Lu, X. Li, T. Zheng, H. Zhang, R. Jiang, M. Liu, X. Qie, Y. Zhang, Y. Zhang, W. Lyu, D. Zheng

Measurements of burst of magnetic pulses during the initial continuous current in rocket-triggered lightning.

Atmospheres

agupubs.onlinelibrary.wiley.com/doi/10.1029/2019JD031237

During the Shandong Triggering Lightning Experiment (SHATLE) in summer of 2014 and 2015 and the Guangdong Comprehensive Observation Experiment on Lightning Discharge (GCOELD) campaign in 2018, we have conducted the observations of the magnetic pulse bursts (MPBs) during the initial continuous current in negative rocket-triggered lightning. The MPBs are commonly recorded at the main site of SHATLE (970 m from the rocket launch site), but the synchronous magnetic field (B-field) measurements at the close site of SHATLE (78 m from the rocket launch site) show the slow variations with small MPBs superposing on them. Note that both the charge transfer and the relative brightness increase notably during the appearance of the MPBs. After shifting up the operation frequency of the magnetic sensor, the MPBs can be observed at close distance (80 m from the rocket launch site) obviously in GCOELD. Observations show that the radiation sources of MPBs originate from the breakdown in the vicinity of the leader tip, but the sources of the initial magnetic pulses (IMPs) measured at the very initial stage of triggered lightning are from the radiation of the whole steel wire. The continuous current measured at the channel base during the MPBs cannot reflect the characteristics of breakdown current, because the current is attenuated and dispersed when propagating along the high-impedance leader channel. The average peak current associated with the MPBs is estimated to be on the order of kiloamperes.

2019	X. Li, G. Lu, Y. Fan, R. Jiang, H. Zhang, D. Li, M. Liu, Y. Wang, H. Ren	Underground Measurement of Magnetic Field Pulses During the Early Stage of Rocket-Triggered Lightning	Atmospheres	agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018JD029682	We examined the underground magnetic field near the lightning channel with low-frequency magnetic sensor based on SHandong Triggering Lightning Experiment (SHATLE). Two sensors were deployed, one at 1-m height above ground and another one at 2-m depth underground at a distance of 78 m from the lightning channel, and the magnetic pulses during the initial stage of triggered lightning were recorded. The experimental results show that the microsecond-scale magnetic pulses radiated by the upward lightning leader can be detected in the subsurface space and the magnetic signal is modified by the soil medium. Specifically, the amplitude at the depth of 2 m is attenuated typically more than 55%, and the attenuation decreases as the timescale of the magnetic pulse increases; meanwhile, the peak time of the underground magnetic pulse is delayed by about 0.6 μ s, and the half-peak width of the magnetic pulse is increased by 0.2–0.8 μ s (namely, by 20% to 32%). The results of Fourier analysis indicate that the component with relatively high frequency is subject to more attenuation than is the component with relatively low frequency. In addition, the simulation of magnetic field with the channel-base current by using the transmission line model is consistent with the measurement, indicating that the modification on the waveform characteristics of the lightning pulse measured underground could provide valuable information for retrieving the electromagnetic parameters of soil.
2018	Y. Fan, G. Lu, R. Jiang, H. Zhang, X. Li, M. Liu, X. Qie, D. Zheng, W. Lyu, Y. Zhang, Y. Zhang	Characteristics of Electromagnetic Signals During the Initial Stage of Negative Rocket-Triggered Lightning	Atmospheres	agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018JD028744	With the measurements in SHandong Triggering Lightning Experiment and Guangdong Comprehensive Observation Experiment on Lightning Discharge in China, we examine the electromagnetic signals associated with the upward positive leaders during the initial stage of negative triggered lightning. The magnetic field (B field) signals measured at close range (<100 m) for both sites can be divided into two categories (i.e., impulsive and ripple pulses) according to the discernibility of separation between individual pulses. The impulsive pulses are well simulated by using the transmission line model, which suggests that these pulses are generated by leader current pulses propagating downward along the steel wire. Because the length of extended leader channel ahead of the wire is not negligible during the stage of ripple pulses, the waveform of impulsive current pulses is changed after traveling through the high impedance leader channel. Taking the filtered current pulse as the input variable, the waveform of ripple pulse can be simulated properly, which indicates that ripple pulses are caused by the attenuation of impulsive current along prolonging leader channel. In addition, the paper analyzes the fast electric field (E field) changes measured at 60-m range from the launching site during the initial stage by using the transmission line model and shows that the polarity of E field change at a given range is determined by the inception height of upward leader, namely the surface E field change caused by the individual charge transfer of initial upward leader also involves the problem of reverse distance as present for a vertical dipole.
2017	Y. Zhang, P. R. Krehbiel, Y. Zhang, W. Lu, D. Zheng, L. Xu, Z. Huang	Observations of the initial stage of a rocket-and-wire triggered lightning discharge	Geophysical Research Letters	agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2017GL072843	Observations have been obtained of the initial stage of a rocket-and-wire-triggered lightning flash with a high-resolution broadband VHF interferometer. The discharge produced 54 precursor current pulses (PCPs) over 883 ms during the rocket's ascent. The interferometer observations show that the PCPs were produced by breakdown at the ascending tip of the rocket, and that individual PCPs were produced by weak upward positive breakdown over meters-scale distances, followed by more energetic, fast downward negative breakdown over several tens of meters distance. The average propagation speeds were $\sim 5 \times 10^6$ m s ⁻¹ and $\sim 3 \times 10^7$ m s ⁻¹ , respectively. The sustained upward positive leader (UPL) was initiated by a rapid, repetitive burst of 14 precursor pulses. Upon initiation, the VHF radiation abruptly became continuous with time. Significantly, breakdown during the UPL appeared to extend the discharge in a similar manner to that of the precursor pulses.
2016	G. Lu, H. Zhang, R. Jiang, Y. Fan, X. Qie, M. Liu, Z. Sun, Z. Wang, Y. Tian, K. Liu	Characterization of initial current pulses in negative rocket-triggered lightning with sensitive magnetic sensor	Radio Science	agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016RS005945	We report the new measurement of initial current pulses in rocket-triggered lightning with a broadband magnetic sensor at 78 m distance. The high sensitivity of our sensor makes it possible to detect weak ripple deflections (as low as 0.4 A) that are not readily resolved in the typical measurements of channel-base current in rocket-triggered lightning experiments. The discernible magnetic pulses within 1 ms after the inception of a sustained upward positive leader from the triggering wire can be classified into impulsive pulses and ripple pulses according to the discernibility of separation between individual pulses. The time scale (usually >20 μ s) of ripple pulses is substantially longer than the leading impulsive pulses (with time scales typically <10 μ s), and the amplitude is significantly reduced, whereas there is no considerable difference in the interpulse pulse. Along with our previous finding on the burst of magnetic pulses during the initial continuous current in rocket-triggered lightning, the new measurements suggest that the stepwise propagation might be a persistent feature for the upward positive leader in rocket-triggered lightning, and the stepping of positive leader early in triggered lightning could be characterized with the observation of ripple pulses. The precedence of impulsive magnetic pulse measured at 78 m range relative to the arrival of corresponding current pulse at the channel base indicates that the ionization wave launched by individual stepping of positive leader propagates downward along the triggering wire at a mean velocity of 1.23 $\times 10^8$ m/s to 2.25 $\times 10^8$ m/s.
2014	G. Lu, R. Jiang, X. Qie, H. Zhang, Z. Sun, M. Liu, Z. Wang, K. Liu	Burst of intracloud current pulses during the initial continuous current in a rocket-triggered lightning flash	Geophysical Research Letters	agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2014GL062127	For a rocket-triggered lightning flash on 2 August 2013, the measurement with one pair of broadband low-frequency (20–400 kHz) magnetic induction coils registered a long sequence of over 600 intermittent pulses during the initial continuous current. The timescale of these pulses is about 3–8 μ s, and the typical interpulse interval is about 30 μ s. The source discharges of these pulses, which are not readily detectable in the frequency range (140–300 MHz) of a short-baseline very high frequency (VHF) lightning imaging system, are attributed to the stepping processes when the positive leader

As a conclusion, we may state that the research about modeling of PBP has been largely conducted using rocket-triggered events. The papers from the group highlighted some common aspects of the different experiments. We report here just some excerpts from the various publications.

- The initial stage of triggered lightning can be divided into two types: a single initial process form and a multiple initial process form. Compared with the former, the latter usually lasts longer, and the corresponding lightning is often triggered under a lower ground-level quasi-static electric field.
- Both precursor discharges and the initial upward leader begin with a small pulse that leads the subsequent major pulses by about 25 μ s.
- Magnetic pulse bursts are commonly observed during the initial continuous current of negative rocket-triggered lightning.
- The radiation sources of the magnetic pulse bursts derive from the breakdown in the vicinity of the positive leader.
- The average peak current associated with magnetic pulse bursts is on the order of kiloamperes by estimation.

3. Research group based at Université Paul Sabatier, Toulouse (FR).

This group, mainly composed by Serge Chauzy and Serge Soula, in '80s and early '90s of last century, tried to measure and model the electric field beneath the thunderclouds. To the best of the writer knowledge, their activity in the modeling stopped in early years of 2000.

Publ. year	Authors	Title	Journal	Link	Abstract
2007	C. Barthe and J.P. Pinty	Simulation of electrified storms with comparison of the charge structure and lightning efficiency	JOURNAL OF GEOPHYSICAL RESEARCH	agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2006JD008241	An electrification and lightning flash scheme was run in a cloud-resolving model to study the electrical structure of idealized convective storms with several charge separation parameterizations. The electrification of an intense multicellular storm was first simulated. The results confirm the sensitivity of the cloud polarity and lightning flash characteristics to three noninductive charging formulations. Furthermore, it is found that the inductive charging is an efficient mechanism to enhance the lower electric charge, which favors cloud-to-ground flashes. Then, microphysical and electrical budgets were calculated for the convective and stratiform regions of a two-dimensional squall line. The simulation shows that the liquid water content is high enough to generate graupel by riming. Thus the noninductive separation process is efficient to charge the stratiform plume as well, and lightning flashes can be triggered. Finally, the application of various noninductive charging schemes to several convective storms showed the storm electrification variability, which heavily depends on the cloud dynamics and microphysics. The study reveals some remarkable features concerning the charge structure and the cloud-to-ground flash polarity.
1991	S. Chauzy, J. C. Médale, S. Prieur, S. Soula	Multilevel measurement of the electric field underneath a thundercloud: 1. A new system and the associate data processing"	JGR Atmospheres	agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/91JD02031	In order to study the formation and evolution of the charge layer created by a corona at the ground underneath thunderclouds, we have developed a new system of electric field detection. It is composed of five self-contained sensors designed to measure the ambient electric field at various altitudes between the surface and a tethered balloon that suspends the entire system of equipment. Each sensor can detect ambient field intensities up to 150 kV/m with an accuracy of 1.5% and without any detectable influence of a local corona effect on the measurement. A standard shutter field mill detects the surface electric field. The data collected aloft are telemetered via a 400-MHz frequency band. An adapted data processing system provides a real-time display of the multilevel evolution of the electric field within the first hundreds of meters above the ground. The digitized data can be used to display the instantaneous vertical profile of field intensity on various time scales.
1987	S. Chauzy, S. Soula	General interpretation of surface electric field variations between lightning flashes	JGR Atmospheres	agupubs.onlinelibrary.wiley.com/doi/10.1029/1029JD0921D05p05676	The evolution of the electric field underneath a thunderstorm is measured and modeled, taking into account ion production by corona at ground level. Measurements of electric field and calculations of charge densities were made at various levels above the surface during two summer experiments. The collected data show that although the corona effect drastically influences the surface electrical parameters, some information about thunderstorm electrification can be obtained from consideration of the Maxwell current density. Thus the rate of change of electric field as well as the rate of generation of corona ions are obtained from the evolution of the surface electric field. Average charge densities ranging up to 6 nC/m ³ are commonly found over intervals of several minutes within the lowest 15 m, especially during periods of intense lightning activity. Modeling reveals the influence of field changes due to lightning flashes and of the corona threshold on the surface electric field variation. The orders of magnitude computed by the model agree reasonably well with the experimental data.

1982	S. Chauzy, P. Raizonville	Space charge layers created by coroneae at ground level below thunderclouds: Measurements and modeling	JGR Oceans	agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JC087iC04p03143	High electric fields created by thunderclouds at ground level are enhanced by the irregularities of the surface. This causes corona discharges to occur. The generated ions, when they are not blown away, form a space charge layer which reduces the magnitude of the electric field at ground level. During the LANDES 79 experiment (south western France), electric field soundings have been performed. The sensor is a balloon-borne double field-mill device designed for measuring the vertical and horizontal components of the external electric field. At several occasions, a strong vertical field increase with height was detected in the lower part of the sounding. This reveals the existence of important space charge layers near the ground. Space charge density profiles are deduced from electric field soundings. They display density values running from 2 to 7 nC m ⁻³ , distributed over shallow layers. A numerical model taking into account ion capture by the neutral aerosol particles leads to theoretical charge density profiles which display features close to those of the experimental profiles. Computation shows that the initial number of neutral aerosol particles has a drastic effect on both density maximum values and layer depths. According to aerosol density, charge density values run from 0.6 nC m ⁻³ (in clean air) up to 3.1 nC m ⁻³ (high aerosol density).
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Finally, *models of PBP* are described in several papers for authors not closely related to the groups identified above. A list, by no means exhaustive, is reported here.

Publ. year	Authors	Title	Journal	Link	Abstract
2019	A. Attanasio, P. R. Krehbiel, C. L. da Silva	Griffiths and Phelps Lightning Initiation Model, Revisited	JGR Atmospheres	agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019JD030399	In this paper we reconstruct Griffiths and Phelps' seminal model of streamer systems to test if it can reproduce the key observational features of fast positive breakdown. We first confirm that our implementation is accurate by reproducing the original results. The model describes how a system of positive streamers exhibits an initial exponential charge growth, as a function of position or time, which rapidly transitions into a quadratic steady state. The charge growth is accompanied by substantial electric field enhancement near the onset location, creating favourable conditions for lightning initiation. Due to the relatively low conductivity of streamers (effectively zero in this model), the electric field enhancement is created by the charge deposited in the first few meters of propagation, in the scale length where the charge growth transitions from exponential to quadratic. The quadratic growth of charge, combined with conical system expansion, makes the surface charge density of the moving front constant. The resulting electric field ahead of the streamer system remains nearly constant during its propagation, consistent with the observations of fast breakdown, which reveal a nearly constant propagation velocity, independently of discharge polarity. Minimal changes to the model allow for simulation of narrow bipolar events, reproducing very well their characteristic bipolar electric field change waveform. Despite its simplicity, the Griffiths and Phelps model provides valuable physical insights in the relationship between fast positive breakdown and lightning initiation.
2017	Q. Cai, J. Jánský, V. P. Pasko	Initiation of positive streamer corona in low thundercloud fields	Geophysical Research Letters	agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2017GL073107	Formation of filamentary gas discharge forms, commonly referred to as streamers, is one of the conditions required for initiation and subsequent propagation of lightning leaders. It is quantitatively demonstrated that streamers can be initiated under thunderstorm conditions when two precipitation particles cause an enhancement of the electric field by passing in close vicinity of each other. Conditions for avalanche-to-streamer transition are documented using a model of two spherical hydrometeor particles placed in uniform ambient field. The results are presented in scaled form using similarity relations for gas discharges and can be applied for a wide range of thunderstorm conditions, including different air pressures, electric fields, and particle dimensions.
2016	L. P. Babich, E. I. Bochkov, I. M. Kutsyk, T. Neubert, O. Chanrion	Positive streamer initiation from raindrops in thundercloud fields	JGR Atmospheres	agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016JD024901	The threshold field for the electric gas discharge in air is ≈ 26 kVcm ⁻¹ atm ⁻¹ , yet the maximum field measured (from balloons) is ≈ 3 kVcm ⁻¹ atm ⁻¹ . The question of how lightning is stimulated is therefore one of the outstanding problems in atmospheric electricity. According to the popular idea first suggested by Loeb and developed further by Phelps, lightning can be initiated from streamers developed in the enhanced electric field around hydrometeors. In our paper, we prove by numerical simulations that positive streamers are initiated, specifically, around charged water drops. The simulation model includes the kinetics of free electrons, and positive and negative ions, the electron impact ionization and photon ionization of the neutral atmospheric constituents, and the formation of space charge electric fields. Simulations were conducted at air pressure 0.4 atm, typical at thundercloud altitudes, and at different background electric fields, drop sizes, and charges. We show that the avalanche-to-streamer transition is possible near drops carrying 63–485 pC in thundercloud fields with intensity of 10 kVcm ⁻¹ atm ⁻¹ and 15 kVcm ⁻¹ atm ⁻¹ for drops sizes of 1 mm and 0.5 mm, respectively. Thus, the electric field required for the streamer formation is larger than the measured thunderstorm fields. Therefore, the results of simulations suggest that second mechanisms must operate to amplify the local field. Such mechanisms could be electric field space variations via collective effects of many hydrometeors or runaway breakdown.
2014	S. Karunarathne, T. C. Marshall, M. Stolzenburg, N. Karunarathna	Modeling initial breakdown pulses of CG lightning flashes	JGR Atmospheres	https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2014JD021553	Electric field change waveforms of initial breakdown pulses (IBPs) in cloud-to-ground (CG) lightning flashes were recorded at ten sites at Kennedy Space center, Florida, in 2011. Six "classic" IBPs were modeled using three modified transmission line (MTL) models called MTL1, MTL2, and MTL3. The locations

					of the six IBPs were obtained using a time-of-arrival method and used as inputs for the models; the recorded IBP waveforms from six to eight sites were used as model constraints. All three models were able to reasonably fit the measured IBP waveforms; the best fit was most often given by the MTL model. For each individual IBP, there was good agreement between the three models on several physical parameters of the IBPs: current risetime, current falltime, current shape factor, current propagation speed, and the total charge moment change. For the six IBPs modeled, the ranges, mean values, and standard deviations of these quantities are as follows: current risetime [4.8–25, (12 ± 6)] μs, current falltime [15–37, (25 ± 6)] μs, current speed [0.78–1.8, (1.3 ± 0.3)] × 10 ⁸ m/s, and charge moment change [0.015–0.30, (0.12 ± 0.10)] C km. Currents in the MTL and MTL models moved a negative charge –Q downward and deposited an equivalent positive charge +Q along their paths; the mean Q values were 0.35 C for MTL and 0.71 C for MTL. MTLK model deposited negative charge along its lower path and positive charge along its upper path with mean values of 0.27 C.
2013	R. Jiang, X. Qie, C. Wang, J. Yang	Propagating features of upward positive leaders in the initial stage of rocket-triggered lightning	Atmospheric Research	doi.org/10.1016/j.atmosres.2012.09.005	The propagation characteristics of upward positive leaders in the initial stage of rocket-triggered lightning flashes have been analyzed using high-speed video images, channel base currents, and electric field changes. The luminous intensity at the tip of leader steps was stronger than that in the channel behind it. The average 2-D speed of the leader was 1.0 × 10 ⁵ m/s with partial speeds ranging from 2.0 × 10 ⁴ m/s to 1.8 × 10 ⁵ m/s between 130 m and 730 m above ground. The leader speed showed an obvious irregularity and an accelerating tendency with height and time. Unipolar current pulses, with peak currents ranging from tens of amperes to about 150 A, were observed at the ground during the initial stage of leader development. The electric field change showed stepped waveforms at this stage and it was evident that the leader involved a stepwise propagating mode. For 34 current pulses occurring in the initial stage of the leader development, the geometric mean values of the peak current, rise time, half peak width, duration, charge transfer and pulse interval were 45.0 A, 0.49 μs, 0.99 μs, 3.2 μs, 4.8 μC and 19.9 μs, respectively. After the leaders extended to several hundred meters above ground, fluctuations were found to be superimposed on the continuous current and the associated electric field.
2013	M. Becerra	Glow corona generation and streamer inception at the tip of grounded objects during thunderstorms: revisited	Journal of Physics D: Applied Physics	iopscience.iop.org/article/10.1088/0022-3727/46/13/135205	The initiation of streamers prior to a lightning strike can be reportedly inhibited by glow corona discharges generated from tall objects. In contrast to previous studies based on a simplified one-dimensional model of glow corona, a two-dimensional evaluation of the corona ion drift from tall objects is used here to analyse this effect quantitatively. Proper estimates for the corona space charge distribution generated during both the charging process of a thundercloud and the descent of the downward stepped leader are thus calculated. It is found that the shielding effect of the corona space charge on the streamer inception is not as severe as previously reported. Estimations of the effective height of the downward leader tip at which streamer inception takes place are presented and discussed for lightning rods and dissipation array systems.
2008	D. Petersen, M. Bailey, W. H. Beasley, J. Hallett	A brief review of the problem of lightning initiation and a hypothesis of initial lightning leader formation	JGR	agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2007JD009036	A brief review of hypothesized mechanisms of lightning initiation is presented, with the suggestion that these mechanisms provide an incomplete picture of lightning initiation. This is followed by two ideas: (1) a combination of previously hypothesized lightning initiation mechanisms as a means for local intensification of the thundercloud electric field, and (2) a process for the formation of a hot lightning leader channel that is analogous to the space leader phase of the laboratory negative stepped leader. Thundercloud electric field observations have consistently yielded peak values that are an order of magnitude weaker than the dielectric strength of air. Various mechanisms have been proposed to explain how lightning can initiate in such weak electric fields, including hydrometeor-initiated positive streamers and cosmic ray-initiated runaway breakdown. The historically favored positive streamer mechanisms are problematic due to requiring electric fields two to three times larger than peak observed fields. The recently favored runaway breakdown mechanisms appear capable of developing in conditions comparable to peak observed fields although it is not clear how these diffuse discharges can lead to creation of a lightning leader. This paper proposes a solution whereby runaway breakdown and hydrometeor-initiated positive streamer systems serve to locally intensify the electric field. Following this local field intensification, it is hypothesized that formation of the initial lightning leader channel is analogous to the formation of a space leader in a laboratory negative stepped leader.
1976	R. F. Griffiths, C. T. Phelps	A Model for Lightning Initiation Arising From Positive Corona Streamer Development	JGR	agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JC081i021p03671	A numerical model is used to calculate the electric field enhancement in a thundercloud due to the propagation of a growing system of positive corona streamers, such as might be initiated by a hydrometeor. These streamers intensify if the ambient electric field E exceeds a critical value E ₀ , which is experimentally determined. The positive charge carried in the head of the system increases in magnitude, and the negative charge is deposited in the trail, and thus an electric dipole that tends to enhance the original field is created. The growth is calculated by solving an energy balance equation for the system, including the potential energy of the dipole, the losses due to ionization and excitation, and the production of new streamer tips. Several systems may propagate sequentially, each one passing into the debris of its predecessor and growing more vigorously as a result. For representative values of E and E ₀ at 6.5-km altitude it is shown that a series of three to seven such systems can give rise to local enhancement of the ambient electric field up to 15 × 10 ⁵ V/m over a distance of a few meters, which is sufficient to insure dielectric breakdown and possibly launch the stepped leader
1966	L. B. Loeb	The mechanisms of stepped and dart leaders in cloud-to-ground lightning strokes	J. Geophys. Res.	agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JZ071i020p04711	Recent observations indicate the rather complete neutralization of volume space charges by induced positive corona streamers. New photographic observations of high-tension power lines in rain and snow storms reveal

strong and heavily branched corona streamers from such hydrometeors. A study of uniform field streamer breakdown in mid gap in clean gases, just published, has provided additional information essential to the delineation of the processes active in the forging of the channel of the cloud-to-ground stroke. On the basis of these findings, consistent sequential qualitative analysis is presented resolving the following moot questions: 1. How is the negative charge stored on raindrops in cubic kilometres of cloud volume drained and channelled to yield a pilot leader channel some meters in diameter? 2. How is this hydrometeor-supported discharge able to leave the cloud base and forge into clean, initially un-ionized air to give a stepped leader? 3. What causes stepping? 4. How is the channel several kilometres in length maintained conducting for the tens of milliseconds needed for it to reach ground? 5. How is it that the stepped leader of some meters diameter leads to a return stroke channel with the most intense luminosity millimetres in diameter and the larger luminous conducting envelope no more than 4 cm in diameter? 6. Why is the pilot leader channel zigzagged? 7. What starts the dart leader stroke and how is the channel maintained conducting for the tenths of seconds between successive strokes?

From the comparison of papers reporting models of the PBP, it can be concluded that the most diffused model is due to Griffiths and Phelps (G&P). The original idea, proposed in *Loeb 1966*, assumes that upward propagating positive streamers at the beginning of negative cloud-to-ground discharges would have the effect of funneling negative charge downward into the localized source region of the streamers, thereby concentrating the negative charge to the point that the downward lightning stepped leader would be produced.

The G&P model can be used to calculate the electric field enhancement in a thundercloud due to the propagation of a growing system of positive corona streamers, such as might be initiated by a hydrometeor. The positive charge carried in the head of the system increases in magnitude, and the negative charge is deposited in the trail, and thus an electric dipole that tends to enhance the original field is created. The growth is calculated by solving an energy balance equation for the system, including the potential energy of the dipole, the losses due to ionization and excitation, and the production of new streamers.

An alternative model is presented in the *Cai, Jánský and Pasko 2017*. They report a model based on two uncharged spheres in uniform electric field. The relation between the minimum electric field for avalanche-to-streamer transition and the normalized gap separation of spheres demonstrated that for realistic particle dimensions the avalanche-to-streamer transition is possible in local electric field just slightly above the minimum field required for propagation of positive streamers in air.

A further model was recently presented in *Karunarathne 2015*. The study focuses on modeling measured E field waveforms of initial breakdown pulses (IBPs) in lightning flashes, with peak current occurring early in time. The models use free parameters to match data from multiple sensor locations, providing physical details about each IB pulse. The study highlights differences in channel length, current amplitude, and total charge on the channel among the modeled IBPs.

3. State of the art about experimental data

The most relevant papers found have been organized according to the research groups. We identified the following active groups:

1. Research group based at different universities in the Scandinavian peninsula. The group gathered around first seminal contributions from A. Rakov, so earlier contributions are not necessarily from Scandinavian researchers.

Publ. year	Authors	Title	Journal	Link	Abstract
2012	Z.A. Baharudin, Noor Azlinda Ahmad, M. Fernando, V. Cooray, J.S. Mäkelä	Comparative study on preliminary breakdown pulse trains observed in Johor, Malaysia and Florida, USA	Atmospheric Research	www.sciencedirect.com/science/article/pii/S0169809512000269/pdf?md5=c77f1432a7949e1b1abe86d3fc4a645d&pid=1-s2.0-S0169809512000269-main.pdf	In this paper, the preliminary breakdown (PB) pulse train preceding the negative first return stroke (RS) is recorded using a broad band antenna system. These analyses were carried out in Johor Bahru, Malaysia and Florida, United States. This is a novel initiative at examining and identifying the characteristics of the PB pulse trains in the negative cloud-to-ground flashes observed in Malaysia. The arithmetic mean of the total pulse train duration is 12.3 ms and the weighted arithmetic mean of the pulse durations and interpulse intervals are 11 μ s and 152 μ s, respectively. The arithmetic mean ratio between the maximum peak amplitude of the PB pulse and the peak RS electric field was 27.8%, and the corresponding value in Florida was 29.4%. The arithmetic mean of the time duration between the most active part of the pulse train, and the RS was 57.6 ms in Malaysia and 22 ms in Florida. A qualitative comparison of our results with those obtained earlier in Sri Lanka, Sweden and Finland supports the hypothesis that the PBP/RS ratio is higher in the northern regions compared to the tropical regions.
2008	J. S. Makela, N. Porjo, A. Makela, T. Tuomi, V. Cooray	Properties of preliminary breakdown processes in Scandinavian lightning	Journal of Atmospheric and Solar-Terrestrial Physics	www.sciencedirect.com/science/article/pii/S1364682608002198/pdf?md5=de1e5a38340bb6e53cd437bfd285bf93&pid=1-s2.0-S1364682608002198-main.pdf	Lightning flashes are usually preceded by preliminary breakdown processes (PBPs) before a stepped leader is initiated. These breakdown processes are not well understood. An early model, the so-called BIL model, has been called into question in later studies. However, we have found that the BIL model is quite successful in describing initial processes at least in high-latitude Scandinavian lightning. We present results from one summer of measurements in Finland, during which the vertical electric field was measured with a standard broadband plate antenna system. Lightning flash locations were provided by a lightning detection network and magnetic fields were measured with an experimental narrowband detection system. The relationship between the preliminary breakdown and the first return stroke (RS) is studied for 193 flashes at distances of 5–70 km. We can identify a preliminary breakdown in at least 90% of the flashes. The peak electric field of the RS is on average four times as intensive as the highest peak of the PBP. However, in 25% of the cases the PBP peak is more intensive. On the other hand, we show that this method of comparing intensities is physically arbitrary, since the PBP is continuous and the RS is impulsive. The narrowband measurement allows a physically consistent definition for intensities as the root-mean-square (RMS) sum of the most intense parts of signals. The PBP and RS are shown to have almost equal intensities at small distances. At larger distances, the PBP weakens more rapidly. This is suggested to be due to different propagation regimes, with the PBP signal changing from space-wave to ground-wave propagation with increasing distance, while the RS is predominantly ground wave at all distances. The result may have practical applications in narrowband detection of lightning. The BIL model suggests a characteristic signal in the narrowband signal, which could be used to identify the start of a lightning flash. The change in the RS–PBP ratio as a function of distance is statistically significant, but is too weak to significantly improve ranging methods
2016	D. Johari, V. Cooray, M. Rahman, P. Hettiarachchi and M. Muzafar Ismail	Characteristics of Preliminary Breakdown Pulses in Positive Ground Flashes during Summer Thunderstorms in Sweden	Atmosphere	www.mdpi.com/2073-4433/7/3/39	This paper presents the characteristics of the preliminary breakdown pulses (PBP) in 51 positive ground flashes recorded during 2014 summer thunderstorms in Sweden. Electric field measurements were conducted remotely using a broadband antenna system (up to 100 MHz) for a recording length of 1 s with 200 ms trigger time. In the analysis, PBP trains were observed in 86% of the cases. Based on the number of trains preceding the first return stroke, the PBP were classified into single and multiple train PBP. Characteristics of the first PBP train were determined and based on the initial polarity of the pulses, three types of PBP were identified. Characteristics of the subsequent PBP trains in the multiple train PBP were also analyzed and they were compared with the first PBP train. Based on the conceptual charge cloud configuration, we found that the inverted dipole is consistent with our observation. We also found that PBP in positive ground flashes during summer thunderstorms in Sweden are weak since the average ratios of the PBP peak to the first return stroke peak lie only between 0.21 and 0.26. Possible reasons for no detection of PBP and the different types of PBP observed were also discussed.
2016	Y. Zhu, V. A. Rakov and M. D. Tran	A Study of Preliminary Breakdown and Return Stroke Processes in High-Intensity Negative Lightning Discharges	Atmosphere	www.mdpi.com/2073-4433/7/10/130	Using an automated data processing algorithm, we examined electric field records of 5498 negative cloud-to-ground flashes reported by the U.S. National Lightning Detection Network (NLDN) within 50 to 500 km of the Lightning Observatory in Gainesville (LOG), Florida. Out of the 5498 flashes, 3496 (64%) had detectable preliminary breakdown (PB) pulse trains. Only 3077 flashes with a single PB pulse train and NLDN-reported first-return-stroke (RS) peak current ≥ 50 kA were selected for detailed analysis. The arithmetic mean values of PB pulse train duration, PB-RS interval, and PB/RS pulse peak ratio were 2.7 ms, 8.8 ms, and 0.15, respectively. The PB-RS

interval was found to decrease with increasing RS peak current (Spearman correlation coefficient was statistically significant and equal to -0.80). The range-normalized PB pulse peak exhibited statistically significant positive correlation with the RS peak current, with Spearman correlation coefficient being 0.48 . Thus, it appears that the high-intensity (≥ 50 kA) negative lightning is characterized by shorter (and, by inference, faster) stepped leaders and more pronounced PB pulse trains.

2008 L. M. Coleman, M. Stolzenburg, T. C. Marshall, and M. Stanley Horizontal lightning propagation, preliminary breakdown, and electric potential in New Mexico thunderstorms JOURNAL OF GEOPHYSICAL RESEARCH agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2007JD009459

Characteristics of lightning flashes in three storms are compared to simultaneous electric field (E) measurements at various altitudes to examine three hypotheses. The first is the idea that horizontal lightning branches propagate at altitudes near potential extrema (or wells). The analyses show that horizontal lightning activity and potential extrema are coincident in time and altitude, and so are consistent with the idea that lightning moves charges into potential wells as a means of using a storm's electrostatic energy to drive a lightning flash's dielectric breakdown processes. Second, these data are used to verify the usual interpretation of breakdown polarity of lightning radiation sources detected by the Lightning Mapping Array. The third hypothesis investigated is that normal cloud-to-ground flashes have a period of preliminary breakdown if and only if a potential well for negative charge exists between the altitudes of flash initiation and ground. The analyses show that in 14 flashes when a low-level well was indicated, the period of preliminary breakdown before the first return stroke lasted an average of 117 ms, considerably longer than the average lifetime of a stepped leader. In 15 flashes in which no low-level well was indicated, the time between initiation and first return stroke averaged 15 ms.

Baharudin, 2012 studies the electric and magnetic fields generated by the initial breakdown processes that precede cloud-to-ground lightning flashes in Finland. The paper uses a combination of broadband electric-field measurements, narrowband magnetic-field measurements, and lightning location network data to identify and analyze the preliminary breakdown pulses (PBPs) and the first return strokes (RSs) of 193 negative flashes.

Findings are:

- Any differences in the PB pulse trains in different geographical regions may indicate differences in the initial breakdown processes in the clouds. For this reason, it is important to analyze and compare the features of these pulse trains in different geographical regions.
- PBPs are present in at least 90% of the flashes, and their peak electric field is on average four times lower than the peak field of the RS, but in 25% of the cases it is higher. The paper also shows that comparing peak fields is physically arbitrary, and that using the root-mean-square (RMS) intensity of the narrowband signal gives a more consistent measure of the PBP and RS intensities.
- The PBP intensity decreases more rapidly with distance than the RS intensity, suggesting different propagation regimes for the two processes.

Makela, 2008 studies the electric and magnetic fields generated by the initial breakdown processes that precede cloud-to-ground lightning flashes in Finland and compares them with previous studies from other regions. The paper uses the BIL model (Clarence and Malan, 1957, where *B* stands for initial breakdown; *I* stands for intermediate stage, with little associated radiation, and *L* stands for lightning) to describe the breakdown processes and compares the peak intensities of the PBP and the first return strokes (RS) using both wideband and narrowband measurements.

Findings are:

- The breakdown is weaker than the return stroke in the electric field, but comparable or stronger in the magnetic field.
- The PBP is a unique phenomenon that can be distinguished from the leader process, and that it has a characteristic signature in the narrowband signal that can be used for identification and ranging of lightning flashes.

Johari 2016 classifies the PBP into single and multiple train PBP and identifies three types of PBP based on the initial polarity of the pulses. It also analyzes the temporal and spatial characteristics of the PBP and compares them with previous studies.

Findings are:

- PBP are observed in 86% of the positive ground flashes, and most of them have the same polarity as the first return stroke. It also finds that PBP are weak, with average ratios of the PBP peak to the first return stroke peak between 0.21 and 0.26.

Zhu, 2016 is about characterizing PBP and RS processes in high-intensity negative lightning discharges. The authors used an automated data processing algorithm to analyze electric field records of 5498 negative cloud-to-ground

flashes reported by the U.S. National Lightning Detection Network (NLDN) within 50 to 500 km of the Lightning Observatory in Gainesville (LOG), Florida.

Findings are:

- 64% of the flashes had detectable PB pulse trains, and only those with NLDN-reported first RS peak current ≥ 50 kA were selected for detailed analysis.
- High-intensity negative lightning is characterized by shorter (and faster) stepped leaders and more pronounced PB pulse trains and discussed the possible implications for lightning physics and detection.

Coleman 2008 studies the horizontal lightning propagation, preliminary breakdown, and electric potential in New Mexico thunderstorms. The authors used electric field measurements at various altitudes to examine three hypotheses: (1) horizontal lightning branches propagate at altitudes near potential extrema, (2) the usual interpretation of breakdown polarity of lightning radiation sources detected by the Lightning Mapping Array is correct, and (3) normal cloud-to-ground flashes have a period of preliminary breakdown if and only if a potential well for negative charge exists between the altitudes of flash initiation and ground.

Findings are:

- Horizontal lightning activity and potential extrema are coincident in time and altitude, and so are consistent with the idea that lightning moves charges into potential wells as a means of using a storm's electrostatic energy to drive a lightning flash's dielectric breakdown processes.
- The PBP is a unique phenomenon that can be distinguished from the leader process, and that it has a characteristic signature in the narrowband signal that can be used for identification and ranging of lightning flashes.

2. Group based at the Czech Academy of Science

Publ. year	Authors	Title	Journal	Link	Abstract
2019	I. Kolmasova, T. Marshall, S. Bandara, S. Karunarathne, M. Stolzenburg, N. Karunarathne, and R. Siedlecki	Initial Breakdown Pulses Accompanied by VHF Pulses During Negative Cloud-to-Ground Lightning Flashes	Geophysical Research Letters	agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019GL082488	This study compares waveforms recorded by "broadband" very low frequency/low-frequency/medium-frequency (VLF/LF/MF) electric field change sensors (bandwidth ~ 0 –2.5 MHz) and very high frequency (VHF) sensors (bandwidth 186–192 MHz) during the initiation of 20 negative cloud-to-ground lightning flashes. In the first 2 ms of each flash, initial breakdown (IB) pulses are detected with the VLF/LF/MF sensors. Comparison shows that all classical IB pulses are accompanied by VHF pulses, where classical IB pulses are defined herein as bipolar with duration >10 μ s and amplitude $>25\%$ of the largest IB pulse amplitude in the flash. There are on average 47% of IB pulses (of all amplitudes and durations) that are accompanied by VHF pulses within ± 1 μ s. There are also many VHF pulses with no associated IB pulses. These observations indicate that the initial in-cloud lightning channel extension process (es) occurs very fast and at multiple length scales, since substantial electromagnetic radiation is emitted in the VLF/LF/MF and VHF bands.
2018	I. Kolmašová, O. Santolík, E. Defer, W. Rison, S. Coquillat, S. Pedeboy, R. Lán, L. Uhlíř, D. Lambert, J. Pinty, S. Prieur & V. Pont	Lightning initiation: Strong pulses of VHF radiation accompany preliminary breakdown	Nature/Scientific Reports	www.nature.com/articles/s41598-018-21972-z	We analyze lightning initiation process using magnetic field waveforms of preliminary breakdown (PB) pulses observed at time scales of a few tens of microseconds by a broad-band receiver. We compare these pulses with sources of narrow-band very high frequency (VHF) radiation at 60–66 MHz recorded by two separate Lightning Mapping Arrays (LMAs). We find that almost none of the observed PB pulses correspond to geo-located VHF radiation sources, in agreement with previous results and with the hypothesis that processes generating VHF radiation and PB pulses are only weakly related. However, our detailed analysis discovers that individual peaks of strong VHF radiation seen by separate LMA stations correspond surprisingly well to the PB pulses. This result shows that electromagnetic radiation generated during fast stepwise extension of developing lightning channels is spread over a large interval of frequencies. We also show that intense VHF radiation abruptly starts with the first PB pulse and that it is then continuously present during the entire PB phase of developing discharges.

Kolmasova, 2019 investigates how initial breakdown (IB) pulses, which are electric field changes during the initiation of cloud-to-ground lightning flashes, are accompanied by very high frequency (VHF) pulses, which are electromagnetic signals emitted by fast and small-scale discharge processes inside thunderclouds. The authors use data from arrays of broadband electric field change sensors and very high frequency sensors deployed in Mississippi, USA, to compare the waveforms recorded during the first 2 ms of 20 negative cloud-to-ground lightning flashes.

Findings are:

- All classical IB pulses, which are bipolar pulses with duration >10 μ s and amplitude $>25\%$ of the largest IB pulse in the flash, are systematically accompanied by VHF pulses, and that about two thirds of larger-amplitude IB pulses and about half of smaller-amplitude IB pulses have coincident VHF pulses within ± 1 μ s.

- The amplitudes of IB and VHF pulses are weakly correlated, and that there is no clear relation between the durations of classical IB pulses and the powers of corresponding VHF pulses.

The paper concludes that the initial lightning extension process occurs very fast and at multiple length scales inside a thundercloud, and that substantial electromagnetic radiation is emitted in both low and very high frequency bands. *Kolmašová, 2018* presents similar results and analysis. **Notably, the data used in this study are available at <http://bleska.ufa.cas.cz/>.**

3. Contributions from other groups.

Publ. year	Authors	Title	Journal	Link	Abstract
2021	C. Granados, H. Rojas, F. Roman	Statistical analysis on preliminary breakdown pulses in negative cloud-to-ground flashes occurred in Colombia	Proc. of 35 th International Conference on Lightning Protection (CLP-SIPDA) 2021	ieeexplore.ieee.org/document/9627401	In this paper, a characterization of preliminary breakdown pulse trains (PBP trains) preceding the first return stroke (FRS) in 76 negative cloud to ground (-CG) lightning flashes occurred in Bogota, Colombia (tropical region located above 2500 meters of altitude) is presented. For the measurement campaign, a broadband parallel-plate antenna system was used with a 500 ms full observation window and a pre-trigger time of 250 ms. After execution a statistical analysis, several results were obtained. The geometric mean (GM) and the arithmetic mean (AM) of the time interval between the largest peak of the PBP train and the maximum value of the FRS (PBP - FRS interval) was 1.08 ms and 1.39 ms, respectively. In addition, the AM of pulse train duration and the ratio between the peak value of the PBP train and its FRS (PBP max /FRS ratio) were 1.39 ms and 0.55 p.u., respectively. Finally, the number of pulses of the PBP trains characterized were located in the range of 3 to 72 pulses.
2016	Y. Wang, X. Qie, D. Wang, M. Liu, D. Su, Z. Wang, D. Liu, Z. Wu, Z. Sun, Y. Tian	Beijing Lightning Network (BLNET) and the observation on preliminary breakdown processes	Atmospheric Research	www.sciencedirect.com/science/article/pii/S0169809515004020	Beijing Lightning Network (BLNET), a regional multi-frequency-band lightning detection and location network, has been developed for both research and operational purposes. The network consisted of 15 stations in 2014, covering an area of about 100 km × 85 km in Beijing area. In this paper, we present the configuration of the network and the detailed description on the sensors for the first time. The Chan algorithm and Levenberg–Marquardt method are adopted jointly in the lightning location algorithm. The Monte Carlo simulation reveals that the horizontal and the vertical location errors within BLNET coverage are less than 300 m and 600 m, respectively. The comparison of total lightning location results with the corresponding radar reflectivity for a thunderstorm case indicates that BLNET has a good capability to track thunderstorms in the Beijing area. Besides, we examine the electric field waveforms of the preliminary breakdown process (PBP) of 111 – CG flashes, 92 + CG flashes, 22 normal-polarity IC flashes and 22 inverted-polarity IC flashes. Statistics on the time interval between the largest PBP pulse and the corresponding first RS pulse for CG flash (PB–RS interval), the ratio of the largest PBP pulse to the corresponding first RS pulse for CG flash (PB/RS ratio), the pulse width for individual pulse in the PBP train (Tw) and the time interval between successive pulses in the PBP train (Ti) are presented. The 3D location result shows that the PBP of a – CG flash initiates at an altitude of ~ 6 km and propagates downward to ~ 3 km with a vertical speed of 5.9 × 105 m/s. The initial 10 ms of an IC flash is found to start at ~ 7.2 km and develop upward to ~ 10 km. The vertical propagation speed is estimated to be 4.8 × 105 m/s during the first 6 ms. A PBP with relatively clear branched 3D structure is presented and discussed in the end of the paper. The average 3D propagation speed of two branches is estimated to be 2.1 × 106 m/s and 2.6 × 106 m/s, respectively.
2012	T. Wu, Y. Takayanagi, T. Funaki, S. Yoshida, T. Ushio, Z. Kawasaki, T. Morimoto, M. Shimizu	Preliminary breakdown pulses of cloud-to-ground lightning in winter thunderstorms in Japan	Journal of Atmospheric and Solar-Terrestrial Physics	www.sciencedirect.com/science/article/pii/S1364682613001685?via%3Dihub	Preliminary breakdown pulses (PBP) of 26 positive and 104 negative cloud-to-ground (CG) lightning flashes observed in winter thunderstorms in Hokuriku region of Japan are analyzed. Pulses in PBP train are mainly bipolar. Zero-crossing time of each pulse is about 7 us and total duration of each pulse train is about 1 ms. PBPs in negative CG lightning are classified as “BIL type” (59 cases) and “BL type” (45 cases). “BIL type” PBP contains an intermediate stage with little electric field changes. The time interval between PBP and the first return stroke (PBP–RS interval) is on average 5.4 ms for “BIL type” PBP, while that for “BL type” PBP is only 1.3 ms. Ratio of peak amplitude of PBP to the first return stroke (PBP–RS ratio) is on average 0.47 and 0.44, respectively, for “BIL type” and “BL type” PBPs, but the ratio for “BIL type” PBP has a much wider distribution. It is speculated that the intermediate stage in “BIL type” PBP is caused by horizontal propagation of leader channel. PBPs in positive CG lightning are classified as +PBP (11 cases) and –PBP (15 cases) according to their initial polarities. +PBP and –PBP have similar distributions of both PBP–RS interval and PBP–RS ratio, but their value of PBP–RS interval is much larger and their value of PBP–RS ratio is much smaller than corresponding values of PBPs in negative CG lightning. It is speculated that different initial polarities of +PBP and –PBP in positive CG lightning are caused by different directions of channel propagation.
1999	J.C. Willett, D.A. Davis, P. Laroche	An experimental study of positive leaders initiating rocket-triggered lightning	Atmospheric Research	http://www.atmos.arizona.edu/students/courselinks/spring07/atmo589/articles/Willett_et_al_RTL_Atmos_Res_July_1999.pdf	Simultaneous, co-located measurements of ambient, electrostatic-field profiles and rocket triggered lightning phenomenology beneath Florida thunderstorms are reported. Ambient-field conditions that are sufficient to initiate and sustain the propagation of positive lightning leaders are identified. It is found that lightning can be triggered with grounded triggering wires approximately 400 m long when the ambient fields aloft are as small as 13 kV/m foul-weather polarity. Ambient potential differences between the height of the triggering wires and ground were as small as y3.6 MV negative wrt. earth when lightning occurred. ‘Precursors,’ the first measurable current pulses from the triggering wires, were initiated at

					similar fields aloft but at wire heights only about half as large, where ambient potentials were as small as γ 1.3 MV. The mean speed of one 'failed leader' is estimated at 1.9=104 mrs over 35 m of propagation. The lengths of 'leader' extension and positive-streamer 'fan' during individual impulses of multiple pulse precursors are estimated to be 0.7 and 2.0 m, respectively.
1992	J. C. Willett, D. C. Curtis, A. R. Driesman, R. K. Longstreth, W. Rison, W. P. Winn, J. J. Jones	The Rocket Electric Field Sounding (REFS) Program: Prototype Design and Successful First Launch	Defense Technical Information Center	https://apps.dtic.mil/sti/citations/ADA257762	The motivation, design and successful first flight of a sounding rocket to measure profiles of vector electrostatic field in the lower troposphere are described. The design employs eight shutter field mills and a corona-charging system in a manner similar to aircraft previously instrumented for the measurement of electric fields. A rocket offers significant advantages over an aircraft in simplicity and calibration. A single cylindrical rotor covering most of the payload acts as the shutter for all eight mills in this design. The cylindrical symmetry and circular cross sections of the vehicle facilitate straightforward calibration. Also included in the payload are a pressure sensor, a longitudinal accelerometer, a transverse magnetometer, and a novel cloud-penetration detector. A fair-weather test flight at the NASA Wallops Flight Facility demonstrated the workability of the basic design and identified a few necessary modifications.
1967	M. M. Newman, J. R. Stahmann, J. D. Robb, E. A. Lewis, S. G. Martin, S. V. Zinn	Triggered lightning strokes at very close range	Journal of Atmospheric Research	https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/JZ072i018p04761	The inability to predict the point of strike of natural lightning flashes to ground makes it very difficult to carry out repeated measurements under reasonably reproducible conditions. This difficulty has been overcome to some extent by measurements on discharges to high buildings, radio towers, power lines, and other fixed structures.

Granados 2021 analyzes a large database of measurements. The criteria employed for analyzing the electric field generated by PBP trains are defined as follows: a) Only pulses with amplitude larger than twice the average noise level were included; b) the individual pulses considered inside a PBP train where those separated by less than 2 ms between them. c) only pulse trains with at least three individual pulses were analyzed. The characterization of the PBP trains was carried out using the following parameters: (a) the time between the first and the last detectable pulse; (b) the time interval between the largest peak of the PBP train and the maximum value of the First Return Stroke (FRS); (c) the ratio between the peak value of the PBP train and its FRS; (d) number of pulses contained in the train (No. pulses). 53 signatures (69.7%) exhibit PBP-FRS interval time below 10 ms. Likewise, 20 samples (26.3%) have separations greater than 30 ms, while only 3 (3.9%) samples were found in the range between 10 ms and 30 ms. The PBP-FRS parameter exhibited a geometric mean GM and an Arithmetic Mean AM of 7.33 ms and 26.67 ms, respectively. In addition, the minimum and maximum time intervals were 0.7 ms and 379.5 ms, respectively. Regarding to the duration of the PBP train, this parameter varied from 0.2 up to 5.9 ms with an AM of 1.39 ms. 28 waveforms (36.8%) have PBP trains with a duration of less than 1 ms. Additionally, 10 signatures (13.15%) had a duration greater than 3.5 ms, while similar quantity of records shown durations between 2.5 ms and 3.5 ms.

Wang 2016, Wu 2012 introduce Beijing Lightning Network (BLNET), a regional multi-frequency-band lightning detection and location network that covers an area of about 100 km \times 85 km in Beijing area. The papers describe the configuration, sensors, location algorithms, and location accuracy of BLNET, and compares its performance with other lightning location systems. The paper presents the 2D and 3D location results of BLNET for a thunderstorm case in 2014 and shows that BLNET can track thunderstorms and locate total lightning flashes with high accuracy. The papers analyze the preliminary breakdown processes of negative and positive cloud-to-ground flashes and intra-cloud flashes, and reveals some characteristics of their electric field waveforms, propagation speeds, and 3D structures.

Willet 1992 and Willet 1999 presents a large USA Defense center program to design and execute a number of experiments with rocket-triggered lightning. The technique is well described here.

Finally, *Newmann 1967* reports very early experiments, and is cited here for historical purposes.

4. State of the art about sensitive devices

1. Impact on Power delivery and distribution systems

Publ. year	Authors	Title	Journal	Link	Abstract
2021	A. Borghetti, K. Ishimoto, F. Napolitano, C. A. Nucci and F. Tossani	Assessment of the Effects of the Electromagnetic Pulse on the Response of Overhead Distribution Lines to Direct Lightning Strikes	IEEE Open Access Journal of Power and Energy	ieeexplore.ieee.org/document/9494606	In the usual practice, the evaluation of overvoltages due to direct lightning strikes to overhead power lines is focused on the representation of the effects of the lightning current injection, whilst the effects of the coupling between the conductors and the lightning electromagnetic pulse (LEMP) is disregarded. Motivated by recent results obtained for the case of a medium voltage line configuration with a shield wire, this paper extends the analysis to assess the contribution of the LEMP on the lightning performance of an overhead distribution line with and without periodically grounded wires and surge arresters. Moreover, the paper deals with the LEMP effect on the occurrence probability of flashovers on different phases, which is an important information on the service continuity of networks with isolated or compensated neutral earthing. A validation of the results is obtained by comparing the overvoltages calculated by the electromagnetic transient program including the model of the line illuminated by the LEMP and those obtained by a three-dimensional finite difference time-domain approach.
2020	I. Petrovic, S. Nikolovski, H. R. Baghaee and H. Glavaš	Determining Impact of Lightning Strike Location on Failures in Transmission Network Elements Using Fuzzy Decision-Making	IEEE Systems Journal	ieeexplore.ieee.org/document/8768412	This paper presents a new approach for determining the impact of lightning strike currents on transmission network elements failures, based on fuzzy logic (FL) and expert systems. The location of lightning strike is determined by means of lightning location system (LLS) and failures in the transmission network, sorted by type of the equipment, are obtained from supervisory control and data acquisition (SCADA) system. The input data set includes two sets. The first set consists of lightning strike locations and current values between the cloud and the ground. The second set consists of current values from SCADA system before and after the fault, protection tripping information, and the state and position of the switches. The proposed FL-based solution is based on a fuzzy decision-making system (DMS), including both data sets in order to provide a power system operator (PSO) with a precise and accurate decision needed in time of emergency. The described model has been tested for functionality and correct results have been obtained, which confirms the membership function (MF) assessment and proves the efficiency and authenticity of the proposed DMS.
2005	N. Balijepalli, S. S. Venkata, C. W. Richter, R. D. Christie and V. J. Longo	Distribution System Reliability Assessment Due to Lightning Storms	IEEE Trans. On Power Delivery	ieeexplore.ieee.org/document/1458892	Lightning is a significant cause of faults and outages in many electric power systems and is one of the major causes of poor system reliability. Predictive assessment of distribution reliability indices can be used to identify areas that have poor reliability so that appropriate changes in system design can be implemented. The assessment of distribution system performance under lightning conditions requires modeling of storm characteristics and system response. In this paper, a Monte Carlo simulation for evaluating distribution system reliability under lightning storm conditions is presented. The results from a practical distribution system show the importance of detailed modeling of storm characteristics and simulation of the system response in assessing distribution system reliability during lightning storms.
2020	M. Doostan and B. Chowdhury	Predicting Lightning-Related Outages in Power Distribution Systems: A Statistical Approach	IEEE Access	ieeexplore.ieee.org/abstract/document/9084149	This paper presents a novel data-driven approach for predicting lightning-related outages that occur in power distribution systems on a daily basis. In order to develop an approach that is able to successfully fulfill this objective, there are two main challenges that ought to be addressed. The first challenge is to define the extent of the target area. An unsupervised machine learning approach is proposed to overcome this difficulty. The second challenge is to adequately identify characteristics of lightning-related outages and to explore the relationship between these outages and weather-related variables (thunderstorm events). In this paper, these outages are clustered into a few manageable groups. Then, a probabilistic model is presented to estimate the likelihood of each group of outages. Finally, a machine learning classification algorithm that can handle the imbalanced problem is developed to predict what group will the outage belong to on a specific day in a specific area of the system under study. Actual outage data, obtained from a major utility in the U.S., in addition to radar weather forecast data are utilized to build the proposed approach. Also, three case studies are provided to show several issues associated with predicting lightning-related outages, and to demonstrate how the proposed approach can address those problems adequately.
2014	A. Piantini, J. M. Janiszewski, T. O. de Carvalho, P. F. Obase and G. J. G. dos Santos	Lightning-caused Transformer Failures in Distribution Systems	2014 Int. Conf. on Lightning Protection (ICLP)	ieeexplore.ieee.org/document/6973261	This paper presents the main results of an investigation conducted with the aim of reducing to an acceptable level the lightning-caused distribution transformer failure rate in a region in the South of Brazil. The region, in the border of the State of Rio Grande do Sul and Argentina, is characterized by a high lightning activity. The analysis of failed transformers and field results shows that the installation of surge arresters at the transformer LV side does not drastically change the failure rate. Computer simulations corroborate this result and confirm that failures are mostly associated with surges coming from the MV side. Therefore, the recommendations are mainly related to the surge arrester installation procedures at the primary side. A discussion is provided on the reasons for the apparent discrepancy with regard to the

					conclusions of similar investigations carried out in Australia, Norway, and the USA, according to which the installation of secondary arresters leads to substantial reduction in transformer failure rates.
1979	J. D. Nordgard, C. Chen	Lightning-Induced Transients on Buried Shielded Transmission Lines	IEEE Trans on Electromag. Compatibility	ieeexplore.ieee.org/document/4091281	This paper is primarily concerned with the analysis of induced transient current and voltage surges on buried shielded transmission lines due to earth-conduction effects of nearby lightning discharges. An analytical method is presented in this paper to model the conductive coupling mechanisms in the earth and to determine the amount of coupling between a lightning discharge to ground and an earth-return transmission line. The transmission line is assumed to be a long straight horizontal coaxial cable with an inner shield and an outer armor, terminated on both ends with typical communication-equipment load impedances. The general case is considered here, in which the outermost conductor is not necessarily in perfect contact with the conducting earth, but has a contact impedance with the earth, as in cables with an outer dielectric covering for corrosion or water protection. Average lightning-channel conditions and a representative buried cable geometry are examined. The results are conveniently displayed via several graphs of the time histories of the resulting transient current and voltage surges.
2007	L. Xu, M. Chow, and L. S. Taylor	Power Distribution Fault Cause Identification With Imbalanced Data Using the Data Mining-Based Fuzzy Classification E-Algorithm	IEEE Trans on Power Systems	ieeexplore.ieee.org/document/4077147	Power distribution systems have been significantly affected by many outage-causing events. Good fault cause identification can help expedite the restoration procedure and improve the system reliability. However, the data imbalance issue in many real-world data sets often degrades the fault cause identification performance. In this paper, the E-algorithm, which is extended from the fuzzy classification algorithm by Ishibuchi to alleviate the effect of imbalanced data constitution, is applied to Duke Energy outage data for distribution fault cause identification. Three major outage causes (tree, animal, and lightning) are used as prototypes. The performance of E-algorithm on real-world imbalanced data is compared with artificial neural network. The results show that the E-algorithm can greatly improve the performance when the data are imbalanced

Transmission lines are obviously the most vulnerable component, due to their dimension and geometrical characteristics. The literature in this field is vast, and dates back to the seventies or earlier.

Borghetti, 2021 is worth mentioning because it addresses the analysis of induced transient current and voltage surges on buried shielded transmission lines due to earth-conduction effects of nearby lightning discharges; the main rationale is obviously due to the fact that these lightning-induced surges tend to cause excessive voltages to appear at the ends of the wires and, therefore, tend to cause excessive currents to flow into the terminating equipment loads. This paper can be considered one of the fundamental contributions to understanding the lightning effect.

Petrovic, 2020 is worth mentioning because it addresses the effect of the Lightning Electromagnetic Pulse (LEMP) on the lightning performance of an overhead distribution line with and without periodically grounded wires and surge arresters. Its novelty consists in considering the LEMP effects and not only of the current injection; in addition, the presence of grounding and surge arresters lead to a full understanding on the effects.

Balijepalli, 2005 proposes a different approach, i.e. a fuzzy-logic based algorithm using the data from a LLS and the output of a SCADA system to better understand the effects of a lightning strike ("certified" by the data coming from a LLS system) and a realistic system's status.

Doostan, 2020 assesses the performance of distribution systems under lightning conditions by a Monte Carlo simulation for evaluating distribution system reliability under lightning storm conditions; the results are compared to the statics of a practical distribution system.

Piantini, 2014 applies a fuzzy based algorithm to Duke Energy outage data for distribution fault cause identification, showing that lightning is a major outage cause.

Nordgard, 1976 proposes a data-driven approach to predict lightning related outages in power distribution systems; actual outage data, obtained from a major utility in the U.S. are used to set-up the approach, showing the importance of the analysis.

2. Impact on Photovoltaic plants

Publ. year	Authors	Title	Journal	Link	Abstract
2021	Nor Izzati A., Zaipatimah A., Mohd Zainal A., Miszaina O., Nur Hazirah Z. and M. Hakirin Roslan	Impacts of Lightning- Induced Overvoltage on a Hybrid Solar PV- Battery Energy Storage System	Applied Sciences	www.mdpi.com/2076-3417/11/8/3633	With increased electrical energy demands projected in the future, the development of a hybrid solar photovoltaic (PV)-battery energy storage system is considered a good option. However, since such systems are normally installed outdoors and in open areas, they are vulnerable to lightning strikes and may suffer from malfunctions or significant damage to sensitive components, which may result in a major breakdown and loss of revenue due to equipment replacement costs and inefficient operation. Thus, the objective of this paper is to investigate the effect of lightning-induced overvoltage on a hybrid solar PV-battery energy storage system, considering indirect lightning strikes nearby the system. The presented hybrid solar PV-battery energy storage system and lightning-induced overvoltage are modeled in Electro-Magnetic Transient Program-Restructured Version (EMTP-RV) software. The lightning-induced overvoltage is simulated based on a lightning waveshape of 10/350 s using the Heidler expression, whilst the Rusck model is used to simulate the lightning-induced overvoltage. Different lightning current amplitudes (3, 19, and 169 kA), lightning strike locations (20, 50, and 100 m), and cable lengths (5, 10, and 20 m) are used to investigate the induced effects on the system and on the impulse withstand voltage of 6kV, as stated in MS IEC 60664-1 for solar PV-battery systems and inverters at the DC side. The results indicate that as the lightning strike distance increases from 20 to 100 m, the percentage of strikes exceeding the impulse withstand voltage reduces from 67% to 54% at 19 kA. At 169 kA, the impulse withstand voltage is exceeded by more than 100%, regardless of the strike distance (from 20 to 100 m). Furthermore, differences in cable length do not have much impact on the lightning-induced overvoltage due to the small voltage drop across the short cable length. This study provides useful information for PV systems owners and will be useful in assigning appropriate lightning protection schemes for PV farms.
2023	Q. Sun, L. Huang, X. Zhong, J. Yang, L. Zhong, S. Chen, H. Jin	Influence of photovoltaic support on lightning transient under direct lightning strike	Electric Power Systems Research	www.sciencedirect.com/science/article/abs/pii/S037877962200894X	Due to the large-scale installation of photovoltaic (PV) plants in open areas, PV plants is exposed to lightning strike at a high risk. The influence of PV support on lightning transient under direct lightning strike is investigated in this paper. Firstly, the PV support composed of multiple branches is classified into vertical conductor, horizontal conductor and oblique conductor. Their wave impedances are individually derived. Considering the air-termination rod and earthing system, four types of PV supports are chosen and their lightning transient responses under direct lightning strike are comprehensively studied. It suggests that the transient response is heavily dependent on the number of grounding legs. The greater the grounding legs, the lower the overvoltage. The equipotential bonding provides additional routes for the discharge of lightning current. Its presence would minimize the voltage but increase the risk for the entire PV system. The additional auxiliary leg also plays a role. The non-isolated air-termination rod is suggested install at the symmetrical center of the PV support from the perspective of discharging the lightning current.
2021	Q. Sun , X. Zhong, L. Zhong, F. Wang, J. Liu, S. Chen, T. Yang	Investigation on induced voltage of photovoltaic system on complex terrain	Electric Power Systems Research	www.sciencedirect.com/science/article/abs/pii/S0378779621005307#:~:text=The%20lightning%20induced%20voltages%20for,reflection%20coefficient%20at%20the%20interface.	Large-scale photovoltaic (PV) systems are normally installed on wide-open area for converting sunlight into electricity. They face a great challenge of lightning strike. A computational model for lightning-induced voltage on PV system is proposed in this article based on finite-difference time-domain (FDTD) method. Both the medium property and electromagnetic wave propagation are considered. The lightning-induced voltages for PV systems on complex terrain, including flat land, lake and mountain, are investigated for the first time. It suggests that the lightning-induced voltage is strongly dependent on the ground conductivity due to the variation of wave reflection coefficient at the interface. The terrain with low conductivity and great permittivity would result in a large voltage, which becomes higher as the mounting height increases. The characteristics for that on lake are completely different from that on land; the lightning threat for floating PV is relatively small. The electromagnetic field, along with the propagation path, leads to the distinction on mountain. The V-shaped terrain has a greater risk; the mountain slope also plays a role. The proposed method is compared with existing methods and further validated. The results provide guidance for lightning protection design for PV system on complex terrain.
2019	Y. Zhanga, H. Chenb, Y. Dua	Lightning protection design of solar photovoltaic systems: Methodology and guidelines	Electric Power Systems Research	www.sciencedirect.com/science/article/abs/pii/S0378779619301968	Solar photovoltaic (PV) system is one of the promising renewable energy options for substituting the conventional energy. PV systems are subject to lightning damage as they are often installed in unsheltered areas, and have vulnerable electronic devices. This paper proposes a partial element equivalent circuit (PEEC) method enhanced with the vector fitting technique for analyzing lightning transients in the PV systems. The frequency-dependent effects and ferromagnetic properties of structural steel are taken into account. Models of major components in the PV systems including structure steels, wiring in panels, and PV cells are provided. The non-linear surge protective device (SPD) is also considered in the modelling. An experiment on a PV panel is presented for the validation of the proposed method. The proposed procedure is finally applied to investigate lightning transients in a practical PV system. The lightning failure mode of bypass diodes is identified for the first time. The results can help to design effective lightning protection and select appropriate parameters of protective devices.

2022	I. Hetita, A. S. Zalhaf, D. A. Mansour, Y. Han, P. Yang, C. Wang	Modeling and protection of photovoltaic systems during lightning strikes: A review	Renewable Energy	www.sciencedirect.com/science/article/abs/pii/S0960148121016682	The integration of renewable energy (RE) sources is increasing day by day because of their permanent existence and the limited quantities of fossil fuels. One of the most promising RE sources is photovoltaic (PV) technology, which is developing quickly in many countries worldwide. PV cells generate electricity by converting the sunlight to DC voltage. PV arrays are installed in outdoor areas and on the rooftops of homes to be directly subjected to the sun. Consequently, they are frequently subjected to lightning strikes, which may cause damage to PV arrays, service interruption, and additional cost for PV replacement. Therefore, an adequate lightning protection system (LPS) must be installed to protect the PV panels. In addition, the transient performance of PV panels during lightning strikes must be analyzed well. This paper presents a comprehensive review of the superior modeling methods of PV systems during lightning strikes. In addition, the paper displays the different platforms to simulate the transient effects of lightning strikes on PV systems. The lightning transient effects on PV arrays are studied based on the system modeling to assess the recommended LPS designs studied in the literature. The paper also gives some recommendations about the modeling methods and protection of PV systems during lightning strike.
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Zhang, 2019 proposes a Partial Element Equivalent Circuit (PEEC) method, considering structure steels, wiring in panels, PV cells and non-linear surge protective device. The resulting model helps to design effective lightning protection and select appropriate parameters of protective devices.

Sun, 2021 uses a FDTD based method to evaluate the effect of lightning-induced voltages on complex terrain, including flat land, lake and mountain, and the results provide guidance for lightning protection design. *Sun, 2023* studies further details about the effects of the PV panels support on induced overvoltages, showing that different technical implementations lead to different effects.

Hetita, 2022 is a well done review on the protection of PV plants against lightning strikes.

Formisano, 2021 shows the effect of indirect lightning on different DC/DC converter architectures, involving three major steps, i.e., the magnetic-field computation, the evaluation of both common-mode- and differential-mode-induced voltages across the PV module, and the use of the calculated voltages as input to a lumped equivalent circuit of the PV module connected to the DC/DC converter.

Lately, energy storage in the form of battery systems is becoming of common use:

Ahmad, 2021 analyzes a hybrid solar PV–battery energy storage system, to evaluate the lightning-induced overvoltage on the system components (solar PV–battery systems and inverters at the DC side).

Zhang, 2023 investigates the lightning transient overvoltages in the hybrid WT – PV - battery energy storage system (BESS). An EMTP HF based model includes the PV string, inverter, cable, power transformer, wind tower, DC/DC converter. Then, three types of overvoltages caused by lightning striking PV array, transmission tower of wind farm (WF) and terminal tower of 500 kV substation are thoroughly studied.

3. Impact on Wind turbines and Eolic systems

Publ. year	Authors	Title	Journal	Link	Abstract
2016	D. Djalel, M. Mourad and G. Sihem	Contribution to the study of the aggression of lightning phenomenon on the wind turbine structures	Wind Engineering	www.jstor.org/stable/90007114	Because of the complexity of the lightning phenomenon in the physical and electrical aspects, the aggression of lightning strokes on the wind turbines has become, for many years, one of the main causes for insurance agencies of these new electric generation systems. Wind turbines have important dimensions of structures, where they can easily attract lightning and his anger, the effect of heights also captures the farthest lightning. The rotation of the blades may also trigger lightning and result in considerable increase in the number of strikes to a wind turbine unit. Since wind turbines are tall structures, the lightning currents that are injected by return strokes into the turbines will be affected by reflections at the top, at the bottom, and at the junction of the blades with the static base of the turbine. Despite the protection in place in wind turbines, statistics show that they are inefficient, because they are placed in locations where repair is difficult and expensive. In this article, we study lightning strikes and their effects on wind turbines and propose other useful elements in the design of efficient wind turbines and optimal ways to protect them against direct and indirect lightning strikes.

2022	R. Torchio, M. Nicora, D. Mestriner, M. Brignone, R. Procopio, P.G. Alotto and M. Rubinstein	Do Wind Turbines Amplify the Effects of Lightning Strikes? A Full-Maxwell Modelling Approach	IEEE Trans. On Power Delivery	ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=9681272	Wind turbines (WTs) can be seriously damaged by lightning strikes and they can be struck by a significant number of flashes. This should be taken into account when the WT lightning protection system is designed. Moreover, WTs represent a path for the lightning current that can modify the well-known effects of the lightning discharge in terms of radiated electromagnetic fields, which are a source of damage and interference for nearby structures and systems. In this paper, a WT struck by a lightning discharge is analyzed with a full-wave modelling approach, taking into account the details of the WT and its interactions with the lightning channel. The effects of first and subsequent return strokes are analyzed as well as that of the rotation angle of the struck blade. Results show that the lightning current along the WT is mainly affected by the ground reflection and by the reflection between the struck blade and the channel. The computed electromagnetic fields show that, for subsequent return strokes, the presence of a WT almost doubles their magnitude with respect to a lightning striking the ground. Such enhancement is emphasized when the incline struck blade is considered.
2011	R.B. Rodrigues, V.M.F. Mendes, J.P.S. Catalão	Indirect Effects of Lightning on Wind Turbines using EMTP-RV	Proc. of the 2011 Int. Conf. on Power Engineering, Energy and Electrical Drives	ieeexplore.ieee.org/document/6036547	This paper is concerned with the protection of wind turbines against the indirect effects of lightning. Lightning damages involving wind turbines have come to be regarded with increasing concern. The wind power generation is rapidly growing in Portugal, but still there are few studies regarding the lightning protection of wind turbines using models of the Electro-Magnetic Transients Program (EMTP). Hence, a case study is presented in this paper, based on a wind turbine with an interconnecting transformer, considering that lightning strikes the soil near the tower. Computer simulations are provided by using the recently restructured version of EMTP, EMTP-RV, highlighting the need for adequate protection measures.
2023	M. E. M. Rizk, A. Ghanem, S. Abulanwar, A. Shahin, Y. Baba, F. Mahmood and I. Ismael	Induced Electromagnetic Fields on Underground Cable Due to Lightning-Struck Wind Tower	IEEE Trans. On Electromag. Compatibility	ieeexplore.ieee.org/document/10231000	In regions having high activity of lightning flashes, it is important to investigate the lightning-induced electromagnetic (EM) transients affecting buried cables, particularly if such buried conductors are extending close to grounded towers, such as wind towers. In this article, the impact of the grounded wind tower, ground conductivity and permittivity, depth of the cable, and its position from the return stroke on the lightning-induced EM fields on the cable sheath are investigated. In addition, the lightning-induced EM fields on the cable sheath are also calculated with the presence of bare-underground wire above the cable as a protection against lightning strikes. The 3-D finite difference time domain method with nonuniform grid technique is implemented for this study. From the results, it is shown that the presence of wind tower increases the magnitude of lightning-induced EM fields on the cable sheath, particularly for close distances between cable and tower. Moreover, the impact of soil permittivity on lightning-induced EM surges becomes significant for low soil conductivity. Also, the impact of cable depth becomes more significant for higher soil conductivity. Furthermore, the bare-underground wire reduces the magnitude of lightning-induced electric field.
2023	J. Zhang, Q. Sun, Z. Zheng, L. Huang, D. Chen, J. Yuan	Lightning surge analysis for hybrid wind turbine-photovoltaic-battery energy storage system	Electric Power Systems Research	www.sciencedirect.com/science/article/abs/pii/S0378779623006922	The lightning transient overvoltages in the hybrid wind turbine (WT) - photovoltaic (PV) - battery energy storage system (BESS) is investigated in this paper. A hybrid system model is developed in the environment of EMTP. The high-frequency (HF) models of components in the hybrid system are established, including PV string, inverter, cable, power transformer, wind tower, DC/DC converter and so on. Then, three types of overvoltages caused by lightning striking PV array, transmission tower of wind farm (WF) and terminal tower of 500 kV substation are thoroughly studied. The installation mode of surge protection device (SPD) within PV system is discussed. Finally, the influence of WF and PV system topologies on lightning surge is discussed. The results show that lightning surges from the PV system do not affect the WF, the BESS, and the hybrid substation. Regarding lightning surges from the substation side, the string structure exhibits a significant decrease of 72.8% in voltage compared to its central structure in PV system. Observing WF, when comparing the star structure against the radial connection, there is a reduction of 63.4% in lightning voltage in the former.
2023	W. Costa da Silva, W. L. Manzi de Azevedo, A. Ricardo Justo de Araújo, J. Pissolato Filho	Full-wave electromagnetic analysis of lightning strikes to wind farm connected to medium-voltage distribution lines	Electric Power Systems Research	www.sciencedirect.com/science/article/abs/pii/S0378779623004868	This paper studies the voltages developed on a wind turbine (WT) and a medium-voltage distribution line (MVDL) connected to a wind farm subjected to lightning strikes and located on frequency-dependent (FD) soils. The ground potential rise (GPR), voltages at the blade tip and on phase conductors of the MVDL are calculated using the full-wave electromagnetic software XGSLab® employing the rigorous Partial Element Equivalent Circuit (PEEC) method. The wind farm comprises four wind turbines with interconnected grounding systems using cables buried in resistivity soils of 1,000 and 5,000 Ω m. The voltages are computed for the first positive impulse (FPI) of 100-kA 10/350 μs and for the subsequent negative impulse (SNI) of 50-kA, 1/200 μs. Results have shown that voltage peaks increase notably as the soil resistivity increases. When the WTs are assumed, oscillations in the GPR waveforms for the SNI occur due to the multiple reflections between the blade and the turbine's base. However, the voltages for the FPI present smooth time-domain responses. Furthermore, the overvoltages developed at the MVDL are significantly dependent on the soil resistivity and lightning current waveform.

Rodrigues, 2011 is one of the first study in which a wind turbine with an interconnecting transformer is modelled to find the effects of an indirect lightning strike, showing the need for adequate protection measures.

Djalel, 2016 performs an analysis of the effects of direct strikes, modeling the turbine as a transmission line. The paper proposes useful elements in the design of efficient wind turbines and optimal ways to protect them against direct and indirect lightning strikes.

Torchio, 2022 presents a more accurate model, i.e. a full-Maxwell approach. The effects of first and subsequent return strikes are analyzed as well as that of the rotation angle of the struck blade. Results show that the lightning current along the WT is mainly affected by the ground reflection and by the reflection between the struck blade and the channel; in addition, the computed electromagnetic fields show that, for subsequent return strokes, the presence of a WT almost doubles their magnitude with respect to a lightning striking the ground.

da Silva, 2023 and *Rizk, 2023* are very recent paper in which the effects produced by a lightning strike hitting a WT are evaluated on a Medium Voltage distribution network and on an underground cable; in both cases, the real characteristics of the ground (in terms of conductivity) are considered, and the studies show how the lightning phenomenon should be taken into account while designing such systems.

4. Impact on other devices and systems

Publ. year	Authors	Title	Journal	Link	Abstract
2021	H. P. Rimal, A. Reatti, F. Corti, G. M. Lozito, S. Quondam Antonio, A. Faba and E. Cardelli	Protection From Indirect Lightning Effects for Power Converters in Avionic Environment: Modeling and Experimental Validation	IEEE Trans. On Industrial Electronics	ieeexplore.ieee.org/document/9162560	This article focuses on a protection system from lightning indirect effects applicable to power converters for avionic applications. The case study considered in this article is a dc-dc pulsewidth modulation buck-boost converter protected by a metal oxide varistor and a series inductive blocking element. The converter is investigated when operated in normal operating conditions, under lightning indirect strokes without protection, and under lightning indirect strokes with protection. A numerical model of the system based on a finite-difference time-domain scheme is proposed. Validation of the system is performed through a comparison with experimental measurements and alternative numerical modeling techniques, showing the effectiveness of the blocking system and the accuracy of the proposed model.
2022	A. Formisano, S. Barmada and M. Raugi	Impact of Nearby Lightning Strikes on Wireless Power Transfer Ground Assembly	IEEE Trans. On Magnetics	ieeexplore.ieee.org/document/10004568	Direct hits from lightning strikes (LSs) are commonly recognized as dangerous events for open air installations, but also the much more frequent case of LS hitting nearby can cause overvoltage potentially damaging connected circuits, if not correctly protected. In this article, adopting a hybrid formulation, we simulate the voltage induced at the terminals of a wireless power transfer (WPT) ground coil by an LS hitting the ground nearby the system. The induced overvoltage has a non-negligible amplitude, depending on the distance of the hit, the tortuosity of the lightning channel, and the inclination of the coil with respect to the ground plane.

Among the components affected by lightning induced surges, transformers need to be mentioned.

In *Piantini, 2014* the analysis of failed transformers and field results shows that the installation of surge arresters at the transformer LV side does not drastically change the failure rate. Computer simulations corroborate this result and confirm that failures are mostly associated with surges coming from the MV side.

Wireless Power Transfer systems are becoming popular, and the future might be characterized by their presence in a large extent.

In *Formisano, 2022*, adopting a hybrid formulation, the voltage induced at the terminals of a WPT ground assembly by an LS hitting the ground nearby the system is evaluated, with respect to the the distance of the hit, the tortuosity of the lightning channel, and the inclination of the coil with respect to the ground plane.

5. Conclusions

For the sake of exposition, a few conclusions are reported here, again organized according to the three sections of the document. These represent the outcome of the bibliographic analysis but can also be interpreted as an indication of the most relevant issues emerged, each leading to a research line within the FELINES project.

- *Modeling:*

Two main models have been identified and will be exploited. The first one is based on the work by *Griffith and Phelps, 1976* and provides the charge distribution of the PBP. The second one is based on the work presented in *Karunaratne, 2014*, which is a TL-type model where the output is the current distribution in a similar way to the return strokes models. Both models will be implemented, and results compared. When model parameters are required, a data-based approach, possibly trained on the Rakov's data set, could be used to estimate model parameters.

- *Experimental data:*

Most of the available measurements are related to rocket-triggered experiments. Data are electric fields measurements, taken using different combinations of broad and narrow band antennas. The best source of data is Rakov's work, as described in the numerous papers from his group. The raw data are available to the research group. They are negative strokes, and the dataset is composed by measurements related to 3000 events. These data will be processed to assess statistical properties, and possibly analyzed using machine-learning approaches.

- *Sensitive devices:*

Transmission Line (TL) and Wind Turbines (WT) are the most representative devices to be investigated. In WT we can place sensors, so they are worth of being considered in the analysis. In some cases, interaction models for the electromagnetic fields generated by the lightning strikes and the device are available, (e.g. in the case of Power Lines). Such cases will be given prominence in the due course of the project.

Bibliography

Just the papers listed in the Project Proposal are reported here to ease reading the preliminary part of the report. The full list of identified bibliographic sources is discussed in the body of the report.

- [1] V. Cooray, Lightning protection. 2009.
- [2] Brignone et al., 'Mitigation of Lightning-Induced Overvoltages Using Shield Wires: Application of the Response Surface Method', in 2018 34th International Conference on Lightning Protection (ICLP), 2018, pp. 1–6.
- [3] Mestriner et al., 'Impact of Grounding Modeling on Lightning-Induced Voltages Evaluation in Distribution Lines', Appl. Sci., vol. 11, no. 7, p. 2931, 2021.
- [4] Borghetti et al., 'Influence of surge arresters on the statistical evaluation of lightning performance of distribution lines', in 2004 International Conference on Probabilistic Methods Applied to Power Systems, 2004, pp. 776–781.
- [5] Nazari et al., 'On the Performance of Grounding, Bonding, and Shielding Systems for Direct and Indirect Lightning Strikes', IEEE Trans. Electromagn. Compat., vol. 62, no. 1, pp. 135–143, Feb. 2020
- [6] Heidler et al., 'Calculation of lightning current parameters', IEEE Trans. Power Deliv., vol. 14, no. 2, pp. 399–404, 1999.
- [7] Brignone et al., 'Analytical Expressions for Lightning Electromagnetic Fields With Arbitrary Channel-Base Current—Part I: Theory', IEEE Trans. Electromagn. Compat., vol. 63, no. 2, pp. 525–533, April 2021
- [8] Y. Baba and V. A. Rakov, 'Electromagnetic models of the lightning return stroke', J. Geophys. Res. Atmospheres, vol. 112, no. D4, 2007.
- [9] 'IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines', IEEE Std 1410-2004 Revis. IEEE Std 1410-1997, pp. 1–50, Jul. 2004.
- [10] Brignone et al., 'Evaluation of power system lightning performance—Part II: Application to an overhead distribution network', IEEE Trans. Electromagn. Compat., vol. 59, no. 1, pp. 146–153, 2016.
- [11] Formisano et al., 'Assessment of induced voltages in common and differential-mode for a PV module due to nearby lightning strikes', IET Renew. Power Gener., vol. 13, no. 8, pp. 1369–1378, 2019.
- [12] Ahmad et al., 'Lightning protection on photovoltaic systems: A review on current and recommended practices', Renew. Sustain. Energy Rev., vol. 82, pp. 1611–1619, 2018.
- [13] Torchio et al., 'Do Wind Turbines Amplify the Effects of Lightning Strikes A Full-Maxwell Modelling Approach', IEEE Trans. Power Deliv., 2022.
- [14] IEC 61400-24:2019. Wind Energy Generation Systems – Part 24: Lightning Protection
- [15] G. V. Cooray, The lightning flash. Iet, 2003.
- [16] Kašpar et al., 'A model of preliminary breakdown pulse peak currents and their relation to the observed electric field pulses', Geophys. Res. Lett., vol. 44, no. 1, pp. 596–603, 2017.
- [17] Wang et al., 'Beijing Lightning Network (BLNET) and the observation on preliminary breakdown processes', Atmospheric Res., vol. 171, pp. 121–132, 2016.
- [18] Rachidi et al., 'Voltages induced on overhead lines by dart leaders and subsequent return strokes in natural and rocket-triggered lightning', IEEE Trans. Electromagn. Compat., vol. 39, no. 2, pp. 160–166, 1997.
- [19] Brignone et al., 'Evaluation of Power System Lightning Performance, Part I: Model and Numerical Solution Using the PSCAD-EMTDC Platform', in IEEE Transactions on Electromagnetic Compatibility, vol. 59, no. 1, pp. 137–145, Feb. 2017
- [20] Formisano et al., 'Computation of Coupling Parameters between Neighboring Panels' in Photovoltaic Arrays, Proc. Of Compumag2021, Cancun (Mexico), 16-20 Jan. 2022.
- [21] Barmada et al., 'Arc detection in pantograph-catenary systems by the use of support vector machines-based classification', IET Electrical Systems in Transportation, vol. 4, no. 2, pp. 45 - 52, 2014
- [22] Betti et al., 'Fault Prediction and Early-Detection in Large PV Power Plants Based on Self-Organizing Maps', Sensors, vol. 21, no. 5, pp. 1–16, 2021.
- [23] Andreotti et al., 'A new tool for calculation of lightning-induced voltages in power systems—Part I: development of circuit model', IEEE Trans. Power Del., vol. 30, no. 1, pp. 326–333, Feb. 2015.
- [24] Nucci et al., "A new finite difference time domain scheme for the evaluation of lightning induced overvoltage on multiconductor overhead lines," in Proc. Int. Conf. Power Syst. Trans., vol. 2, no. 5, pp. 596–602, Rio de Janeiro (Brazil), Jun. 24–28 2001.
- [25] M. Paolone, 'Modeling of lightning-induced voltages on distribution networks for the solution of power quality problems, and relevant implementation in a transient program', Ph.D. dissertation, Dept. Elect. Eng., Univ. of Bologna, Bologna, Italy, Mar. 2002.
- [26] Farina et al., 'The Lightning Power Electromagnetic Simulator for Transient Overvoltages (LIGHT-PESTO) Code: A User-Friendly Interface With the MATLAB-Simulink Environment', in IEEE Letters on Electromagnetic Compatibility Practice and Applications, vol. 2, no. 4, pp. 119–123, Dec. 2020.
- [27] Nicora et al., 'A 10-year study on the lightning activity in Italy using data from the SIRF network', Atmospheric Research, vol. 256, p. 105552, 2021.