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Measuring low-current discharges from grounded rods under high background electric fields

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ABSTRACT

This work presents the development of an inductive current sensor for measuring pulsating corona discharges observed under high background electric field. Laboratory and field experiments in different setups are used to corroborate the discharge features. The first location is on the roof of a regular building, and the second is on a flat area. Due to the enhancement of the E-field caused by lightning strikes in the vicinity of a grounded rod with a sharp tip, positive and negative pulses before or after the strikes are observed. When lightning activity is far from the structure, but the electric field remains high, pulses are also observed. Finally, one prototype of this sensor was modified to work as a pulse detector with a higher current threshold, allowing detections of leader currents above 0.5 A. The sensor performance is validated in the laboratory and investigated in the field, in association with lightning events.

1. Introduction

Under thunderstorm conditions, charged particles present in storm clouds cause the background electric field to increase at ground level. Many studies addressed effects of the electric field enhancement under such conditions [1–6]. At the ends of grounded sharp structures, this phenomenon can, in turn, lead to the onset of corona/point discharges. The space-charge formation can generate a layer that decreases the magnitude of the local electric field [1,7–9]. In this way, the highest spots that should be the ones struck by lightning can become shielded, and lightning can strike somewhere else.

The corona current has been extensively studied in laboratory experiments. The first studies performed [10,11] reported the pulsating behavior of the current when a continuing high voltage is applied. As the applied electric field increases, the average current and the pulse frequency increase. However, pulse amplitude and pulse duration are constant for certain geometries [5,12,13]. Such discharge bursts are also observed in laboratory long air-gap discharges during the voltage rise of impulse waveforms [14,15], with similar pulsating features [16,17].

Works that evaluated the corona current under thundery weather reported an average current of a few microamperes [2,3]. However, pulse peaks can range from hundreds of microamps to hundreds of milliamps [5,12,13]. A sufficiently high electric field is required for corona onset and the average current increases with the background electric field. The system geometry and weather conditions such as pressure, humidity, and wind can affect these parameters. The role of wind was studied in [4,5], indicating that higher wind speeds accelerate the ion removal from grounded structures and increase the corona current for the same electric field level.

The influence of corona discharges on lightning initiation from grounded structures was studied for upward lightning. Self-initiated events were correlated with stronger winds that could remove space charges, creating conditions of high local electric field for the leader initiation [18]. For wind turbines, observations reported in [19] indicate that moving structures can avoid the shielding effect caused by space charges and increase the probability of lightning strikes. Measurements performed by [6] showed the features of pulsating discharges from a grounded sharp rod thirty milliseconds before a return stroke nearby; comparisons between sharp and blunt rods revealed the effectiveness of structures for space charge generation. The amplitude and duration of these pulses are different than induced currents caused by approaching downward leaders [20,21], as well as induced currents from vertical conductors during return stroke currents [22], which can reach a few amps or even more.

This work presents the development of a current sensor for measuring corona discharges. In the laboratory, the current signature is

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studied in a plane-to-rod setup at atmospheric pressure, and for outdoor experiments, pulsating discharges were measured in two different experimental sites with different orography, as initially presented in [23]. This extended publication proposes one application based on the same sensor. A current detector with a higher current threshold is developed and presented in section III. Although corona currents are not detected, laboratory experiments validate the applicability of the sensor. Preliminary results in the field show that the detections are due to current bursts associated with leader inception during nearby lightning events.

2. Development of a current sensor for measuring corona discharges

2.1. Laboratory investigation

The currents of corona discharges at atmospheric pressure can be measured with high-bandwidth current probes. Depending on the current amplitude, shunt resistors can also be used as long as low inductance and low resistance are ensured to avoid oscillations. For the development of a simple and reliable current sensor for corona discharges, a current transformer with a ring core made of ferrite with high magnetic permeability was employed. A low-inductive shunt resistor of 50 ohms was used to corroborate signatures of the discharges and to not interfere significantly with the measurements performed.

Fig. 1 shows the diagram of connections of the sensor in the setup. A grounded conductive rod 30-cm high with a sharp tip is placed between two plates (with 1.4 m and 2.0 m of diameter) separated by 50 cm, leading to a gap distance of 20 cm. The high-voltage power supply is connected to the upper plate and provides up to 30 kV DC at positive or negative polarity. This setup reproduces the conditions of sharp grounded structures subject to high electric fields when charged clouds are in the vicinity.

The current sensor is composed for the inductive current transformer connected in cascade to a stage with surge protection components and measuring components. It is aimed to obtain an output voltage that is proportional to the actual current through the rod.

When a positive voltage is applied to the upper plate, a negative corona can emerge from the grounded electrode and vice-versa. The shape of a single pulse is shown in Fig. 2(a) and (b), respectively for +17 kV and −17 kV applied to the upper plate. Those cases present amplitudes of 3.8 mA for positive corona and 0.52 mA for negative. A single pulse has a rising time of tens of nanoseconds and a duration of 300–400 nanoseconds. Negative pulses present slightly lower rising times and durations, as observed in [5] and [6].

The output voltage of the sensor is smoother than the current measured by the shunt resistor and presents polarity reversal before the decay to zero, due to the features of the inductive sensor. In Fig. 2(c), the V/A ratio of the sensor is presented according to the frequency. The bandwidth of the sensor ranges from 55 kHz to 800 kHz, with a peak ratio of 7.7 V/A at 178 kHz. The peak ratio for negative discharges is about 4.7 V/A, while for positive discharges is 5.7 V/A, which is expected since negative discharges are faster and present more content with higher frequencies. The sensor can measure currents ranging from

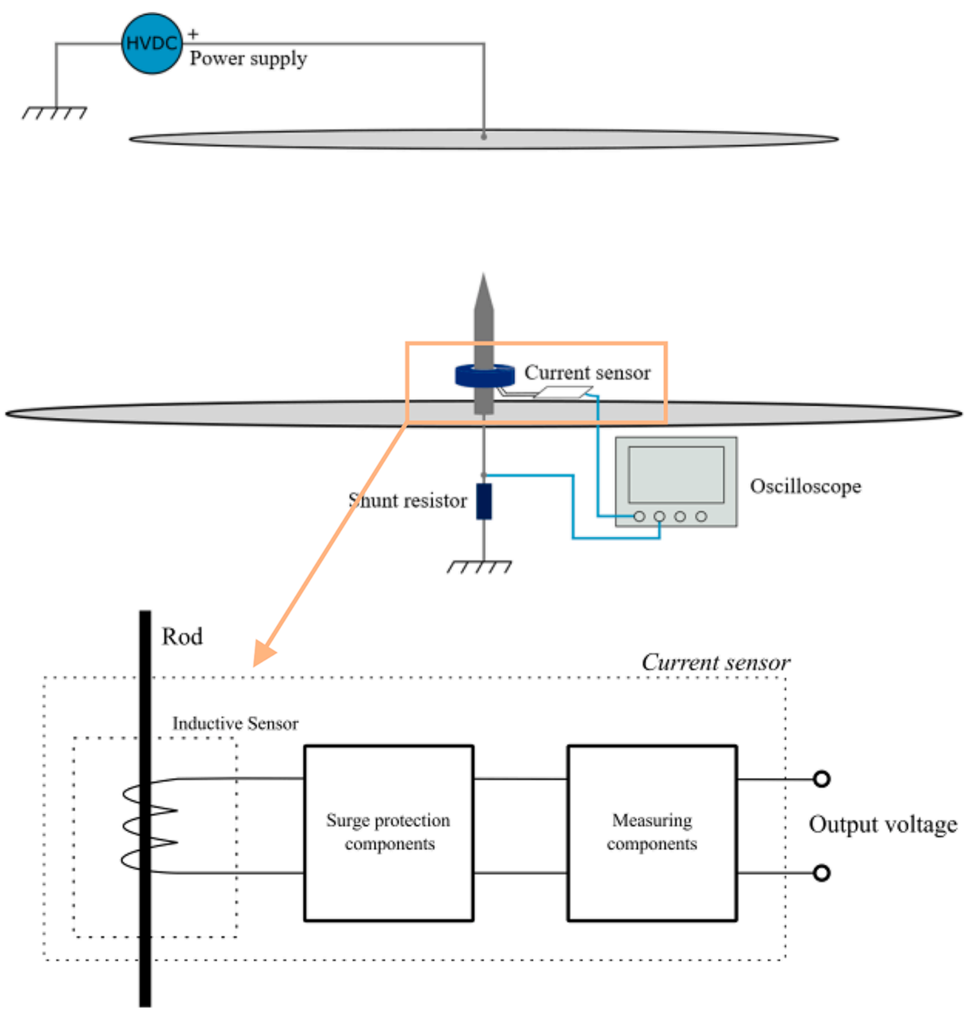


Fig. 1. Sketch of connections for the plate-to-rod setup and conceptual diagram of the sensor.

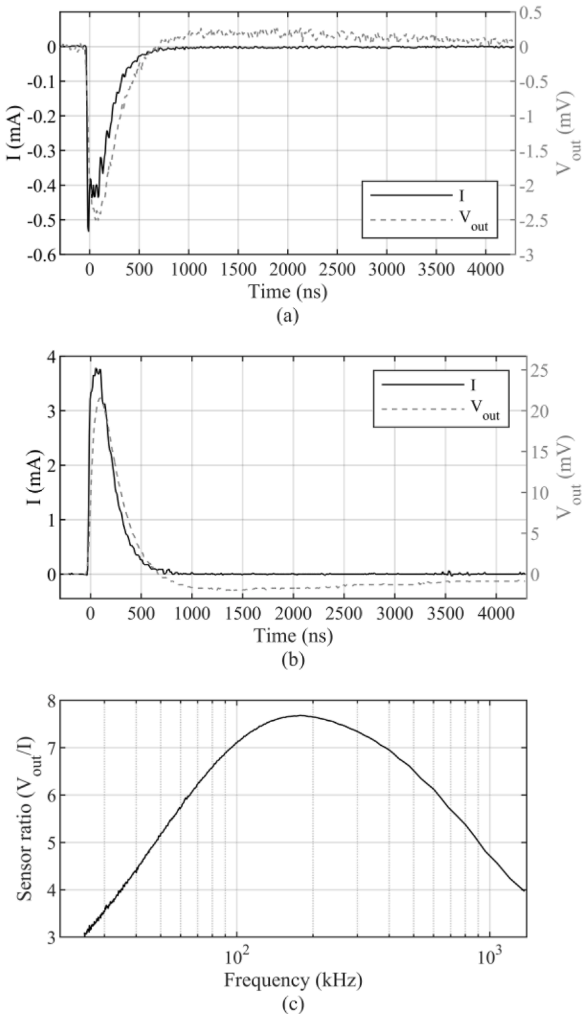


Fig. 2. Measurements obtained with and the current sensor for (a) negative corona (+17 kV applied at the upper plate) and (b) positive corona (- 17 kV). Frequency response of the sensor (c).

100 μA to approximately 3 A, clipping the output voltage for higher currents.

2.2. Field experiments: concept

A compact system was developed for acquiring corona current and electric field data. An aluminum bar with a length of about 1.5~2 m and a sharp tip was used for the conductive grounded rod. Fig. 3a shows the scheme of the installation. The current was measured using either a shunt resistor in series with the rod or the developed current sensor. The shunt resistor was employed only in the first weeks of operations of the setups. It was connected in series with the grounding cable of the rod with low inductance and low resistance to ensure the quality of the measurements.

The background electric field was measured by a 10-Hz electric field mill, with acquisitions performed directly by a minicomputer. The measurements of the Field Mill consider the static component of the electric field [24], which inhibits the possibility of differentiating return strokes within the same flash. The recordings were synchronized with a GPS timestamp with millisecond precision. Data from the LINET lightning location network [25] was used to monitor the distances between lightning strikes and the sensor's site.

The first site is a typical roof of a building in Terrassa, Spain (Fig. 3b). This site is in an industrial region with many metallic structures nearby. The second installation was performed in the Observatori de l'Ebre, in

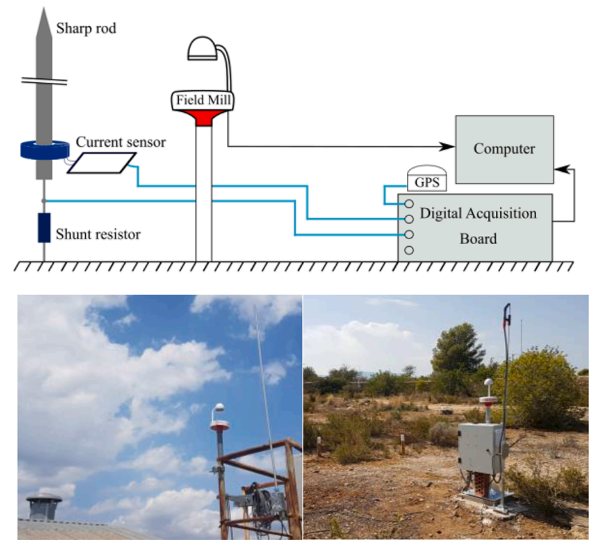


Fig. 3. Scheme of the setups for measuring corona discharges (a) and installations of rooftop (b) and flat-ground (c).

Roquetes, Spain (Fig. 3c). The sensor was installed in a flat area near bushes, trees, and other structures of the same height or higher than the tip of the rod. In both installations, the tip of the sensor is at least 1-m far from the field mill.

The use of the shunt resistor allowed for corroborating the matching between the current signal measured with the inductive sensor in the field [23] and the transformation ratio of the current sensor. The pulse shape presents a fast rise time (in the order of tens of nanoseconds) and decay of hundreds of nanoseconds, similar to what is reported for laboratory experiments [5,6,12,13].

The experimental results obtained during two years of investigation validate several characteristics already reported for corona discharges in the laboratory. Namely, for similar electric field levels in opposite polarities, the amplitude of positive discharges is greater than negative discharges. Conversely, their pulse frequency (number of pulses counted per second over a nearly constant electric field) is lower [5]. During most of the equipment's operating period, the shunt resistor was removed to not affect the pulse waveform. Thus, only the current sensor waveforms were recorded.

2.3. Field experiments: rooftop site

For this setup, the acquisitions of corona pulses were performed at a sampling rate of 50 MS/s, and the digitizer was unable to acquire long-time windows. The detections were timestamped and then correlated with the electric field. In this work, the electric field waveforms are presented according to the atmospheric electricity sign convention [26].

Fig. 4a shows a detailed portion of 20 min of electric field enhancement from May 21st, 2019, when a thunderstorm approached the region of Terrassa. The increase in the background electric field started at 13:20 (UTC), and at 13:22, when the electric field reached about −7 kV/m, the system started to detect a large number of positive pulses during about two minutes. The closest lightning was observed at 13:30 and according to LINET, represented an intracloud discharge 11 km far from the sensor's site. The FM signal reveals a very small step at this moment.

Fig. 4b depicts 10 min of data from Aug 12th, 2019, in which several lightning strikes were observed. Given that the field mill measures the quasi-static electric field, the steps observed usually are related to all return strokes of a flash or even different flashes that happened in a short time interval. Pulses were registered by the sensor at the instants shown by the dots. For the period shown in Fig. 4b, they have negative polarity.

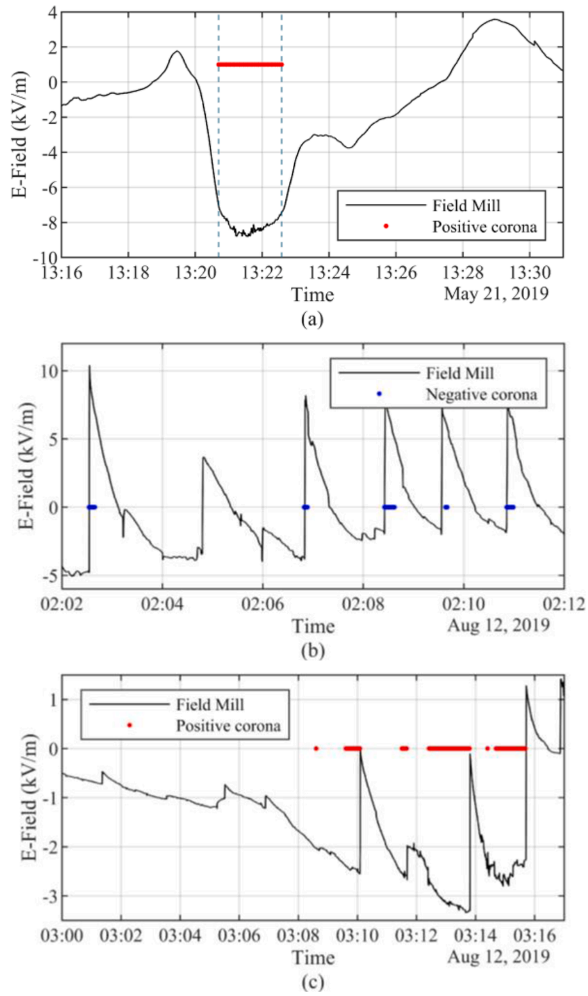


Fig. 4. Recordings of corona pulses at the rooftop site: Uninterrupted detections of positive corona during a 2-minute interval (a). E-field record leading to negative (b) and positive (c) discharges after and before nearby lightning strikes.

One can note that all pulses exhibited were recorded after the step detected by the field mill, corresponding to periods of a few seconds of an intense positive electric field. Lightning strikes records are in a range within 10 km from the sensor, the closest one being at 2.3 km (at 02:02).

On the same day (Aug 12th, 2019), some pulses were recorded for several seconds before lightning strikes, as seen in Fig. 4c, in a time window of 17 min. The positive pulses were registered in high negative E-field and the closest lightning strike was reported at 3.7 km far from the sensor (at 03:16). For the cases shown in Fig. 4c, positive values of the E-field after the return strokes are probably not high enough for triggering negative pulses from the rod. However, in the event shown in Fig. 4b, when the E-field is negative, one can see that it reaches similar values to the ones present in Fig. 4c (that led to positive corona detections), and positive corona was not detected in that interval. It is speculated that several other factors, such as humidity conditions, wind, and presence of water along the tip of the conductive rod can also affect the onset of corona pulses from the rod, in such a way that establishing a E-field threshold for the discharges may not be consistent.

2.4. Field experiments: flat-ground site

The acquisitions of corona pulses were performed at 33 MS/s with a time window of one second. Thus, it was possible to capture many pulses within the same event. Compared to the roof configuration, much fewer events were observed on the flat terrain due to the installation characteristics and proximity to structures of similar height. Another feature of the events observed was that, unlike the roof setup, in which pulses were recorded continuously during periods of sufficiently high electric fields, the corona pulses obtained at this site were recorded only during fast variations in the electric field resulting from near lightning strikes. Due to the bandwidth of the inductive sensor, atmospheric processes' signatures in VHF were also measured by the system, but with a very low amplitude and not hindering the actual corona pulses.

Fig. 5 depicts recordings of high-resolution data of two different events measured for this setup. Since the Field Mill data is acquired at a much lower sampling rate, the signals are not shown in this plot. Both events were recorded on Jan 21st, 2020, when lightning activity was nearby the sensor. Fig. 5a shows the current measurement obtained when the electric field changes from −2 kV/m to 7.1 kV/m. At the time indication of zero, a positive cloud-to-ground (CG) return stroke (RS) was registered 4.2 km far from the sensor, with an estimated peak current of 12.5 kA. A remarkable noise is observed in the background, correspondent to possible negative leader in-cloud development after the return stroke. The noise is bipolar and presents very high frequency content, clearly differentiating it from the corona discharges. Negative current pulses start 70 milliseconds after the lightning strike and last for a short period (about 50 milliseconds). The pulse amplitude reaches approximately 4 mA and decreases until the pulses are indistinguishable from the VHF background noise.

Fig. 5b is related to the occurrence of three return strokes detected from a wind farm that is about 9 km far from the corona sensor. The electric field measured exhibited a variation from 1 kV/m to −5.2 kV/m. The signals were synchronized with the current detection by GPS. The return strokes had peak currents of −14.3, −9.1, and −4 kA, respectively. Several positive pulses with amplitudes greater than 10 mA start to be recorded 34 milliseconds after the first return stroke and cease after 150 milliseconds. One can note that the highest concentration of pulses is observed after the third return stroke and that decreases as the interpulse interval increases and the background electric field decreases. For the flat-ground setup, several events like the ones presented in Fig. 5

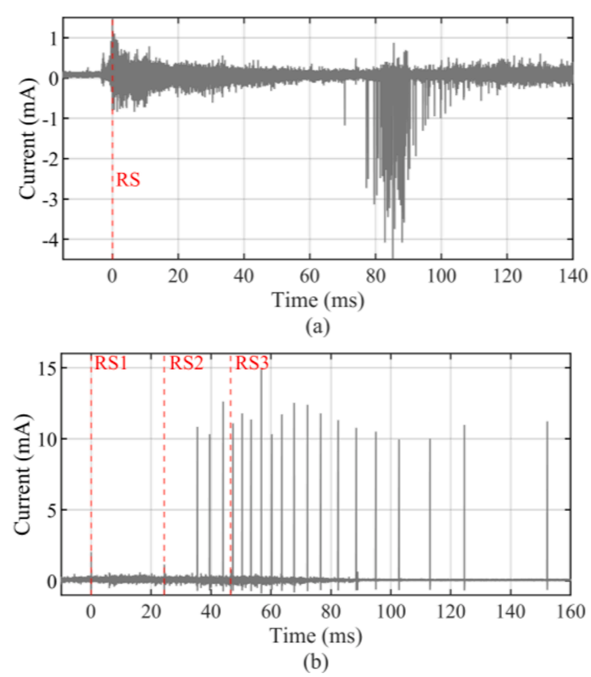


Fig. 5. Current events of Jan 21st, 2020. In (a), negative corona pulses are detected after a positive return stroke. In (b), positive corona pulses are observed when three negative return strokes are recorded from a Wind Farm in the vicinity of the sensor.

were recorded.

By comparing the pulses obtained for negative and positive corona, as the ones depicted in Fig. 5, several features of corona discharges observed in laboratory discharges are confirmed. For similar levels of electric field, the amplitude of positive pulses is much greater than negative pulses, and the opposite is observed for their frequency, as reported in [5].

From Fig. 5a, the appreciable VHF content observed after the positive CG suggests that the movement of charges inside the cloud causes the emergence of negative corona pulses from the rod. The corona pulse polarity is not associated with the polarity lightning strike, depending only on the local electric field.

Pulse parameters such as rise time and pulse charge were studied for both setups. Due to reflections on the decay of many measured waveforms, the pulse charge is not reliable. The rise time varied between the two setups due to the sampling rate and bandwidth limitation of the setups. Even though, the rise time observed for positive pulses (tens of nanoseconds) is significantly higher than for negative pulses in both setups. The duration of the pulses is also higher (320 to 500 nanoseconds) for positive pulses.

3. Application of current sensor for pulse detection

This section presents one of the applications intended for the current sensor shown in section II. In addition to measuring low currents associated with corona discharges, whose peak currents are in the range of milliamperes, the bandwidth and configuration of the inductive sensor allow for detecting leader currents incepted from a grounded rod that can be in the range of a few amperes.

For this application, the threshold of detection was increased. The output of the sensor was coupled to a voltage-to-optical converter to produce, instead of the voltage measurement related to the current, one optical pulse that can be connected to an acquisition system meters away through a fiber-optic cable. In this way, the sensor takes power from the measured signal to convert the current pulse into an optical pulse that is recorded by the powered acquisition system. Note that by increasing the current threshold, the sensor would miss corona pulses such as described in Section II, therefore, working as a detector of current pulses associated with streamers/leader discharges.

3.1. Laboratory investigation

Fig. 6 illustrates a scheme for the setup used for the current detector validation. A Marx Generator was used in a plate-to-point setup to produce a fast-increasing electric field and generate discharges from the ground electrode. The configuration used produced a "switching impulse" voltage waveform with a rising time of about 150 microseconds, in which the voltage can reach approximately −450 kV. The main gap is a one-meter separation between the sharp electrode and the high voltage plate. A secondary gap with two spheres and 30 cm of separation is where the breakdown likely occurs, even though streamers and leaders emerge from the ground electrode. A Pearson coil was used to measure current and verify the thresholds for detections.

The optical sensor components are shown at the bottom of Fig. 6. Fiber-optic cables with up to 50 m were tested. A powered optical receiver was deployed for converting the signal back to a voltage pulse representative of the measured discharge.

An oscilloscope is used for acquiring the current measured by the Pearson coil and the optical detection. A summarized description of the testing procedure is described in the following: The Marx Generator charges up to the desired voltage with negative polarity. By applying negative high voltage in the upper plate, the strong electric field created

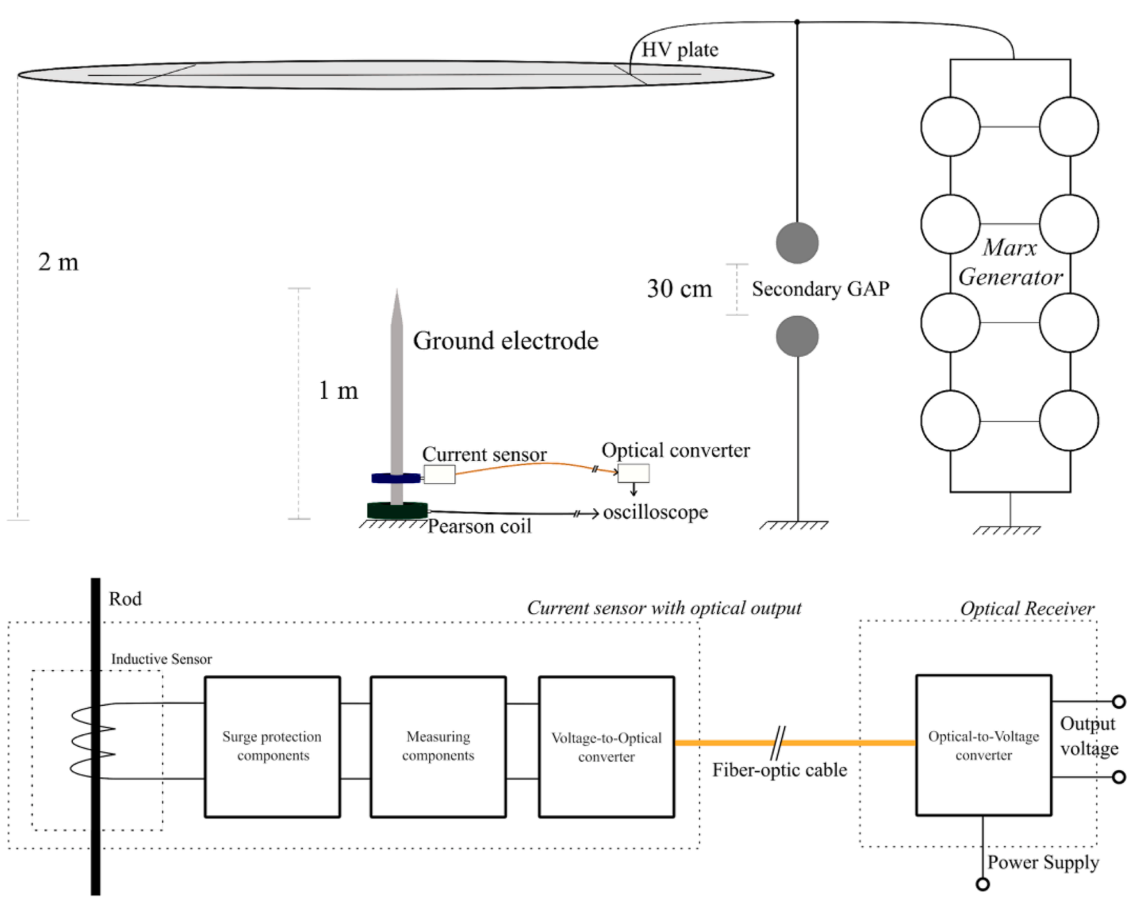


Fig. 6. Setup scheme for validating current detector in the laboratory (top) and conceptual design of current sensor used (bottom).

allows the formation of intermittent positive streamers and leaders at the ground electrode during the voltage rise. As this voltage increases, the secondary gap (much shorter but composed with spheres) can also present development of leaders. In the case of breakdown at this gap, part of the charges stored in the forming upward leader from the main gap will return to the ground, simulating a development observed of unconnected leaders during lightning, such as described in [20,21].

Fig. 7 shows the current and the converted optical pulses measured in one of the numerous discharges performed for the detector validation. The entire process, from the start of the voltage rise to the breakdown, takes about 165 microseconds. At the very beginning ($t = 0$), the strong bipolar oscillations are noise measured during the breakdown at the spheres of the Marx Generator. A few current pulses of amplitude less than 0.3 A are not detected until about $t = 60$ μs, when a current pulse of 1 A produces a detection that last similar time than the current pulse (500 nanoseconds). Later, pulses of about 0.65 A and 0.5 A are also detected with shorter pulses. At $t = 158$ μs, a small current is observed in an almost continuing stage. This current (with amplitude of about 0.1 A) is not detected by the sensor. Later ($t = 164$ μs), the breakdown takes place at the spheres (secondary gap), and a strong oscillation in current is observed. The fast return of charges to the ground electrode is detected with a pulse that lasts for 1.4 μs. On the right side of Fig. 7, one can see a picture of the grounded rod with a time exposure of 3 s. The short leader extended in 6 cm in that case.

Several discharges with the configuration shown in Fig. 6 were performed to obtain the current threshold of the detector, as well as verify the width of optical pulses produced at the output. Fig. 8 depicts a dispersion plot for the peak current observed for the initial streamer/leader pulses and the time width of the detection, measured in the fiber-optic receiver. One can note that this threshold lies at about 0.5 A, and most pulses with lower current were not detected by the sensor (the ones corresponding to the stage of first corona developments).

The detector with optical fiber is not sensitive to the current levels of corona discharge since they do not have enough energy to activate the optical converter. However, the detection of pulses from streamers and leaders of higher current levels is one of many applications that could be based on the current sensor developed. The sensor was tested under high current tests up to 100 kA to ensure that it can withstand real lightning strikes.

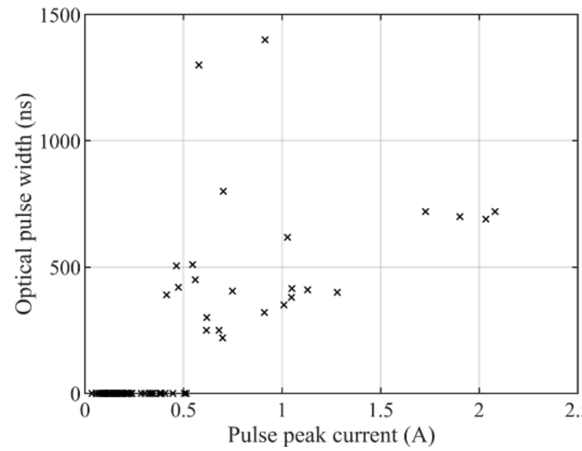


Fig. 8. Pulse peak current measured and correspondent optical pulse width detected. Pulses that are not detected are represented with optical width of zero.

3.2. Field experiments: La Tossa D'Alp site

The current detector was installed at the top of the Eagle Nest Tower, a communications utility located at La Tossa d'Alp, in the Spanish Pyrenees (2525 m above sea level). The tower is 15-m height and is instrumented with Rogowski coils for measuring currents of lightning impacts. The optical receiver is placed inside the nearby shelter, and an optic cable of 40 m connects it to the detector. Fig. 9 shows a picture of the site and depicts the sensor placed 1 m away from the tip of a regular sharp rod.

The sensor operated for 40 days of summer in 2021. Several events were recorded associated with lightning strikes in the vicinity of the sensor (5 km range). Some events within the same range did not trigger current detections in the prototype. During this period of operation, no false detection was observed, that is, all optical pulses recorded by the

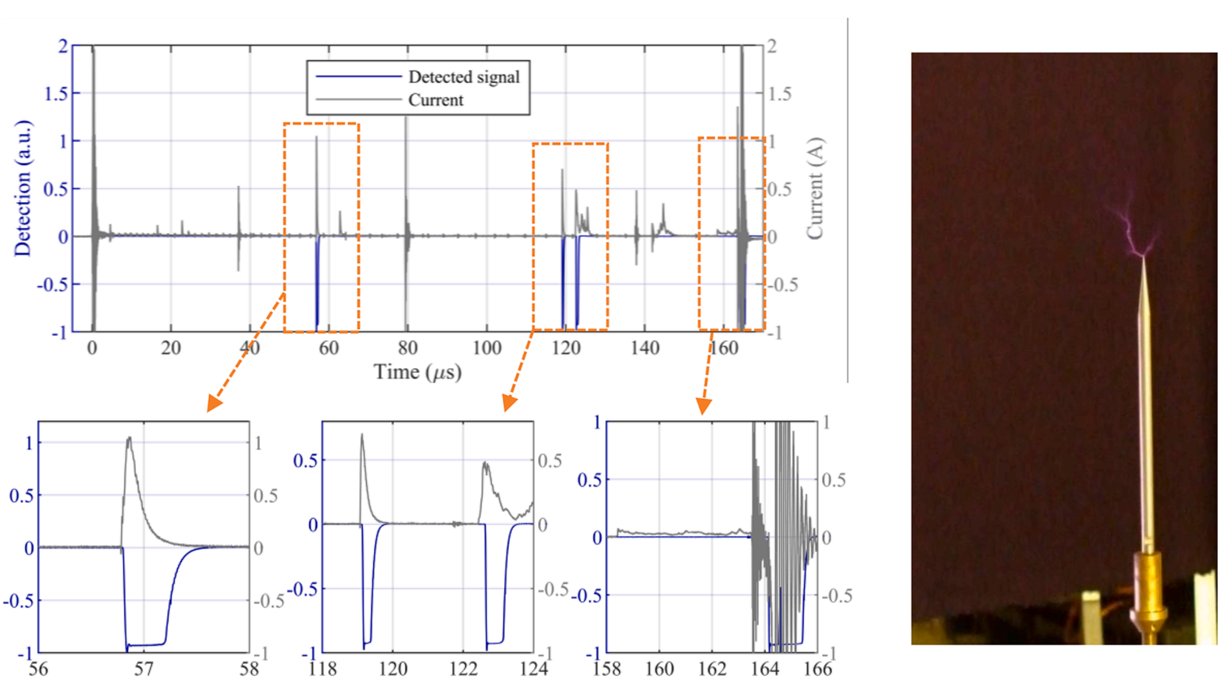


Fig. 7. Laboratory discharge produced with the Marx generator and detections correspondent to the short streamer/leader bursts. Measurements of current and detections (left) and 3-second picture of the discharge (right).

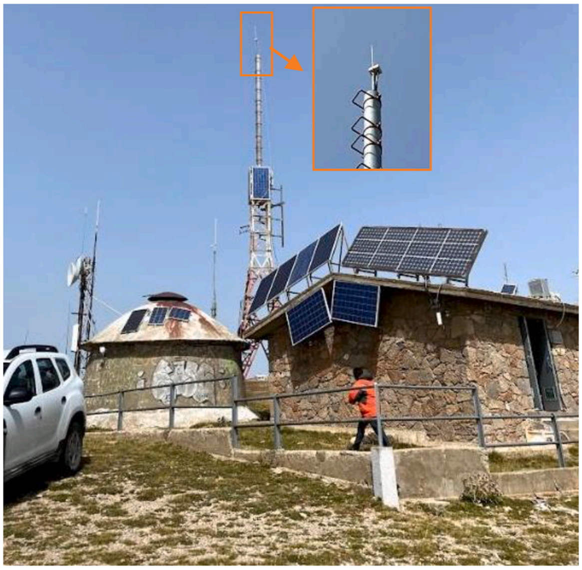


Fig. 9. Site for current detector installation: Eagle Nest Tower.

sensor were associated with electrical current events induced by nearby discharges.

Fig. 10 shows data from typical detections, in this case, with several pulses before the return stroke. The Lightning Location Network LINET [25] reported one flash of a single negative stroke 1.9 km far from the sensor, with an amplitude of 38.9 kA. Pulses were recorded during the last 1600 μs before the lightning strike. The pulse duration is related to the current flow through the rod, as shown in Fig. 8, from the laboratory experiments, and for this event ranges from 0.65 μs to 5 μs.

The several pulses detected before a single return stroke are associated with the process of the descending negative leader, which can enhance the local electric field at grounded structures, induce pulses and generate upward positive leaders and coronas [20,21]. For the case shown in Fig. 10, the interpulse interval is compatible with values reported in [20], for either unconnected upward leaders or in the case of return strokes of negative cloud-to-ground lightning. Induced currents during the return stroke can also be detected for the sensor if the current amplitude exceeds its threshold.

During that summer, no lightning or high-current detection was observed with the Rogowski measuring system installed in the Eagle Nest Tower.

Table 1 shows a summary of detections for the first period of operation of the prototype (from 11/08/2021 to 20/09/2021). From the 16 observed events, they were all very close to the sensor (up to three kilometers away). Following the classifications provided by LINET, both polarities of clout-to-ground return strokes as well as intracloud lightning were able to produce current detections. The events produced either single pulse detections, during the return stroke current or multiple pulse, like the one shown in Fig. 10, associated with an approaching leader.

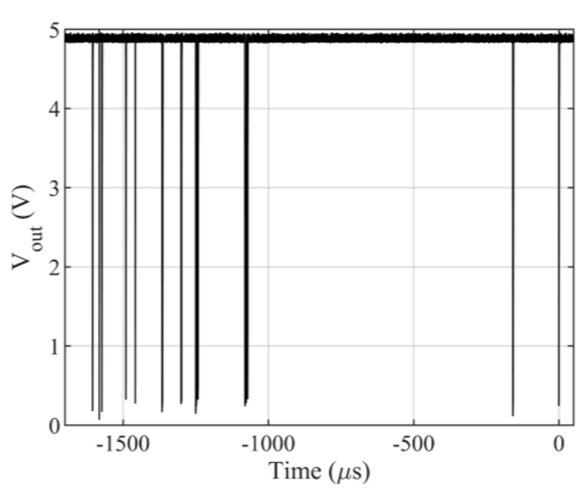
4. Final remarks

This work presented the use of a low current sensor for measuring corona discharges from grounded structures and one possible application in a surge-current detector of lightning related activity. Pulses of negative and positive discharges from sharp grounded rods were measured with an optimized current sensor in two different installations.

The features of corona discharges observed in laboratory were discussed in previous works [3–5,12,13], and they were corroborated in this work. The average peak currents obtained are about four times lower for negative pulses in both setups. The amplitude of negative pulses seems to be more variable than positive pulses. The noticeable difference in negative pulses' amplitude can be exemplified in Fig. 5a, whereas this is not remarkable for positive pulses (as seen in Fig. 5b).

It was observed that the rooftop setup was more susceptible to register corona discharges than the flat-ground setup, presenting steady detections over several seconds. For other grounded structures, such as high towers and wind turbines, the enhancement of the local electric field plays an important role. Consequently, corona discharges are expected to be more recurrent for lower levels of background electric field. It was confirmed that pulsating corona discharges can occur during the approach of a downward leader [6], before or after lightning strikes nearby, or when atmospheric activity is distant, being the main requirement for its occurrence at an electric field level higher than a certain threshold. This threshold, in turn, depends on the geometries involved and climate conditions such as pressure, humidity, and temperature [5].

The application of the sensor as a current detector is the first step in achieving a low-cost sensor that is able to detect current associated with lightning activity. Future steps towards the development of a sensor that integrates the inductive coil with a receiving circuit without the optical communication will constitute a device that can detect and register low-current activity, as an evolution of the typical lightning counter devices that are required as part of lightning protection systems.



	Pulse time (μs)	Pulse duration (μs)
13/09/2021 22:20:52.541 (GMT)	-1605	1.01
	-1582	0.92
	-1573	0.76
	-1490	0.80
	-1458	0.65
	-1366	3.10
	-1300	2.60
	-1250	3.90
	-1244	2.70
	-1081	5.00
	-1074	4.20
	-158	1.63
	0	1.25

	Distance from detector	Current
Lightning event:	1.9 km	-38.9 kA

Fig. 10. Typical pulses measured in La Tossa D'Alp using the detector with fiber-optic cable.

Table 1
Summary of events that led to detections.

	Number	Distance from sensor			Type of Event		Detection produced	
		Closest event	Farthest event	Average distance				
Nearby events that triggered pulse detections from prototype	16	0.5 km	3.0 km	1.45 km	+CG	8	Single pulse	10
					-CG	5	Multiple pulse	6
					IC	3		

CRediT authorship contribution statement

Marcelo Arcanjo: Conceptualization, Methodology, Software, Data curation, Writing – original draft. **Joan Montanyà:** Supervision, Writing – review & editing, Funding acquisition. **Michele Urbani:** Visualization, Investigation. **Victor Lorenzo:** Supervision, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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