Lightning Polarity and Upward Flash Statistics on a Wind Turbine in Croatia Based on Current Measurements

Franjo Vuković, Božidar Filipović-Grčić, and Bojan Franc

Abstract – The paper presents a 2.5-year deployment of a Rogowski-coil–based current measurement system on a wind turbine in southern Croatia. This instrumented observatory enables detailed waveform analysis to assess the cumulative impacts of lightning flashes on the monitored turbine, neighboring turbines, and their protection systems by deriving statistical distributions of current parameters. These distributions can serve as benchmarks for similar lightning-prone regions worldwide. The high-speed camera was installed at the local substation 1 year after the current measurement system deployment, supporting current measurements and providing additional insight into the initiation, development, and progression of lightning flash events. From its installation on July 5, 2022, until February 20, 2025, the system collected a total of 194 lightning waveforms. This paper presents the statistical results of these measured flashes, including flash polarity and type (upward vs downward), and compares them with associated lightning location system data.

1. Introduction

Since 2022, lightning activity has been actively monitored in a wind farm (WF) that contains 14 wind turbines (WTs), which are spatially separated into two groups, with the 110/20 kV substation right in the middle. The rated power of each WT is 3 MW, the towers are 80 m high, and the blades are 49 m long. The WF is located in winter lightning activity areas indicated by meteorological data and lightning location system (LLS)-based maps [1]. On July 5, 2022, two Rogowski coils were installed on the WT that is located at the highest altitude among all WTs. The installed lightning current waveform measurement system (LCWMS) consists of two Rogowski coils placed around the base of the WT tower and connected via coaxial cables to the integrators inside the tower, housed in an electrical cabinet that also contains the automated acquisition system. The high-frequency sensor (Rogowski + integrator) is optimized for frequencies up to 1 MHz and currents of ±250 kA. In contrast, the low-frequency sensor (the other Rogowski + integrator) is optimized for frequencies up to 10 kHz and currents of ±12.5 kA. Before its installation, the LCWMS was tested in the high-voltage laboratory [2]. In April 2023, a high-speed (HS) camera was set up at the substation, focusing on the WT with the LCWMS. The camera was tested in the high-voltage laboratory before its deployment [3] to verify that it was properly synchronized with the LCWMS system, as it was configured to be triggered by the measured current. Initial results associated with the measured waveforms were presented in [4]. Camera footage of lightning flashes was first shown in [5] during the correlation of current waveforms with LLS data.

The site was equipped with a current measuring system based on Rogowski coils, like the renowned Japanese studies [6–8] that monitored lightning activity across multiple WF locations, including winter lightning areas. Those investigations used standard speed cameras for optical observations. More recent work on wind turbines has employed high-speed imaging of lightning events [9–11]. On tall towers, high-speed optical observations of lightning flashes have been combined with current measurements and additional monitoring, such as local electric field sensors, magnetic field sensors, and X-ray detectors, as well as large-scale national lightning location systems [12–16].

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2. Overview of the LLS Data Available for WF

Figure 1 shows a brief topological overview of the site, including the substation containing the HS camera at an elevation of 750 m above mean sea level and the WT instrumented with Rogowski coils. The WT is located on a hill at 1265 m above sea level, with an effective height of 132 m (when one of its blades is vertically aligned with the tower). This WT is part of a group of seven WTs east of the 110/25 kV substation, along with their collection areas. There is another group of 7 WTs west of the substation. The LCWMS is installed on the WT labeled WTG4. For each WT, the collection area has a radius of 396 m (3 × 132 m), defined by IEC 61400-24. This is important for the correlation of LLS data with LCWMS measurements. The process used to determine whether a cloud-to-ground (CG) stroke that LLS detected struck the WT is as follows. The smaller circles in Figure 1, centered on each WT, represent the equivalent collection areas. If a stroke is located inside the collection area, it is considered to

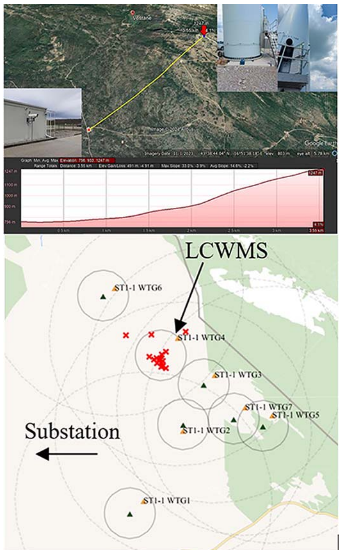

Figure 1. Site overview: substation and instrumented WTG4 with the equivalent collection areas.

hit the WT. Additionally, if multiple strokes occur within a limited time frame and are located inside the collection area, they are considered to belong to the same flash, with the flash's start time defined as the time of the first stroke. This is important because, in this study, strokes are grouped into flashes and analyzed as such rather than as individual strokes. In Figure 1, each red mark denotes a specific stroke location. Only CG flashes were considered.

Furthermore, a flash was considered positive if all its strokes were positive, negative if all were negative, and bipolar if there was at least one pair of CG strokes of different polarity. Note that this bipolar classification criterion pertains only to the LLS data. The LCWMS data provides information on the entire waveform, and a different, more comprehensive criterion was used, as detailed later in the paper.

Table 1 shows LLS data statistics for CG flashes for the full years 2022, 2023, and 2024 and for the winter period of 2025. It is worth nothing that when analyzing a specific year, the winter season includes December of the previous year, along with January and February of the considered year (e.g., for 2022, December 2021 is considered, along with January and February 2022). The total number of flashes was 45 in 2022, 53 in 2023, and 34 in 2024, with two additional flashes recorded during the 2025 winter period. In total, there were 134 flashes, of which 110 (82.1%) were negative, 17 (12.7%) were positive, and seven (5.2%) were bipolar.

Table 1. Summary of CG flash statistics from LLS data

Year	Flashes	Negative	Positive	Bipolar
2022	45	38 (84.4 %)	6 (13.3 %)	1 (2.2 %)
2023	53	45 (84.9 %)	4 (7.6 %)	4 (7.6 %)
2024	34	25 (73.5 %)	7 (20.6 %)	2 (5.9 %)
2025	2	2 (100 %)	0 (0 %)	0 (0 %)
Total	134	110 (82.1 %)	17 (12.7 %)	7 (5.2 %)

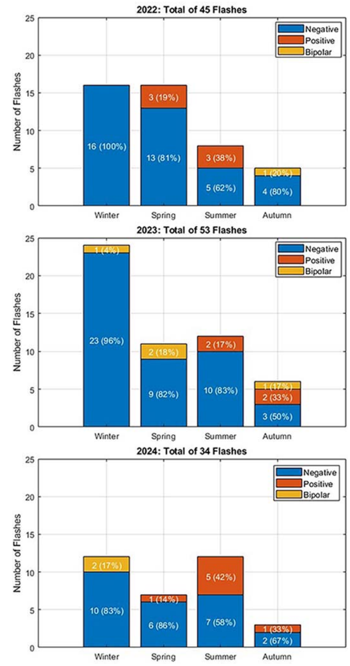

Figure 2. LLS CG flash data: seasonal analysis (2022–2024).

Figure 2 presents the seasonal analysis of several CG flashes in 2022, 2023, and 2024, breaking down flashes by season (winter, spring, summer, and autumn) and polarity (positive, negative, and bipolar). Winter 2023 was especially active compared with the other seasons of that year and was more intense than the winters in 2022 and 2024. Of note, lightning activity during winter in 2022 and 2024 is similar to or even greater than that observed in the summer of 2023. In fact, in 2023, winter lightning activity was 50% greater than summer activity. It should be noted that this analysis is based on LLS data and is therefore expressed in terms of the number of CG flash events, each of which may consist of a single stroke or multiple strokes. During the winter season of 2025 (comprising December 2024, January, and February 2025), lightning activity was observed only in January, with only two negative flashes recorded on two separate days.

3. LCWMS Data Analysis for the Period July 2022 Through February 2025

During the period of operation, from July 5 until the end of the winter season 2025 (February 28), the current measurement system measured 194 lightning flashes. During the same period, the LLS registered a total of 97 flash events. Figure 3 illustrates the breakdown of the flash events based on polarity (positive, negative, and bipolar) for LCWMS and LLS data.

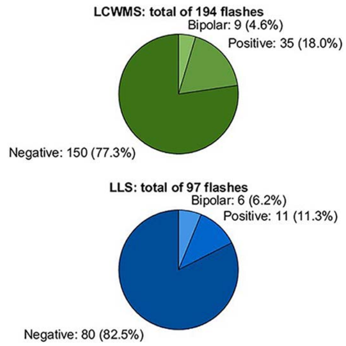

Figure 3. LCWMS and LLS data: the number of flashes and their breakdown based on polarity.

However, it must be noted that the 97 flashes detected by the LLS do not form a complete subset of the 194 flashes recorded by the LCWMS. In fact, the LLS located several flashes within the collection area that the LCWMS did not record at the WT. This discrepancy is explained as follows: In certain cases, the LLS locates a flash somewhere inside the WT collection area, but camera footage clearly shows that the flash struck the nearby ground rather than the WT itself.

The breakdown of flash polarity in the LCWMS statistics (77.3% negative, 18.0% positive, and 4.6% bipolar) is roughly like that of the LLS data (82.5% negative, 11.3% positive, and 6.2% bipolar) shown in Figure 3. When comparing the data, one must keep in mind that an entire subset of the LLS statistics is missing: upward flashes that only contain initial continuous current (ICC) or ICC with low-intensity pulse-type currents. Figure 4 compares LCWMS and LLS data for each

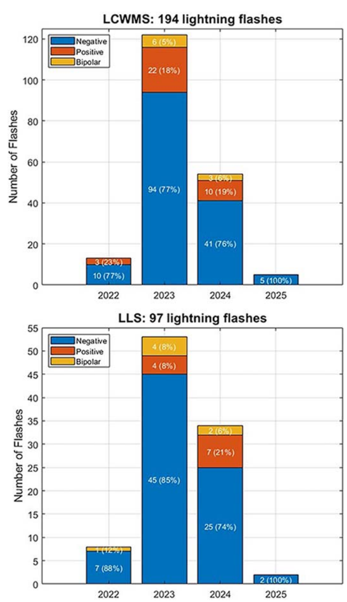

Figure 4. LCWMS and LLS data: a yearly breakdown based on polarity.

observational period (2022, 2023, 2024, and 2025) based on the polarity of flashes. Note that the 2022 observational period spans from July 5, 2022, to December 2022, while the 2025 observational period spans from December 2024 to February 20, 2025. Only the 2022 and 2023 data represent full seasonal years. In terms of flash polarity, the yearly results align with the overall trend of predominantly negative flashes, followed by positive, and finally, a small portion of bipolar.

Regarding the total number of flashes, the results show that the LCWMS flash count (194 events) is twice that of the LLS (97 events). This is not unusual, as the difference roughly corresponds to the number of upward flashes measured by the LCWMS that the LLS cannot detect: upward flashes that either only contain ICC or contain ICC with low-intensity pulse-type currents. It is also important to note that when comparing flash counts from the LCWMS and LLS, an LLS flash is considered to hit the WT if it is located within the equivalent collection area (Figure 1). However, there are several cases where a flash, although located inside the collection area, actually strikes the local soil, as confirmed by the HS camera. Thus, not all of the 97 events captured by the LLS correspond to events recorded by the LCWMS; however, such cases are very few. In summary, when looking at CG flash data from LLS, there are probably at least that many upward flashes containing only ICCs or ICCs with low-intensity pulse-type currents based on the direct current waveform measurements at the WT.

Based on the measured waveforms, approximately 96.4% of the flashes were upward, as shown in Figure 5. In almost all of these cases, there is a clear no-current period between the ICC and return strokes. Several examples exhibit an unusually short (2–3 ms) ICC with an unclear no-current period; however, camera video confirms that they are upward flashes. The authors also believe that 3.6% of the flashes are downward, based on the current waveform and/or video recordings.

Figure 5 provides a detailed categorization of the measured flashes into upward negative, upward positive, upward bipolar, downward negative, and downward positive. Among all the flashes, 73.7% were upward negative, and 18% were upward positive. Additionally, LCWMS recorded nine upward bipolar flashes, representing 4.6% of the total. The authors believe that, since its installation, the system detected seven downward flashes, all of negative polarity.

4. Discussion of Results

Based on the LCWMS waveforms collected over a 2.5-year period (July 5, 2022, to February 20, 2025) and supported by available camera footage, the authors identified 194 lightning flashes. Figure 6 shows the following two examples of measured negative flash events: ICC with superimposed pulses and ICC-only flash.

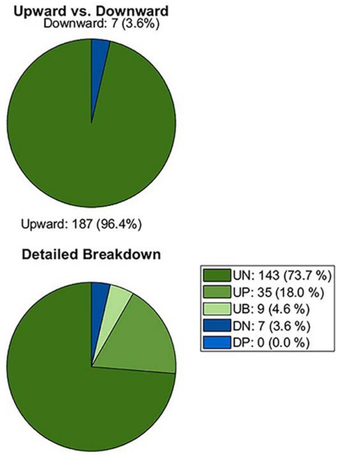

Figure. 5 LCWMS data statistics: classification of downward and upward flashes with detailed polarity breakdown (positive, negative, and bipolar).

Of these, 187 (96.4%) were classified as upward flashes and 7 (3.6%) as downward flashes. Table 2 presents the ratio of upward lightning flashes observed at the following selected sites: Santis Tower, Sentech Tower, Morro do Cachimbo Station (MCS), Gaisberg Tower, and Peissenberg Tower. These results indicate that, at the listed sites, the vast majority of lightning activity is characterized by upward flashes, with only a small proportion of downward flashes observed, which is consistent with the results of this study.

Of 194 lightning flashes that hit the WT, 150 (77.3%) were negative, 35 (18.0%) were positive, and nine (4.6%) were bipolar. Table 3 shows the polarity percentages for different well-known sites. The results from this study align with those of similar studies. However, the percentage of positive flashes (18% in this study) appears somewhat higher compared with a maximum of 11% reported in other studies. This discrepancy could be due to a nonnegligible number of very short, low-amplitude upward positive flashes containing only ICC. These flashes last only a few milliseconds and reach currents of several tens to low hundreds of amps. Although these events were assumed to be flashes, further validation is required. In one case, video confirmation was available; however, for the other events, confirmation relied solely on detecting lightning activity at the WF site or in its vicinity based on LLS data. The frequency of bipolar lightning flashes [17] is consistent with the values determined at the Santis and Peissenberg towers.

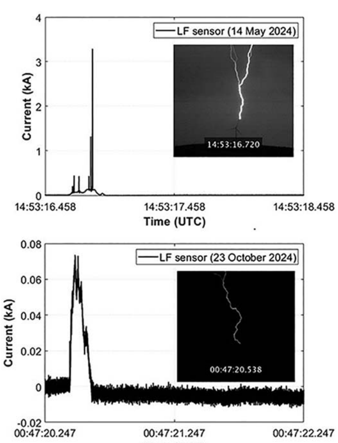

Figure 6. Examples of measured current and captured HS camera frames of associated lightning channels.

Table 2. Ratio of upward lightning flashes across different sites

Structure	Period, yr	Total	Upward
WT Croatia	2.6	194	187 (96.4 %)
Santis [12]	10	1000	950 (>95 %)
Sentech [13]	0.5	42	41 (97.6 %)
MCS [14]	6	61	9 (15 %)
Gaisberg [15]	19	827	823 (99.5 %)
Peissenberg [16]	2.1	61	60 (98.4 %)

5. Future Work

In future work, we plan to further validate the dataset, particularly the ICC-only and downward flashes. For ICC-only flashes, several very short-duration and low-amplitude events (lasting a few milliseconds and reaching only a few tens of amperes) require additional verification to confirm that they are indeed flashes. The only indication that these events are flashes is their occurrence during obvious lightning activity in the area. In one such case, the camera footage shows that this is an unconnected leader. For downward flashes, it is necessary to verify whether they were truly downward or if the LF sensor failed to properly detect the ICC current, as they appear to have little or only a very brief period of current.

Additionally, we aim to determine lightning current parameters such as duration, amplitude, and the charge contained in specific lightning components (ICC, pulse-type currents) once proper system calibration has been completed. Furthermore, the current measurements will be consistently paired with optical space-based lighting detection [19] and ground-based LLS data. For this purpose, the first-ever satellite instrument that continuously detects lightning over Europe,

Table 3. Polarity percentages of lightning flashes observed for different sites

Structure	Flashes	Negative	Positive	Bipolar
WT Croatia	194	77.3 %	18.0 %	4.6 %
Santis [12]	849	84 %	11 %	5 %
Sentech [13]	42	100 %	0	0
MCS [14]	61	100 %	0	0
Gaisberg [15]	827	79.2 %	4.2 %	16.6 %
Peissenberg [16]	61	85.2 %	9.8 %	4.9 %
Nikaho [18]	213	74 %	11 %	15 %

the Meteosat Third Generation Lightning Imager [20], will be used.

Finally, we plan to further equip the WF site with additional cameras and sensors, similar to the work in [12, 17], to enable more comprehensive monitoring of lightning activity across the WF [21].

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