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Device for Lightning-current Measurement with Remote Access

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***Abstract* — This paper presents the fundamental aspects of a device developed for recording current waveforms of lightning flashes striking nearby grounded structures. Its principle of operation is based on measuring the voltage induced by the close magnetic field yielded by lightning currents flowing along high structures. A Digital Signal Processor (DSP) supports data acquisition. Accurate parameters, such as peak and time parameters of return stroke currents, can be promptly determined from the records. The low-cost device includes means for remote internet access, self-test and data transfer. Laboratory tests demonstrated the good performance of the device, before three prototypes were installed 15 m away from the instrumented tower of Morro do Cachimbo Station (MCS). They recorded the current waveform of a single return stroke of a recent strike to the tower, which was compared to that recorded by the accurate measuring system of MCS.**

Keywords — measuring system; lightning discharge; impulsive current

I. Introduction

Acquisition of lightning-current waveforms is important for providing parameters required for lightning-protection design and for estimating effects resulting from lightning events. Currently, measured and estimated lightning parameters are obtained by means of instrumented towers, triggered lightning and Lightning Location Systems (LLS). Due to the high cost associated to building and maintaining such systems, there are a few research stations in the world able to obtain accurate current waveforms from natural lightning flashes.

This paper presents and discusses a low-cost device designed at Lightning Research Center (LRC), Brazil, to provide accurate parameters of lightning currents, by recording their waveform. Peak value and time parameters can be determined promptly from the records. Such device consists of a largely improved version of a prototype developed at LRC a few years ago [Silvino et al., 2003; Mesquita et al., 2014]. A potential application of the device is the calibration of LLS by providing reliable ground-truth references to assess the quality of the correlated results provided by LLS [Mesquita et al., 2014].

II. Basic Considerations

The device's principle of operation is based on the detection of the close magnetic field produced by return stroke currents flowing along high grounded structures struck by lightning. Figure 1 shows the developed device installed nearby an elevated structure.

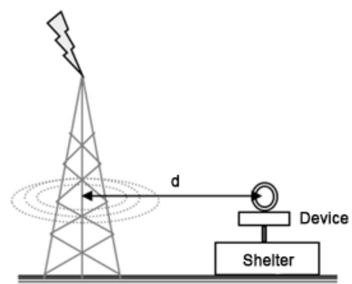

Fig. 1. Device installed nearby an elevated structure. Adapted from [Mesquita et al., 2014].

The time-varying magnetic field produced by the lightning discharge illuminates the internal area of a loop antenna, which is the device's transducer, and, according to Maxwell equations, induces a voltage $emf(t)$ between its terminals:

$$emf(t) = -\frac{A_e \mu_o}{2\pi d} \times \frac{di(t)}{dt} \qquad (1)$$

In (1), $i(t)$ is the instantaneous value of the current flowing along the structure, d is the distance between such structure and the center of the loop antenna, A_e is the loop antenna internal area and μ_o is the air permeability. Equation (1) comes directly from the application of the Ampère's Law. The lightning instantaneous current value is recovered from the integration of the induced voltage $emf(t)$.

The signal conditioning system was developed in two stages. The first one refers to the construction of the loop antenna to obtain signals of induced voltage. The second one refers to the project and assemble of an analog integrator able to process the induced voltage in order to recover the current waveform of the lightning discharge. The following topics make a brief comment on each of the steps.

A. Induced voltage on loop antenna terminals

The very first consideration on the main features of the device concerns how the signal of the voltage induced by the first-return-stroke current is obtained. The device's transducer, a loop antenna, is positioned completely aligned to the tower so that the close magnetic field crosses its internal area and performs the maximum influence upon the system, inducing a voltage signal between the loop terminals.

B. Signal Conditioning

The next steps are analogically integrating, filtering (removing high frequency components, over 1.5 MHz) and adding up an offset level. In addition, a protection circuit was also projected to prevent damage to sensitive components. These steps compose the signal conditioning procedure.

III. Features of the Device

The current version of the measuring device is equipped with microcontrollers and peripherals. The acquisition system was configured to digitize data in the maximum conversion rate of the analog-to-digital converter (ADC). In addition, such device has a signal conditioning board and a management software operated by internet. Figure 2 presents the block diagram of the developed device.

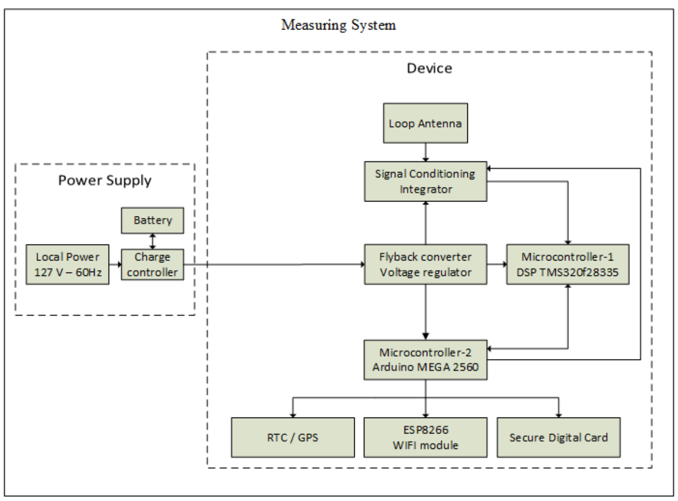

Fig. 2. Block diagram of the developed device.

As shown in the block diagram, the device was designed to operate directly from an AC 127 V voltage source or from a battery, which is able to keep the system working for approximately 100 hours.

The induced voltage measured by means of a loop antenna is integrated in order to obtain the actual current waveform. Then, the data processed by the signal conditioning board feed the ADC of microcontroller 1 (DSP TMS320f28335), which was configured as a circular buffer that samples the conditioned signal at a rate of 12.5 MS/s. The digitized signal is cyclically stored in the random access memory (RAM) of the DSP and compared to a predefined threshold voltage (corresponding to a current level). It is worth mentioning that there are both upper and lower trigger values so that the device can record positive and negative lightning discharges waveforms. When the signal crosses the thresholds, the circuit is triggered to record the current waveform and, therefore, the recorded data are transferred from the RAM of the DSP to microcontroller 2 (Arduino MEGA 2560). This procedure allows the access to data prior to the trigger signal, so that significant information of the early phase of the lightning current is recovered; from the $1200\ \mu s$ recording window, $120\ \mu s$ are related to data prior to the trigger signal and $1080\ \mu s$ comprises the data after the trigger signal.

The device has a GPS receiver, which provides accurate information about date and time. By the time of an event, such information is extracted and sent to microcontroller 2. The Arduino transfers the data that were recorded by the DSP and are stored within its RAM to the secure card.

The ESP8266 is the hardware that allows wireless connection between the device and a router connected to the internet.

IV. Calibration and Installation

As discussed in section II, the lightning current is obtained from the integration of the induced voltage $emf(t)$. This procedure is performed by the analog integrator and it yields a gain to the output signal. Once this signal is directly connected to the DSP's analog-to-digital converter, it cannot exceed $3\ V$ and neither be negative. On the other hand, the device must be able to record peak values of $\pm 100\ kA$ for $d = 15\ m$. Considering these impositions, and assuming that d is an important parameter for obtaining the current module, it is interesting to create an equation that relates the integrated signal, named $V_{out}(t)$, to the current $i(t)$, given the distance between the device and the structure that may be struck by a lightning discharge. Equation (2) describes the current $i(t)$ in kA as a function of the distance d in meters.

$$i(t) = 4.445 \times d \times V_{out}(t) \qquad (2)$$

After the laboratory calibration of the three devices, they were installed at MCS to validate their measurements by comparing them with results obtained for strikes to the station by the measuring system installed at the instrumented tower.

Table 1 summarizes the scales and trigger levels of three devices as a function of their distance to the tower.

TABLE I. Properties of all Three Devices Installed on the Main Shelter Roof

Device	Distance (to the tower)	Maximum Current Scale	Trigger
1	15 m	-100 kA to +100 kA	33 kA
2	15 m	-100 kA to +100 kA	16 kA
3	20 m	-133 kA to +133 kA	25 kA

V. Remote Access

The remote control by internet is an important feature looking after the device's operationalization, as they can be installed in remote sites with difficult accessing. The communication system allows the transmission of acquired data and self-tests can be remotely commanded. Such functionalities prevent the need of constant displacements of the maintenance team to the site where the device is installed. This denotes the relevancy of implementation of the remote access.

Figure 3 shows the web page developed with Personal Home Page (PHP) language, which allows communication between any computer or smartphone connected to the internet and the ESP8266 module.

Fig. 3. The management software of the devices.

The web page contains information about the device that is intended to be controlled, such as its MAC address and IP. This page also allows updating the database, self-test, data download and record removal from the server and secure digital card (local memory of the device). When the self-test command is sent to the ESP8266, a voltage pulse is applied to the signal conditioning board and the device starts the process of recording one event that corresponds to this test. When the recording is finished, data are downloaded and it is verified whether the device is operating normally or requires maintenance.

VI. EXPERIMENTAL RESULTS

A. Laboratory tests

Several tests have been performed in the laboratory to assess the consistency of the proposed device in terms of software and hardware when it is subjected to impulsive currents.

Figure 4 shows the measurement system using a loop antenna positioned 30 cm away from the white wire where the impulsive current provided by the high voltage generator flows.

Although the high voltage generator did not provide peaks of currents close to those of natural lightning current, the device was positioned near the wire so that electromagnetic field levels were expected to be similar to the ones obtained in field measurements.

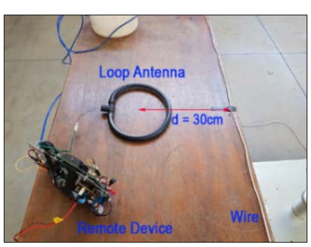

Fig. 4. Measurement system using a loop antenna positioned 30 cm far from the white wire.

The high voltage generator was set to operate with a peak current of approximately 210 A and front time of 5 µs. Figure 5 shows the comparison between the current waveform recorded by the developed device and the reference current provided by the generator.

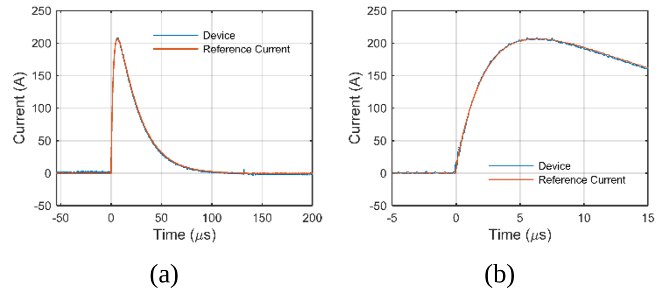

Fig. 5. Comparison between the current waveform recorded by the developed device and the reference current provided by generator. (a) Full event. (b) Comprising the interval between -5 µs to 15 µs.

Besides the great result from the waveforms matching, which shows the quality of the device's measurement system with low noise level, it is important to highlight that the trigger system and the download of the data through the webpage were performed and worked fine, playing properly their role.

Figure 5 (b) comprises the time interval between -5 µs to 15 µs of the full event presented in figure 5 (a). From both figures, it is possible to notice that the current waveforms followed the same trend.

B. Measurements at MCS

Since the devices were installed at MCS, only a single lightning current was recorded in February 2018. Figure 6 compares the current measured by the developed device with that measured by the reference system.

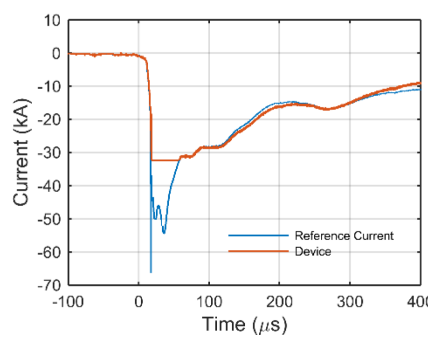

Fig. 6. Comparison between the current measured by the developed device and the records obtained from the accurate measurement system.

The current waveform recorded by the device is quite similar to the one provided by the accurate measuring system, except for the interval between 17 µs to 57 µs. The current signal was clamped by the device's protection system at approximately -32 kA.

After the reported event, adjustments were taken in order to recalibrate the gain of the devices to ensure the full scale up to $\pm 100\ kA$.

Figure 7 shows the same current event on a larger time scale, which comprises the time interval from -200 µs to 1000 µs.

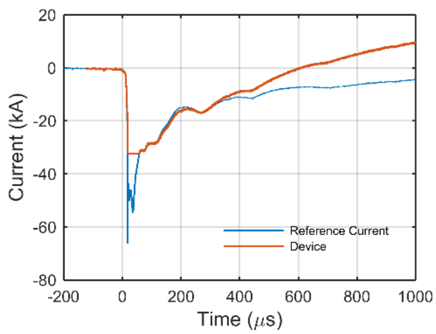

Fig. 7. Full event: Comparison between the current measured by the developed device and the records obtained from the accurate measurement system.

Note that there is a considerable difference between the curves in the wave tail after 400 µs. It was identified that this was due to the fact that the frequency response of the device had not a constant gain; low-frequency components had a greater gain than that of high-frequency components. This was not noticed in laboratory tests stage because in such experiments the current duration to half peak was shorter than 50 µs. The recorded event corresponds to a very slow current, since the current duration to half peak value was approximately 90 µs, whose value is greater than the median value (53.49 µs) of the MCS.

After the event measured in February 2018, the integrator circuit was adjusted to ensure a frequency response with a constant gain along the whole range of interest.

It is worth mentioning that it was the first natural lightning current measured by the developed device. At the initial stage, performing adjustments and improvements are naturally expected.

On the other hand, it is important to point out that the device was practically immune to electromagnetic interferences, as the recovered current waveform exhibits very low noise level. In addition, the communication and the transferring data systems have been working well since then.

VII. Conclusions

This paper presented a brief description of an electronic device developed at LRC designed to measure lightning currents based on the detection of close magnetic field yielded by lightning current flowing along a monitored elevated structure.

A low-cost device was developed and presented great results while it was under laboratory tests. The first measurement at MCS exhibit high quality, although the current was clamped due to system protection. Two problems were detected on the recording; the first one refers to the system's gain and the second one concerns the frequency response of the device. It is worth mentioning that both problems were solved and these improvements are present in the current version of the devices installed at MCS.

Electromagnetic interferences did not cause significant disturbances in the measured current signal by the devices installed at MCS. In addition, the communication and data transferring systems worked properly after the lightning struck the instrumented tower.

The authors expect that, on the next thunderstorm period, new return strokes currents will be measured in order to validate the recent improvements on the device circuits.

Acknowledgment

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