A Novel Self-Powered Lightning Current Measurement System

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Abstract—To address the lack of reliable power supplies for lightning current measurement systems (LCMS), this paper proposes a novel self-powered LCMS. The required operation power of a LCMS can be provided by harvesting the surge current that is measured using a power coil such that the system can be energized to complete a single-cycle measurement and data recording. In this manner, the stand-alone LCMS is triggered by lightning currents, and, hence, the signal acquisition can be activated automatically. In particular, this paper designs a two-channel passive peak-holding circuit as a low-power substitution to the conventional high-speed sampling modules. The polarity, current peak, and trigger time can be measured and ultimately be stored in a nonvolatile memory. The theoretical and simulation studies are presented in detail to determine the structure, size, and number of winding turns of the power and signal coils. The circuitry design of the power supply and signal conditioning units are also addressed. Experimental results verify that the proposed LCMS can accurately measure the amplitudes of lightning currents, achieving an accuracy of a maximum error of 4%, while the LCMS is fully self-powered to satisfy the energy demand from the measurement and data acquisition tasks.

Index Terms—Lightning current measurement, measurement system, power supply, self-powered.

I. INTRODUCTION

TRANSMISSION-LINE faults represent a substantial proportion of power grid failures, among which the faults on high-voltage overhead lines are mainly caused by lightning accidents [1]. In the case of lightning strokes, when large surge currents are directly channeled through, or flowing via the vicinity of electricity facilities (e.g., transmission towers), the formulated overvoltages, as a top exogenous threat, can gravelly jeopardize the grid security. Therefore, overvoltage severity evaluation should be done first in lightning protection. The most common approach at present is to simulate the direct lightning overvoltage using an electromagnetic transient program [2]. The essence of lightning event is then translated into surge currents that are mathematically modeled (e.g., double-exponential function [3], Heidler function [4]). Lightning currents act as simulation excitation sources and the overvoltage can be computed under certain system topology as well as its surge impedance characteristics. As for lightning-induced voltages, the generated electromagnetic fields are computed first using certain numerical methods, such as finite difference in time domain. Thereafter, the coupled surges in overhead lines can be computed using induction models like Telegrapher’s traveling wave equations [5]. In this regard, for any certain systems with given structures, the characteristics of the stroke itself determine the resulted surges on power systems. However, such analytical currents cannot fully characterize the natural flashes, which lead to differences between the simulated surge voltages and that of natural lightning. Thus, it is of primary importance in the lightning protection calculation to have accurate knowledge of the lightning current features (polarity, magnitude, duration, etc.). Understanding characteristics of lightning current is also beneficial for developing protective measures for other components and systems (e.g., wind turbines, buildings, rail, and telecom facilities) against direct and induced effects of lightning.

Natural lightning is stochastic in its intensity, duration, and the appearance of surge current, and also irregular in its choice of a time and place to strike. Therefore, the original raw parameters acquired from natural lightning currents worldwide are insufficient to support the purposes of comprehensive research on lightning. To date, a variety of methods have been proposed for detecting and measuring lightning currents, including surge-crest ammeter links [6], [7], lightning detection networks (LDNs) [8], [9], magnetic tape lightning current detectors [10], [11], cathode-ray oscillography [12], and lightning current measurement systems (LCMS) using Rogowski coils [13], [14]. Concerning surge-crest ammeter links, due to the differences in steel rod materials and the variations of production technologies, it is quite difficult to obtain uniform relationship between the remanence of the rod and the current crest, which leads to a significant measurement error. Besides, the links can only record a single instant, which is quite inconvenient. Regarding LDNs, since the detection antennas may be far from actual lightning striking points, the propagation of lightning electromagnetic waves can be affected by terrain and structures, causing
varying degrees of attenuation and dispersion. Consequently, LDNs measurements can contain large errors in estimated magnitudes of lightning currents and positioning results. As for magnetic tape detectors, only surge crests can be recorded and the measurement is nonrepetitive. For the cathode-ray oscillography, the setup is quite costly, which limits its application scope. By contrast, the direct measurement of lightning current with a Rogowski coil has a good feature that the full waveform can be acquired. Unfortunately, the system is usually complicated, and the system must be able to perform on a demanding level to sample the fast transient current signals [15]. For instance, pre-triggering and high-speed sampling modules are indispensable within the system to capture high-frequency lightning currents. The modules are energy consuming, which necessitate high quality and large power supply in a conventional LCMS.

Paradoxically, LCMS are normally deployed close to lightning paths, like transmission towers, lightning rods, and lightning arresters [16], [17]. In this case, conventional power supplies become inapplicable, because any ready-made low-voltage power sources are difficult to be found in remote locations for the LCMS on transmission towers. Even for those mounted on lighting rods of facilities or lightning arresters in substations, the LCMS cannot be connected with any on-grid power sources, so as to prevent the grid from lightning surge intrusion via the connection. Hence, the lack of usable and reliable power supplies has become one of the constraint factors to deploy LCMS [18]. Until now, several major off-grid power solutions have been proposed for general-purpose monitoring devices in power systems, such as solar panels [19], [20], optoelectric power transmission [21], [22], and current-transformer-based draw-out power supplies [23], [24]. These technologies are good candidates to energize LCMS; however, drawbacks still remain in reliability and power capacity. The low efficiency of photovoltaic conversion, sensitivity to weather conditions, and the aging of batteries are problems in the power supplies provided by solar panels [25]. Regarding optoelectric power transmission, low-voltage power sources are still needed to generate the laser for energy transmission, which constrains the application scope. Moreover, the laser device is expensive, and its transmission power is strictly restricted because lifetimes of optoelectronic component tend to decrease as their power dissipation is increased [26]. Besides, most draw-out power supplies are designed to be clamped on overhead lines, which can be utilized only for LCMS mounted on transmission towers with energized lines [27]. Therefore, the fundamental challenges associated with power supplies of LCMS remain to be solved.

To this end, this paper proposes a novel self-powered LCMS. Motivated by the nature of the transient characteristic and high amplitudes of lightning currents, the self-powered LCMS can be completely powered by harvesting energy from the lightning current being measured. In the following, Section II details the designs of the power coil, signal coil, and the subsequent modules, including the energy management circuit, signal conditioning circuit, as well as the data acquisition unit and also presents the simulation studies on the power supply and signal conditioning units. Section III discusses the prototype and experimental verification; and Section IV concludes this paper.

**II. DESIGN PRINCIPLES OF THE SELF-POWERED LCMS**

**A. System Overview**

The proposed self-powered LCMS scavenges power by converting the magnetic energy excited by the lightning current via an electromagnetic induction. The system consists of the power supply, signal conditioning, and data acquisition units. As is self-powered and energy limited, the corresponding signal measurement units have been tailored to meet the low-power requirements. The system schematic diagram is illustrated in Fig. 1.

Both the signal coil and power coil encircle the same grounding lead that channels lightning currents. The signal conditioning unit converts lightning currents into proportional voltage signals and holds the voltage crest. Meanwhile, the power supply unit converts the transient energy into a stable dc voltage source. The signal and power are then fed into a microcontroller unit (MCU) to accomplish data acquisition and logging.

The system functions are outlined in Fig. 2. Four curves are shown in the figure: the lightning current, proportional voltage signal, held voltage (current peak information), and the converted dc power. First, the lightning current is captured by the signal coil and is converted into a proportional voltage signal using an integral resistor, as shown in Fig. 1. The voltage front charges the peak-holding capacitor; and the held voltage peak then declines very slowly within a sufficient period of time. This makes it possible for the subsequent data acquisition unit to sample the voltage in a low-speed manner. For the peak-holding circuit with a given decay factor, the initial voltage peak can be determined by several back calculations from multiple sampling points (see $S_1$, $S_2$, and $S_3$ in Fig. 2) and then averaging the calculation results. Meanwhile, the induced voltage from the power coil is rectified and regulated into a 3.3-V dc to provide a power supply for the MCU to accomplish the above tasks.
It should be noted that an energy-storage capacitor is utilized in the system rather than a rechargeable battery. This is because maintenance free of the LCMS is expected, and the transient and intermittent nature of lightning energy tends to reduce the battery lifetime. They are considered unreliable as a long-term energy storage.

Due to these facts, while the power supply unit is loaded, the obtained dc voltage is varying. To complete a single-cycle transient measurement and data logging tasks using the quite limited energy, it is critical to well coordinate active periods of different modules in the system. In Fig. 2, \( t_{\text{power-on}} \) denotes the time delay before the dc/dc converter is powered up; \( t_{\text{on}} \) denotes the output duration of the 3.3-V dc from the power supply unit; \( t_{\text{charge}} \) denotes the time to charge the peak-holding capacitor to the voltage peak \( V_p \); and \( t_{\text{hold}} \) denotes the voltage holding period, which is defined as the corresponding duration from \( V_p \) to 0.9\( V_p \). As indicated in Fig. 2, \( t_{\text{on}} \) should cover the four sequential tasks of the MCU, while \( t_{\text{hold}} \) must last until the voltage sampling is accomplished. The above single-cycle process can be triggered automatically and repeatedly by multiple lightning currents flowing through the channel. Due to nonvolatile protection against power losses, the recorded data can be read and transferred afterward onsite at any time necessary by connecting the communication module with a host computer.

### B. Power Supply Unit

This paper focuses on the proper configuration of the power coil and sizing of components in the power-management circuit, which aims to generate a voltage with a well-defined range and a sufficient power capacity to keep the loaded units operational within their specifications. As the data acquisition unit consumes small current, the power coil is nearly no load. Consequently, the iron coil will saturate even when the primary current is only several amperes, which is much lower than the lightning current to be measured. Saturation of iron core may increase core loss, and, thus, decreases the energy conversion efficiency. Therefore, the power coil is specially designed to have an air gap, as illustrated in Fig. 3. The introduction of air gap increases the equivalent reluctance of magnetic path, and, hence, the coil can work in its linear (unsaturated) zone according to its \( B-H \) characteristics.

The basic parameters \( L_0 \) (self-inductance), \( M \) (mutual inductance), and \( R_0 \) (resistance of the power coil) can be calculated as

\[
L_0 = \frac{\mu_0 \mu_e N^2 h}{2\pi} \ln \frac{b}{a} \quad (1)
\]

\[
M = \frac{\mu_0 \mu_e Nh}{2\pi} \ln \frac{b}{a} \quad (2)
\]

\[
R_0 = \frac{8\rho(h+b-a)N}{\pi d^2} \quad (3)
\]

where \( N \) denotes the number of winding turns; \( a \) and \( b \) are the inner and outer radiuses of the coil; \( h \) is the thickness of the coil; \( \rho \) is the resistivity of copper wire; and \( d \) is the diameter of the copper wire. The magnetic path consists of two parts: the air gap and iron core; hence, \( \mu_e \) in (1)–(3) should be regarded as the equivalent relative permeability, which can be determined by [23]:

\[
\mu_e = \frac{1}{l_g/l_m + 1/\mu} \quad (4)
\]

where \( l_m \) and \( l_g \) are the lengths of the magnetic path and the air gap; and \( \mu \) denotes the relative permeability of the core material. The system is practically considered to be installed on grounding leads of lightning rods. Typically, the cross section of band iron is sized as 40 mm \( \times \) 5 mm and the length of the two edges in the cross section of an angle steel for grounding is 80 mm. In this case, the inner diameter of the coil should be no less than 80\( \sqrt{2} \) mm, and the spatial margin as well as thickness of system enclosure is further considered. Accordingly, the coil’s inner, outer diameters, and the thickness were determined as 0.2, 0.26, and 0.03 m, respectively. The length of air gap \( l_g \) was set as 0.02 m. The average length of magnetic path along the core \( l_m \) can be calculated as 0.7 m. The iron core is made of silicon steel, the relative permeability of which is 8000. Therefore, \( \mu_e \) can be calculated to be 35 using (4).

Because the secondary induced voltage features high equivalent frequency under lightning current injection, the transfer function of the power coil can be approximately written as

\[
H(s) = I'(s)/I(s) = M/L_0 = 1/N \quad (5)
\]

where \( I(s) \) and \( I'(s) \) are the primary and secondary currents.

The subsequent power management circuitry connected to the coil is illustrated in Fig. 4. A MAX5035 step-down dc–dc converter was selected to regulate the converted voltage into a 3.3-V dc for the MCU. Two bidirectional transient voltage suppressors (TVS) of type 5KP78CA (reverse stand-off voltage of 78 V) were employed for overvoltage protection, which aim to restrict the output of the power coil in the valid input range (up to 80 V) of MAX5035.

Another same TVS was added between the capacitor and dc/dc converter, acting as a second overvoltage protection for the converter to prevent the circuit from lighting surge damages. SF54 superfast rectifiers were used in the full-wave
recertification bridge, which was designed to channel both positive and negative lightning currents.

To parameterize the lightning current for calculation, this paper uses the triangular wave of 8/20 $\mu$s. When charging the capacitor, the charge released via the dc/dc convertor is negligible because the whole duration of the lightning current is generally quite short (hundreds of microseconds), and, meanwhile, the converter is still inactive (power-on time delay of 2 ms). Based on the charge conservation and (5), the charge transfer can be calculated as

$$\int_{0}^{T} \frac{i_1}{N} dt = I_{\text{max}} T / (2N) = C u_{\text{max}} \tag{6}$$

where $i_1$ is the lightning current; $T$ is the period of lightning current, which is 32 $\mu$s deduced from the wave shape; $I_{\text{max}}$ refers to the current peak, which is set to 10 kA; and $u_{\text{max}}$ is the maximum voltage the capacitor can be charged. After substituting the above values in (6), $u_{\text{max}}$ can be obtained as

$$u_{\text{max}} = 0.16 / (C N). \tag{7}$$

The energy balance between the capacitor and the afterward unit can be written as

$$(C u_{\text{max}}^2 / 2 - C u_0^2 / 2) \eta = pt \tag{8}$$

where $u_0$ denotes the minimum voltage of the capacitor while energizing MAX5035. The conversion efficiency of MAX5035 can be as high as 94%, and to maintain sufficient energy margin, $\eta$ was substituted as 90% in the calculation. The average power consumption $p$ of MCU (C8051F912) in the data acquisition unit was calculated to be 0.05 W, which incorporates CPU processing, ADC, and data storage activities. The throughout operating duration $t$ was set as 0.5 s, which is approximately the actual period to run the program loaded in the MCU to accomplish the data acquisition process. Under constraints (7) and (8), the $C$ value and the number of turns $N$ have been determined as 68 $\mu$F and 50, respectively. Therefore, $u_{\text{max}}$ and $u_0$ can be calculated as 47 and 37 V. Note that although the component sizing was based on the minimum injected lightning current of 10 kA, while the actual current may exceed 10 kA, the circuit with the designed components can still work properly. This is because once the capacitor voltage surpasses the stand-off voltage of TVS under lower primary current, the voltage will be clamped by the first TVS, and, hence, the circuit afterward is protected. The fabricated power coil and power management circuit are illustrated in Fig. 5.

**Fig. 5.** Photograph of the power supply unit: (a) Power coil and (b) the power management circuit.

**Fig. 6.** Two-channel peak-holding circuit.

### C. Signal Conditioning Unit

The signal conditioning unit consists of a signal coil and a two-channel passive peak-holding circuit. Because lightning currents are normally the impulses with microseconds in front rise and pulse widths, and the arrival time is uncertain, a data acquisition module with pretrigging and high-speed sampling capabilities is conventionally needed to acquire the full waveform. However, this topology is inapplicable for the proposed self-powered LCMS, because there is a large gap between the harvested energy and the high-power consumption of the hardware like a high-speed ADC. In this case, a low-power alternative for high-speed sampling is designed, which also simplifies the entire system and makes it low cost.

Another advantage of the proposed topology consists in the cancellation of impulse electromagnetic interference from the lightning stroke, which is extremely hazardous for electronic circuits. For the previous work, the authors have done on natural trigging lightning experiments, the malfunction of data acquisition was encountered several times at the moment of lightning event occurrence. The malfunction was mainly attributed to the harsh transient interference from the lighting. The proposed new circuit solves this problem since the MCU activation and data sampling significantly lag behind the lightning stroke, when the transient interference almost completely attenuates.

The two-channel passive peak-holding circuit is given in Fig. 6. First, the integration resistor $R$ establishes the voltage signal from the lightning current acquired by the signal coil. Thereafter, regarding the positive lightning current, the diode $D_1$ conducts and $D_2$ switches OFF; then, $D_1$ switches OFF after $C_1$ is charged to the voltage peak. Next, $C_1$ discharges via $R_1$ and $R_3$, the duration of which relates to $RC$, where $R$ is the sum of $R_3$ and $R_5$. The scaled-down voltage signal as divided by $R_1$ and $R_3$ that satisfies the valid input range is then fed into the data acquisition unit. Likewise, the negative loop which consists of $D_2$, $C_2$, $R_2$, and $R_4$ works in a similar way for the negative lightning current.

For the front-end signal coil, it should provide good spectral performance, and, meanwhile, with minimal distortion of the original lightning current signals. A self-integral Rogowski coil was employed to establish voltage signals from the surge currents.

To facilitate the layout and fabrication of the device, the geometrical structure of the signal coil was kept the same as the power coil (see Fig. 3). Different from the conventional air-core
structure, a Rogowski coil with iron core was designed in this study and the simulation has been carried out here to demonstrate the differences.

Fig. 7 shows the simulated waveforms of the output voltages from the signal coil and the peak-holding capacitor, in both cases of using iron core and air core.

Under the same geometry structure, it is observed that at the wave tail, the voltage signal from the air-core coil drops more dramatically and cannot follow the current waveform, which is attributed to the different low cut-off frequencies. Iron core increases self-inductance \( L_c \); hence, the duty cycle \( f_d \) is decreased as \( f_d = (R + R_c)/(2\pi L_c) \), where \( R \) denotes the resistance of the integral resistor and \( R_c \) denotes inner resistance of the signal coil; and \( L_c \) and \( C_c \) denote the self-inductance and parasitic capacitance of the coil.

Better low-frequency response makes the converted voltage signal more closely follow the wave tail of the lightning current, and it provides a higher signal peak. On the other hand, the deviation between the held voltage peaks and the signal peaks can be regarded as the known front voltage drop of the diode and the capacitor charging error, which is associated with the signal peak, coil resistance, and peak-holding capacitance. The latter error is uncertain and variable, thus it is difficult to be calibrated. A flatter wave tail can prolong the capacitor charging, resulting in a higher signal peak, which can reduce this uncertain deviation. Besides, an air gap was also introduced in the iron core of the signal coil to prevent saturation. Therefore, in the present application, the developed signal coil with iron core is more adaptive for the circuit to capture and hold the signal peak more accurately.

Under a zero initial condition, the transfer function of the signal coil can be obtained as

\[
H(s) = \frac{U_2(s)}{I_1(s)} = \frac{MR_s}{RL_cCs^2 + (L_c + RR_c)Cs + (R + R_c)}
\]  

where \( M, L_c, C, \) and \( R_C \) denote the mutual inductance, self-inductance, parasitic capacitance, and internal resistance of the signal coil, respectively; and \( R \) refers to the integrating resistor.

In the self-integral pattern, the coil parameters should satisfy the following condition:

\[
\omega L_c \gg R + R_c. \tag{10}
\]

Note that as the positive and negative peak-holding loops are mutually symmetric in their topology, \( C_1 \) and \( C_2 \) should share the same constrains and have the same value. For conciseness, \( C_1 \) and \( C_2 \) are simply denoted by their capacitance \( C \) in the following, unless otherwise stated. To maintain the linear relationship between the converted voltage signal and the primary current, the capacitance \( C \) should fulfill the condition

\[
R \ll 1/(\omega C). \tag{11}
\]

The analog input range of the adopted MCU is 0–3.3 V; therefore, the peak voltage should satisfy the following constraint:

\[
R_{t_{\text{max}}} / N \leq 3.3n \tag{12}
\]

where \( n \) is the divider ratio, i.e., \((R_1 + R_3)/R_1 \) or \((R_2 + R_4)/R_2 \), as shown in Fig. 6. To guarantee that the capacitor \( C_1 \) and \( C_2 \) can be charged to the voltage peak, the time constant of charging \( \tau_1 \) in each peak-holding loop should be significantly shorter than the current rise time. Hence, \( \tau_1 \) should satisfy the following condition:

\[
\tau_1 = RR_cC/(R + R_c) \ll 8 \mu s. \tag{13}
\]

The held voltages during sampling needs to be kept large enough to reduce relative sampling errors. As stated in Section II-A, \( t_{\text{hold}} \) is defined as the duration in which the output voltage changes from \( V_p \) to \( 0.9V_p \). Thus, \( t_{\text{hold}} \) satisfies the following equation:

\[
\exp(-t_{\text{hold}}/\tau_2) = 0.9. \tag{14}
\]

Substituting the decay constant \( \tau_2 \) in (14) with the capacitance and resistance in each loop, \( t_{\text{hold}} \) can be calculated as

\[
t_{\text{hold}} = 0.1(R_1 + R_3)C_1, t_{\text{hold}} = 0.1(R_2 + R_4)C_2. \tag{15}
\]

The designed \( t_{\text{hold}} \) should cover the period for the MCU to complete a whole cycle of voltage acquisition (\( S_1 \) to \( S_3 \) in Fig. 2). To determine the amplitude of lightning currents, first, apply back calculations as \( U_p(n) = u_n \exp(t_n/\tau_2) \), where \( u_n \) and \( t_n \) represent the time and the voltage of the sampling point \( S_n \). Thereafter, average the set of \( U_p \) to obtain the initial held voltage peak \( V_p \), as \( V_p = \frac{U_p}{S_3} \). Finally, the amplitude of the lightning current can be obtained using the transfer relation of the self-integral Rogowski coil, as \( I_m = V_p N / R \).

According to (9)–(15), \( C_1 \) and \( C_2 \) were chosen to be 0.47 \( \mu F \), and \( R \) was set as 0.04 \( \Omega \). The number of winding turns of the signal coil was determined to be 200. For the chosen configuration, the self-inductance \( (L_C) \) and internal resistance \( (R_c) \) of the coil are calculated as 2.2 \( mH \) and 0.53 \( \Omega \) using (1) and (3), respectively.

The frequency response of the signal coil was then obtained, as shown in the Bode diagram in Fig. 8. Referenced to the cumulative spectrum of lightning current amplitudes, the cumulated amplitudes can reach over 97% till 1 MHz [28], which means lightning currents have a frequency spectrum with an upper frequency bound less than 1 MHz under typical wave shape of lightning currents. Therefore, the designed signal coil provides good frequency performance and meets the requirements of data acquisition since the frequency band of the coil well matches the concentration of lightning current amplitudes.
On the other hand, the value of $\tau_1$ is calculated as 0.018 $\mu$s, which is proven to be much shorter than the rising time of 8 $\mu$s. As programmed in the MCU, the last sampling point $S_3$ occurs at 14 ms after the dc power is on. Since $t_{\text{hold}}$ is calculated as 705 ms, it fully covers the above voltage sampling period.

To study different cases, we have exactly converted the design of the signal coil into a simulation model using a finite-element software. The model comprises the physical part of the signal coil in which the electromagnetic induction occurs, and the connected peak-holding circuit. The two parts are coupled by the transient analysis module in the software. For the simulation studies, six lightning currents with different wave-front and wave-tail times are loaded on the central current lead. Meanwhile, the waveforms of the surge current and the held crests are analyzed to figure out the variations under different primary currents (see the Fig. 9). Table I further lists the relative errors resulted from the peak-holding process under six sets of input surge currents.

According to the errors listed in Table I, it can be concluded here that with the increase of wavefront or wave-tail durations, the held peaks from the converted voltage waveform of primary surge currents will increase, and the measurement error, thus, decreases. Besides, to control errors under various waveforms, the voltage drop can be decreased by scaling higher crests $U_m$ of the coil, and decreasing peak-holding capacitance as well as the inner resistance of the coil.

Please note that the listed errors are not the end-to-end, or the terminal measurement errors. As it will be presented later, there is calibration of the whole set. The end-to-end transform coefficient is actually experimentally measured for real-life applications so that small error is guaranteed in terms of onsite deployments.

There is a delay between the instants of current start and the actual startup of the MCU. The time delays ($t_{\text{charge}}$ and $t_{\text{power-on}}$ in Fig. 2) are actually undetectable, as the MCU is totally “unaware” of all the incidents before it is powered up, which yields peak errors in the back calculation. Extensive research has been carried out on the impacts of time delays upon system performance and the methods to mitigate the negative impacts caused by time delays [29], [30]. Here, we estimate the maximum resulted error in a simple way. Because averaging the sampled values cannot eliminate this error, we can just take the first sampling point $(t_1, u_1)$ to estimate the error as follows:

$$\delta = \frac{u_1 \exp[t_1/\tau_2] - u_1 \exp[(t_1 + t_d)/\tau_2]}{u_1 \exp[(t_1 + t_d)/\tau_2]} = 1 - \frac{\exp[t_d/\tau_2]}{\exp[t_d/\tau_2]}$$ (16)
where \( t_d = t_{\text{power-on}} - t_{\text{charge}} \) and \( \tau_2 = 7 \) s. Since \( t_{\text{power-on}} \) (maximum of 2 ms specified by the MAX5035 datasheet) is substantially larger than \( t_{\text{charge}} \) (less than 1 \( \mu s \)), \( t_{\text{charge}} \) can be disregarded here. In this case, the maximum error resulted from the chip time delay can be estimated to be \(-0.03\%\) from (16). The final fabricated signal coil and the peak-holding circuit chip are illustrated in Fig. 10.

### D. Data Acquisition Unit

All the data sampling and processing tasks are physically implemented by the data acquisition unit. The unit is designed to have low-power requirement. The hardware counterpart consists of a CPU, reset circuit, memory circuit, debugging interface, and a communication circuit. MCU C8051F912 is used in the unit. Besides, FM3130 with real-time clock and 64-kB ferroelectric nonvolatile RAM is used as the nonvolatile memory. A button cell with 3-V rated voltage is loaded in the unit, which only serves for keeping the system clock running such that the time of lightning event can be recorded.

Two isolated MCU channels, namely CH0 and CH1 that are connected to nodes \( a \) and \( b \) in Fig. 6, are used to sample the positive and negative currents separately. The polarity of the acquired signal can be recognized by identifying the channel number since the signal data only exist in the channel that with the correct current polarity, while only a weak background noise can be found in the other channel. Fig. 11 shows the data acquisition unit.

To validate the design that is based on the parametric calculations, we further investigated the power supply and signal conditioning units via simulation studies using Saber software package.

The configuration considered in calculation has been translated into a simulation model. In the simulation, a resistor was used to represent the load. Under such conditions, the output voltage waveform of the unit was simulated, as shown in Fig. 12.

As illustrated in Fig. 12, the output voltage reaches 3.3 V, and the duration is found to be approximately 0.4 s. As for the signal conditioning unit, because the divider ratio of the signal conditioning unit must be regulated every time in accordance with the application condition, the divider structure in the two peak-holding loops were temporarily disregarded in both the simulation studies and experiments. Instead, only \( R_1 \) and \( R_2 \) remained and were set to 10 M\( \Omega \). Lightning currents with four positive amplitudes were employed as the excitation sources: 10, 15.2, 20, and 25.6 kA. In this case (i.e., positive polarity), the output voltage waveforms across \( R_1 \) were simulated, as illustrated in Fig. 13. The voltage peaks can be identified from the figure as 1.66, 2.67, 3.74, and 4.84 V, respectively.

### III. Prototype and Experiment

One of the critical considerations in developing the prototype is the equivalent potential shielding for the cancellation of impulse electric field interferences from lightning. The casing of
the device mainly consists of the shielding enclosures for the coils and for the signal conditioning and data acquisition chips. A major slot located between the coil ends (i.e., the position of the air gap) was employed to cut off the magnetic bypass. The auxiliary horizontal slot was used to cut off the eddy current in vertical section of the casing. The device can be clamped on the grounding leads using the fixation apparatus. The two shielding cases are placed on the apparatus and interconnected by sockets. The structure of device enclosure is shown in Fig. 14.

To validate feasibility of the designed system, we have carried out experiments on the power supply and signal conditioning units separately as well as a test on the performance of the entire LCMS. The tests utilized artificial lightning currents generated by an impulse current generator ICS200 kA/100 kJ in the laboratory. The generator was adjusted to generate surge currents with amplitudes of 10, 15.6, 20, and 25.6 kA. Meanwhile, the system housed on the current lead generated dc power and held current measurement voltage signals, which were then fed into an oscilloscope. A Pearson coil was used to provide a standard voltage signal reference for the test. The experimental setup is demonstrated in Figs. 15 and 16.

First, the output from the power supply unit was inspected separately. A resistor of 200 Ω was used to represent the load. Fig. 17(a) shows the waveform of measured 3.3-V dc from MAX5035 under surge current of 10 kA. Thereafter, Table II also lists the dc levels and their durations under the primary currents of 10, 15.6, 20, and 25.6 kA, respectively.

Fig. 17(a) reveals that the measured output dc waveform is almost identical to the simulated result while compared with Fig. 12. Table II demonstrates that the dc voltages are 3.3 V constantly under different amplitudes of primary currents, which proves that the power supply unit is able to stabilize the output for the load. The duration $t_{on}$ are 0.41, 0.68, 0.84, and 1.04 s, indicating that an increase in the lightning current amplitude is expected to increase the powering time.

Then, the signal conditioning unit was tested to verify the applicability. First, when 10-kA current was injected, the output voltage waveform from node $\phi$ (see Fig. 6) was measured and shown in Fig. 17(b). Table III lists the calculated, simulated, measured, and calibrated voltage peaks considering the diode
front voltage drop. The errors of amplitude measurement were also calculated.

Table III shows that the measured and simulated amplitudes are approximately equal. In the four tests, the voltage–current conversion coefficients are 0.204, 0.205, 0.208, and 0.206 V/kA, which are almost the same, indicating a very good linearity in measurement. Furthermore, the measured voltage amplitudes were calibrated by adding a diode voltage drop 0.4 V of the SF24. The maximum error between the calibrated and theoretical amplitudes is 4%. The test of the entire self-powered LCMS device has also been conducted under the previously discussed experiment setup. The recorded data in the nonvolatile memory allocated for CH1 and CH2 were retrieved and analyzed, as shown in Table IV. Because the positive currents were injected, the recorded voltages in CH1 are much larger than those in CH2 as designed. Hence, the recorded results prove that the polarity of measured surge currents can be well identified.

We again have examined the voltage–current conversion coefficient in this test. The coefficients are obtained to be 0.0550, 0.0551, 0.0555, and 0.0551 V/kA, which indicate that the recorded voltages exhibit a clear linear relationship with the injected impulse current peaks.

Note that in Table IV, the voltages in the memory have not been back calculated into original current peaks to be directly compared with the actual injected amplitudes, as what has been done and shown in Table III. However, the linear relationship between the measured voltage signals and the peaks of the impulse currents, as considered throughout the designing process and finally observed in the experiments, already indicates the effectiveness of the system. Because the system requires calibration before onsite installation, which can be achieved by experimentally measuring the end-to-end (the current peak at the primary side of the signal coil to the voltage value recorded in memory) transfer coefficient values. As long as the coefficient holds constant, the lightning current amplitudes can then be precisely back identified. The experimentally verified measurable range of the proposed system is 10–25.6 kA. It should be noted that the range is adjustable. From a practical point of view, the measurement range should be adjusted first based on the onsite lightning characteristics and thereafter calculate the component values as detailed above to satisfy the determined range.

### IV. Conclusion

In this paper, we proposed and developed a novel self-powered LCMS. From the simulation and experimental studies, we have observed 3.3-V dc with 400-ms duration under a lighting current of 10 kA in the amplitude, which reveals that the designed self-powered topology can keep the loaded units operational throughout the measurement task. The maximum discrepancy between the calibrated and calculated voltage signal peaks is 4% under the lightning currents with four different amplitudes ranging from 10 to 25.6 kA. In the tests of the whole device, the voltage–current coefficient was observed to hold constant, which guarantees a precise identification of lightning current amplitudes, as long as the system is calibrated beforehand. It can be, therefore, concluded that the proposed self-powered measurement system is feasible and has high accuracy in measuring lightning current peaks.

In November 2015, the prototype was mounted on the grounding lead of a lightning arrester in a 110-kV substation in Guizhou and has been in operation since then. The future work will be focused on the impact from the natural onsite lightning currents on the system accuracy. With the underlying current model of 8/20 μs used in this study, it is confirmed that for a current with front time longer than 8 μs, the system can provide high accuracy as required. However, the error can be enlarged for currents with steeper fronts, and the impacts need to be further studied.
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