Measurement of Negative Lightning Return Strokes Using a Proposed Small-Scale Parallel Plate Antenna at the Central Region in Peninsular Malaysia

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Abstract. Lightning can occur between the clouds (intra-clouds), ground-to-cloud (CG), and inside the clouds. The lightning strike hazards can be managed appropriately using a lightning detector system consisting of an antenna, buffer amplifier circuit, and a measurement device. In this study, the development and fabrication of small-scale parallel plate antenna were carried out by reducing the physical height and antenna dimension to measure the generated electric fields. The experimental work was conducted at the rooftop of the College of Engineering, Universiti Tenaga Nasional (UNITEN), Selangor, Malaysia, from August 2019 to March 2020. The total number of 115 return strokes (RS) of negative lightning events were recorded during the measurement period. Characterization of seven types of criteria for negative return stroke has been analysed and compared to the existing parallel plate antenna with a similar climate condition and different countries. Based on the comparative study, the proposed and the existing parallel plate antenna shows a good agreement. Hence, the proposed small-scale parallel plate antenna can be used as a portable, lightweight, and easy to install device for the lightning measurement system.

1. Introduction

Lightning has been defined as a transient, high-current electric discharge whose path length is measured in kilometres which the main sources are thunderstorms clouds (cumulonimbus) [1]. The effect of lightning strikes has received considerable critical attention from the electricity industry, which this electrical discharge has a significant impact on the power transmission line. The damage to a power plant is almost certain if the lightning strikes the transmission line immediately near a station, as the ordinary lightning arrestor probably could not divert such a powerful discharge to earth [2]. The evaluation of a lightning location is one of the critical issues for lightning mapping and considers the level of lightning risk for the protection of power systems. The system can be operated based on the measured and validated data obtained by the lightning detection system (LDS). Apart from the requirement of modern and sophisticated equipment in the lightning detection system (LDS), a proper detection network also requires a fundamentally important element. One of it is the characteristic and features of lightning due to the lightning is a very complex nature/ atmospheric phenomenon. In a tropical region such as Malaysia, it was located on the equatorial point, which receives a high number of thunderstorms and lightning activity due to frequent rainfall in this country, particularly in Selangor [3].
For research purposes, many studies were carried out a lightning-generated electric field measurement and a lightning characterization to assess the features of this electrical discharge, mainly on the negative return strokes, by using a parallel plate antenna [4-6]. In most of the previous studies, the characterization of negative lightning return strokes mainly on the zero to peak rise time, 10-to-90% rise time, zero crossing time, slow front time, slow front amplitude relative to peak, fast transition 10-to-90% rise time, and width $dE/dt$ pulse at half peak value. Apart from that, the existing parallel plate antenna is too bulky with minimum height and diameter was observed as 1.5 m and 0.3 m [8], [7] which is not easy to carry or move for installation by looking at the antenna dimension. Table 1 presents the details of the height and diameter of the existing parallel plate antenna that has been used from the previous studies to measure the lightning-generated electric field at different locations such as Malaysia, Indonesia, and the USA. Hence, this study proposed measuring the lightning-generated electric field using a proposed small-scale parallel plate antenna under seasonal variations in Malaysia.

| Authors               | Location | Height (m) | Diameter (m) |
|-----------------------|----------|------------|--------------|
| Wooi et al. [7]       | Malaysia | 1.50       | N/A          |
| Salimi et al. [8]     | Malaysia | 1.50       | N/A          |
| Arshad [9]            | Malaysia | 1.85       | 0.45         |
| A. Hazmi et al. [10]  | Indonesia| N/A        | 0.30         |
| Haddad et al. [11]    | USA      | 1.60       | N/A          |

2. Methods

2.1 Small-Scale Parallel Plate Antenna Development

A parallel plate antenna is used to measure the fast electric field signal. In this study, the small-scale parallel plate antenna has been developed by reducing the antenna's physical height and diameter. The size of physical height was obtained based on the experimentally calibrated from the previous study conducted by Galvan and Fernando in Sweden [12]. The experiment was performed by placing the parallel plate antenna in a large parallel grid capacitor. A known voltage is applied and by using a known charge to the antenna through a series combination of an external voltage source. Hence, the electric field can be measured by dividing the voltage applied to the grid with the height at the central point of the metallic grid as equated in (1) [12],

$$E = \frac{V_{\text{grid}}}{h_{\text{grid}}}$$

$E$ is denoted as measured electric field (V/m), $V_{\text{grid}}$ is the voltage applied to the grid, and $h_{\text{grid}}$ is the height at the central point of the metallic grid in metres. The parallel plate antenna's calibration process was conducted by generating an electric field produced using an Impulse Marx Generator. In this process, the impulse voltage was applied to a metallic grid plate 4.82 m above the earth's surface. Meanwhile, the parallel plate antenna was placed at different heights (from 0.555 to 2.000 m) at the central part below the metallic grid and overground. Hence, the parallel plate antenna's physical height for this study was selected based on the calibrated minimum value of 0.555 m. The antenna used in this study had a diameter of 0.25 m and a distance between plates of 0.03 m. The static electric and magnetic field theory can be applied when the object is very small compared with the field wavelength across the object,
which corresponds to the quasi-static case, with a frequency range of 300 Hz to 1 MHz [13]. The field wavelength can be determined as,

\[ \lambda = \frac{V}{f} \]  

Where \( \lambda \) is denoted as the wavelength (m), \( V \) is the wave velocity (m/s), and \( f \) is the frequency in Hertz. Based on the equation above, the wave velocity in free space is equal to \( 3\times10^8 \) m/s. Meanwhile, the maximum radiated energy occurs with a frequency of \( 10 \) kHz [14]. By using equation (2), the wavelength is calculated as 30 km. Hence, the quasi-static theory is well applicable because the wavelength of the electromagnetic signal is much larger than the antenna dimension, which is 0.25 m that proposed for the lightning electric field measurement. Since this study focuses on the electric field measurement, the quasi-static theory is well applicable to this measurement as the electromagnetic wavelength signal is significantly larger than the size of the sensor.

**Figure 1.** The Proposed Small-Scale Parallel Plate Antenna

Figure 1 shows the proposed small-scale parallel plate antenna with a physical height of 0.555 m. The antenna is composed of two circular aluminium plates that parallel to each other. The diameter of the upper plate is 0.25 m, and the bottom plate is 0.20 m. The gap between two parallel plates is 0.03 m, which consists of 3 insulations made up of Perspex with a diameter of 0.02 m each. The primary function of this insulation is to avoid two conducting circular aluminium plates touching each other and prevent a corona discharge appear between the plates. The other part of this antenna is the metal box which the buffer amplifier circuit is placed inside a box with a dimension of 0.11m x 0.11m. Both the metal box and antenna rod are made up of stainless-steel material.

**2.2 Buffer Electronic Circuit Fabrication**

For lightning electric field measurement, a specific electronic circuit is used to measure an interest lightning electric field waveform. In this study, an electronic buffer circuit has been designed based on Figure 2, which the measurement has been used widely in the previous research such as [15-17]. This element is composed of the RC filter circuit which the decay time constant should be within a range of 10 ms for fast field and 1s for slow field measurement. Based on the schematic diagram, the electronic buffer circuit can be divided into three parts, which are RC filter, buffer amplifier, and impedance matching circuit. The RC filter is connected with input from the parallel plate antenna, \( V_g \), which is
composed of \( R_1 = 50 \, \Omega \), \( R_2 = 100 \, M\Omega \), and \( C = 15 \, pF \). To control the decay time constant, the value of the capacitance, \( C \), in the RC filter circuit must be chosen carefully. Based on this part, a 15 pF is required to control the decay time constant for fast field measurement. Meanwhile, for slow field measurement, it is required a value of 10 nF. Apart from that, the value of \( R_2 \) must be high as 100 M\( \Omega \) to maintain the decay time constant of fast field measurement since the input impedance is very high.

Figure 2. Schematic Diagram of Buffer Amplifier Circuit

Hence, it is crucial to keep the value of \( C \) as low as possible to keep the whole system's gain at a reasonable value, which when the value of capacitance is high, the overall gain of the antenna system will become low. In this study, the MSK0033 component is used as a buffer amplifier that offers a high current drive at frequencies from DC to over 100 MHz which reasonable for a peak frequency range between 10 kHz to 300 kHz. The high-speed operational amplifier MSK0033 also controls the whole system's bandwidth up to 140 MHz with the input\( 10^{13} \, \Omega \) and low output of 6 \( \Omega \). The last component of the electronic buffer circuit is the impedance matching circuit connected to the output/ transient recorder system, \( V_m \), which consists of \( R_0 = 43 \, \Omega \) and variable capacitance, \( C_v \). This impedance matching is composed to match the MSK0033 buffer amplifier output impedance with the RG58 cable connected to the transient recorder system.

2.3 Field Test Measurement

In this study, the field test measurement was conducted on the rooftop of the College of Engineering building at Universiti Tenaga Nasional (UNITEN), proximity to the equator (Latitude: 2.973270N, and Longitude: 101.728536E), which can be viewed from Figure 3(b). The waveform of the lightning-generated electric field was recorded from August 2019 to March 2020, which covers a different seasonal period in Malaysia which are northeast monsoon (December to February), first inter monsoonal (March to April), southeast monsoon (May to September) and second inter monsoonal (October to November). Figure 3(a) shows a measurement setup between the proposed parallel plate antenna with the transient recorder system. The transient recorder system is situated in one empty office room located at level 3. Apart from that, the measurement system must be installed inside a closed room to protect the transient recorder unit.

Meanwhile, the electronic buffer circuit is protected from the wet weather by placing inside a metal box of the parallel plate antenna. The lightning-generated electric field waveform was recorded using the PicoScope (PC Oscilloscope) 4000 series, which a virtual instrument formed by connecting a PicoScope oscilloscope to a computer via Picoscope software. This 12-bit oscilloscope is composed of BNC oscilloscope connectors which inputs have an impedance of 1 M\( \Omega \) that compatible with all standard scope probes, including x1, x10, and switched types. In this study, the sampling rate was set to
25 MS/s (Mega samples per second); meanwhile, the total length of recorded waveforms is 200ms per division.

![Measurement setup and location of parallel plate antenna](image)

**Figure 3.** (a) Measurement setup; (b) Location of Parallel Plate Antenna

3. Results and Discussions

A total of 115 negative return strokes has been observed; from the 205 lightning signals. Figure 4 shows an example of the measured negative return stroke signal with the negative stroke's zooming, which the signal represents up to the zero crossings. Table 2 compares the results obtained from this study from the same country [9], which has been conducted in Universiti Putra Malaysia (UPM), Serdang, Selangor, Malaysia at the coordinate of 20°59′19.9″ N latitude and 101°04′32.9″ E longitude. Based on the coordinate, it is known that the measured data in [9] has the same tropical climate and country location as this study. Generally, four major parameters are involved in the analysis of negative return stroke: rise time, zero crossing, slow front, fast transition, and dE/dt waveform characteristic. It was observed that the range of all parameters in this study is within the range as in [9].

![Measured negative lightning return strokes](image)

**Figure 4.** Measured Negative Lightning Return Strokes

Meanwhile, the arithmetic mean (AM) of zero to peak rise time was observed 0.8% higher, and 10-to-90% rise time is 4.66% higher than recorded by Arshad [9]. The finding of this value is consistent with the previous work reported by Wooi et al. [7]. The measurement was conducted in southern peninsular Malaysia with the AM value of 6.6 µs and 3.9 µs, respectively. The zero crossing time of this study was discovered slightly longer with a percentage difference of 2.7%, and Wooi et al. [7] reported a much longer time which is 50.7 µs. Meanwhile, the dE/dt waveform characteristic is 4% lower than in [9], which this finding is in agreement with Wooi et al. [7], where the AM of this characteristic is determined as 2.4 µs. There are total percentage differences of 3.11%, 7.6%, and 9.8% on slow front...
duration, slow front amplitude relative to peak, and fast transition from tabulated data. The data in Table 2 shows that it is not much different from the recorded data from the proposed small-scale antenna compared with the measured data reported by Arshad [9]. In addition, there was a significant positive correlation between the data recorded in [9] with the data reported by Wooi et al. [7].

**Table 2. Data Comparison from the Same Country**

| Parameters                      | Arshad [9] | This Study |
|---------------------------------|------------|------------|
|                                 | Sample Size | Range | AM | Sample Size | Range | AM |
| Zero to Peak Rise time, µs      | 142         | 1.68 – 19.72 | 6.65 | 115 | 1.92 - 13 | 6.70 |
| 10-to-90% Rise time, µs         | 142         | 0.54 – 9.32 | 4.30 | 115 | 3.7 – 8.90 | 4.51 |
| Zero crossing time, µs          | 142         | 4.66 – 82.06 | 32.8 | 8 | 4.69 – 82.52 | 33.79 |
| Slow Front Duration, µs         | 142         | 0.30 – 9.92 | 4.5 | 115 | 0.606 – 9.18 | 4.36 |
| Slow Front Amplitude relative to peak, % | 142         | 0.98 – 78.76 | 34.4 | 115 | 7.5 – 43.2 | 31.8 |
| Fast-transition 10-to 90% Rise-time, µs | 142         | 0.10 – 11.32 | 2.14 | 115 | 2.8 – 10.18 | 3.95 |
| Width dE/dt pulse at half peak value, µs | 142         | 0.56 – 7.48 | 2.70 | 115 | 1.4 – 6.9 | 2.57 |

**Table 3. Data Comparison with Different Countries**

| Parameters                      | Different Studies | This Study |
|---------------------------------|-------------------|------------|
|                                 | Location          | Sample Size | AM | Sample Size | AM |
| Zero-to-Peak Rise time, µs      | Florida, USA [11] | 265         | 7.7 | 115 | 6.70 |
| 10-to-90% Rise time, µs         | Japan [18]        | 8           | 3.90 | 115 | 4.51 |
| Zero crossing time, µs          | Sri Lanka [19]    | 57          | 72 | 115 | 33.79 |
| Slow Front Duration, µs         | Florida, USA [20] | 62          | 4.0 | 115 | 4.36 |
| Slow Front Amplitude relative to peak, % | Florida, USA [21] | 83          | 28 | 115 | 31.8 |
| Fast-transition 10-to 90% Rise-time, µs | Japan [22] | 7           | 0.14 | 115 | 3.95 |
| Width dE/dt pulse at half peak value, µs | Germany [23] | 148         | 0.62 | 115 | 2.57 |

The data measurement in this study also has been compared with different countries, such as in Florida, USA [11]. Further analysis shows that the AM of zero-to-peak rise time was observed as 7.7 µs, similar to this study, 6.7 with a percentage difference of 12%. There is also a similarity between the
finding in this study and those described by Cooray and Lundquist [24], in which the AM of zero-to-peak rise time is 7 µs. From Table 3, it can be seen that the AM of 10-90% rise time was comparable that has been recorded in Japan [23]. It is apparent from the tabulated data a positive correlation of slow front duration between the measured data in Florida, USA [20] and this study. The AM was observed 4.36 µs and 4.00 µs with a percentage difference of 8.2%. The results are consistent with those of other studies conducted by Cooray and Lundquist [24], in which the AM was observed as 4.6 µs, respectively. Apart from that, the result of slow front amplitude relative to peak is in agreement with Mater et al. [21] findings which the AM was identified as 28 µs. Meanwhile, the AM of fast transition 10-90% rise time and width dE/dt pulse at half peak value was observed higher than recorded data in Japan [27] and Germany [28] 0.14 µs and 0.62 µs, respectively. In addition, the zero-crossing time of this study was determined significantly lower than the measured data in Sri Lanka [19], which is 33.79 µs compared to 72 µs. It was observed with the same pattern discovered by Cooray and Lundquist [24], which 49 µs respectively. A possible explanation for these results may be that different meteorological conditions, geographical area, and climatic factors could affect the findings.

4. Conclusions

This study proposed a small-scale parallel plate antenna for lightning electric field measurement. A total of 115 negative return stroke (RS) were recorded from this antenna. All these measured data were analysed and validated with similar climate conditions, which accessible at Selangor and Johor. Besides that, the data recorded by the proposed antenna were compared with the measured data based on different countries such as the USA, Japan, Germany, and Sri Lanka. Various parameters of both lightning characteristics have been analysed, which refer to the arithmetic mean (AM). Based on the negative return stroke analysis, the AM of zero-to-peak and 10-90% rise time was determined as 6.70 µs and 4.51 µs. The slow front duration, slow front amplitude relative to peak, and the fast transition observed are 3.95 µs, 31.8 µs, and 3.95 µs, respectively. Meanwhile, the zero-crossing time and width dE/dt pulse at half peak value are recorded as 33.79 µs and 2.57 µs. The analysis shows that the data obtained in this study is comparable with results under the same climate and different countries. Hence, this study demonstrated that the proposed small-scale parallel plate antenna could be operated as a portable, which the proposed 0.05 metres height can be easily to carry from one place to another as compared to the existing dimension. The proposed antenna also could be performed as a convenient lightning-generated electric field measurement device.

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