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IJIE

http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Significant Lightning Stroke Count in Negative Ground Flashes Featuring the Relationship of Preliminary Breakdown and The First Return Stroke

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DOI: https://doi.org/10.30880/ijie.2023.15.01.022
Received 17 July 2022; Accepted 10 January 2023; Available online 28 February 2023

Abstract: The separation duration of Preliminary Breakdown (PB) to the First Return Stroke (PB-RS duration) and the ratio between the highest amplitude pulse of negative CG flashes and the first Return Stroke pulse (PB/RS ratio) were successfully used as a tool by many researchers to determine the relationship between lightning ground flashes and physical changes (latitude, regional and thunderstorm). Malaysia is one of the countries with the highest lightning flash density globally, and the occurrences of ground flashes are mainly due to monsoon seasons. Monsoons in Malaysia are Northeast, Southwest, and two transition periods. However, there is no available information to relate the lightning activities in Malaysia under the influence of all monsoon seasons. The above statements motivated our team to present a new statistical analysis of lightning flashes under two seasons' effects (Northeast and Southwest). 83 out of 332 electric radiation field data (fast fields) from six thunderstorms were selected and analyzed. The data recorded were using a 12-bit high-speed transient recorder (HDO 4024) with a resolution of tens of nanoseconds and sampling of 12.5 MS/s. PB/RS ratio between the monsoons is similar to each other. The PB-RS separation has two factors longer during the Southwest monsoon than during the Northeast monsoon. We classified the PB/RS ratio into four categories (>100%, 50-100%, 20-50%, and < 20%) as an indication of the preliminary breakdown strength. It found that the weakest pulse train (PB/RS ratio less than 20%) has shown a longer duration of PB-RS and produces higher lightning return strokes in a negative ground flash than the strong one. The results of this study could be evident that the lower strength of preliminary breakdown correlates to a lower Low Positive Charge Region (LPCR), which means the initial breakdown process only requires low energy to break the LPCR. Hence, these features have shown the highest number of stroke counts compared to pronounced ones. However, it would be more remarkable if one could provide bulky data for this specific study.

Keywords: Stroke count, PB/RS ratio, PB-RS duration, return stroke, tropical monsoon

1. Introduction

The work of [1] showed that the failure modes of surge protective devices deployed in power systems depended on the number of stroke counts and interstroke duration. This study noted that the number of stroke counts in a flash and the interstroke duration were crucial parameters to consider in coordinating the circuit breakers in power system protection.

The meteorological structure of thunderclouds corresponding to latitude (which influences the preliminary breakdown stage of negative ground discharge) has attracted numerous researchers' interest in understanding its nature. For instance, across the region South Africa by [2], Sweden and Sri Lanka by [3], Finland by [4], Florida by [5], Florida and Malaysia by [6] and Austria, Florida, South Dakota by [7]. Overall, it is a consensus that the strength of the electric

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field peak pulse of preliminary breakdown produced by cloud measured to the peak of return stroke (PB/RS ratio) is high in the upper region. In other words, pronounced PB is consistently related to latitude dependence.

Apart from that, the parameter for the duration of the highest peak of PB pulse to the first return stroke (PB-RS duration) does not indicate any dependency on latitude. This statement was according to the inconsistent result of PB-RS duration across the region, for instance, the PB-RS duration reported by [6] in Malaysia (1ºN) (57.6 ms) was inconsistent with [3]in Sri Lanka (6.9ºN) (11.9 ms), although both are in a similar region. Moreover, the result by [6] in Malaysia (1ºN) (57.6 ms) was comparable to [7] in Austria (48ºN) (53.1 ms), although both studies were in different latitudes. In this case, it might be due to distinct types of storms or other parameters. The meteorological state could also influence the lightning discharge characteristics [8], [9], [10]. For instance, pronounced PB type of ground flashes and PB followed by no return stroke flashes, which are typically observed in the higher region, were numerous times related to the denser LPCR [11],[12], [13]. However, the event may occasionally occur in the lower region due to the meteorological state [14]. It implies that; besides latitude, the meteorological state could influence the distribution and type of lightning discharge.

The data recorded in the present study were under the influence of tropical monsoon (Northeast Monsoon (March until November), Southwest Monsoon (May until Sep) and two Inter-monsoons (March until May and Sept – Nov)), specifically during the Northeast Monsoon. In general, the PB/RS ratio from the previous study (cited above) shows an agreement that the ratio decreased as the latitude decreased, regardless of which monsoon or season of the data measured. In other words, it showed simple latitude dependence. On the other hand, the parameter of PB-RS duration shows the variation of results across latitudes. In the present study, "does the monsoon influence the parameter of PB-RS duration?" this question arises. The variation results of PB-RS duration mentioned above motivate us to study the correlation of PB-RS duration with the meteorological variation and how it influences the stroke count produced.

In this study, we present the ratio of the highest pulses of PB to the FRS (PB/RS ratio) in the vicinity of a tropical thunderstorm. The parameter of PB-RS duration, pre-RS duration, stroke count and the number of BIL and BL structures are also analyzed. PB-RS duration is the highest peak of PB pulses to the FRS. The pre-RS is the duration of the first pulse of the PB pulse train to the FRS. The results from other researchers with different monsoon seasons, were compared. To comprehend the meteorological influence on the physics of lightning in the tropical region, we would need more data and research. However, the reports available in the tropics are very scarce. Since the meteorological state could influence the lightning characteristic, there is a need to gather more data from this region for future power system energy enhancement.

2. Methodology

The electric field measuring sensors are similar to the measurement layout performed by [15] and [14]The operations of the antennas for electric field radiation (fast field) comprehensively were described in [16] (see Fig. 1 and 2). The measurements of the electric fields generated by the lightning flashes were conducted in Universiti Teknikal Malaysia Melaka (UTeM) and Paya Rumput, Malaysia.

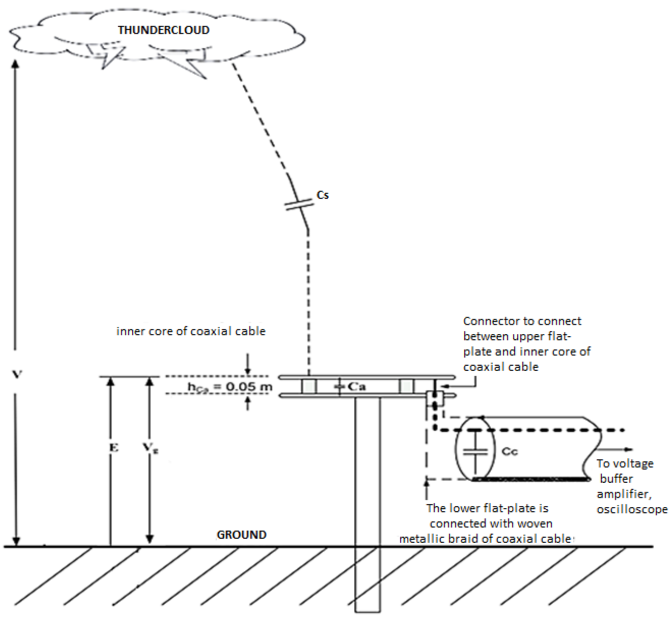

Fig. 1 - Flat-plate antenna for the fast field measurement, depicted in [16]

The electric field measurements of the whole flashes were record in two stations on May 26, 2018, during the rainstorm monsoon period in the southern part of Peninsular Malaysia near equator. The two stations in UTeM and Paya Rumput located at the latitude: 2°16'39.8586''N, longitude: 102°16'30.72'' E and the latitude: 2°18'07, 6"N, Longitude: 102°12'13.4"E, respectively.

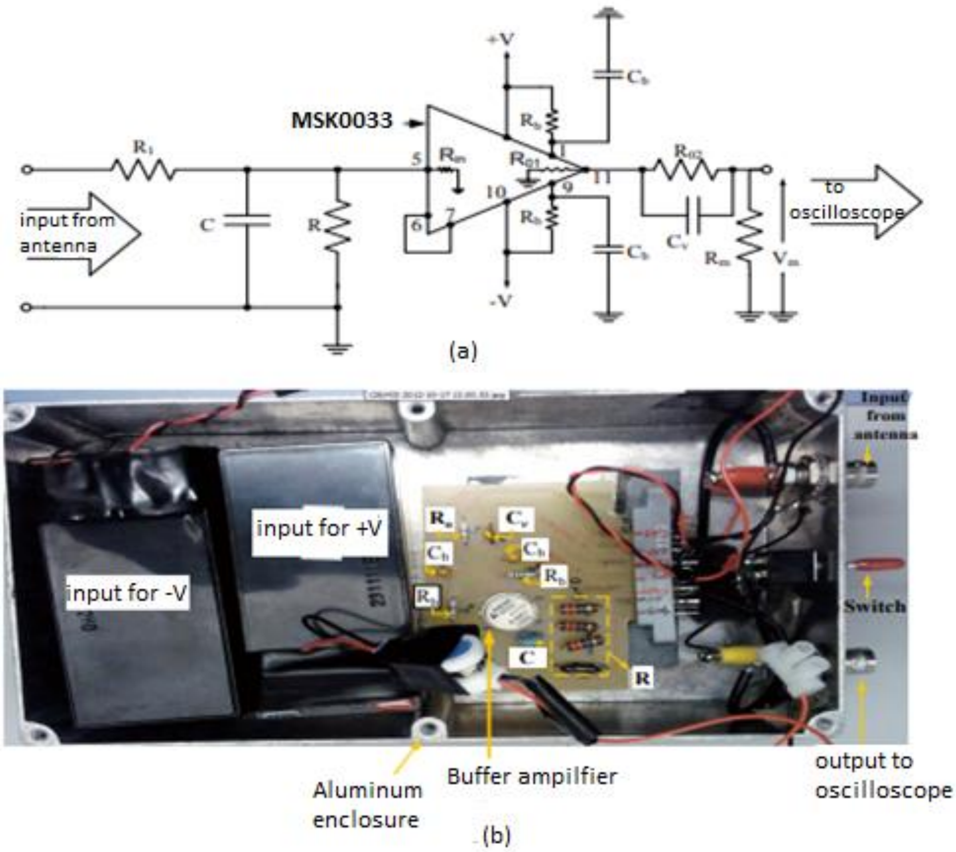

Fig. 2 - Coaxial cable driver used to control the signal between the antenna and the transient recorder; (a) the electronic circuitry of slow or fast electric field measurement; (b) the circuit board of the coaxial cable driver supplied with a lead acid battery; these components are fixed inside an aluminum container, the edges of which are just visible, depicted in [16]

Two parallel flat plate antennas are used to detect the broadband radiation electric field (or fast field). The flat antenna was used to sense the vertical electric field. In the interest of avoiding the horizontal component of the electric field, the plane of the antenna is adjusted perpendicular to the electric field vector or in other words, parallel to the ground. The physical height of the antenna is 1.5 m and the effective height is 0.25 m. The antenna was connected to the electronic buffer circuit by using a 60 cm long coaxial cable (RG58). Using the 10 m long coaxial cable (RG-58), the signal from the antenna is transmitted into a 12-bit digital transient recorder (Lecroy HDO4024) equipped with a 200 MHz High-Definition Oscilloscope. The sampling rate was set to 12.5 MS/s and the total duration of waveform recorded was 2 s. The trigger setting of the oscilloscope was such that signals of both polarities could be captured. The trigger level is set to either 50 mV to 500 mV for the far flashes or 500 mV to 2 V for the close flashes. The transient recorder was operated at a 300 ms pre-trigger mode. The rise time of the broadband antenna system (fast field) for step input pulses was less than 30 ns, while the decaying time constant was set to approximately 17.5 ms. The determination of the measuring voltage Vm, only considered the effects of the total capacitance CT since the value of the resistance was relatively high compared to CT. If h_{phy} was the physical height of the upper metallic antenna above the ground, then, Vm in Fig. 1 can be represented as:

$$V_m = V_g . C_a \; C_a + C_c + C \qquad [1]$$

Where,

$V_g = E_n . h_{phy}$

In addition, by having a narrowband radiation electric field at 3 MHz measurement system (as mentioned above), it helps to support for differentiating the single or multiple flash in the whole flash event. Furthermore, according to [16], a narrowband radiation electric field at 3 MHz signature is pronounced within the distance of less than 50 to 60 km which means that the association of other flashes in a certain of the whole flash event can be isolated in a proper manner. Any ambiguity of the whole flashes events such two flashes event for the ground flashes and unclear profile of preliminary breakdown pulse were discarded in the analysis. Fig. 3 shows the overall methodology features which begin with the electric measurement and recording then followed by the analysis work. Fig. 4 illustrate the definition of PB-RS duration, pre-RS duration, and PB/RS ratio.

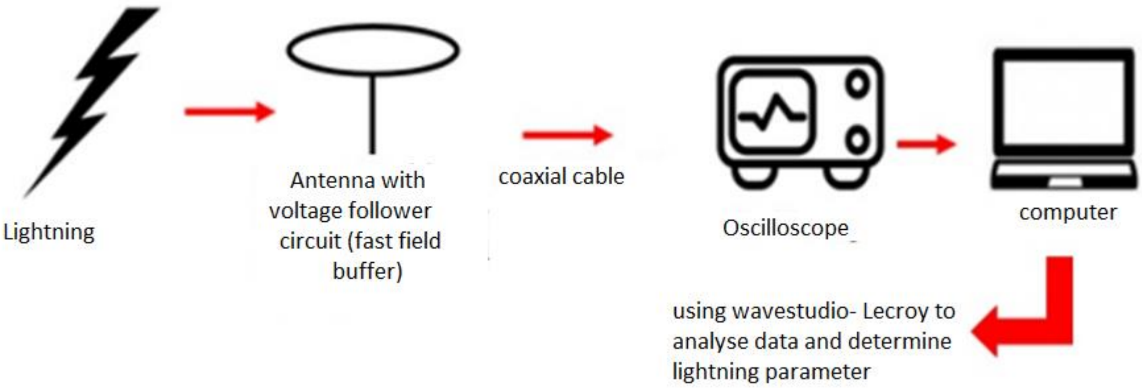

Fig. 3 - Overall methodology featuring the electric field measurement, recording and analysis

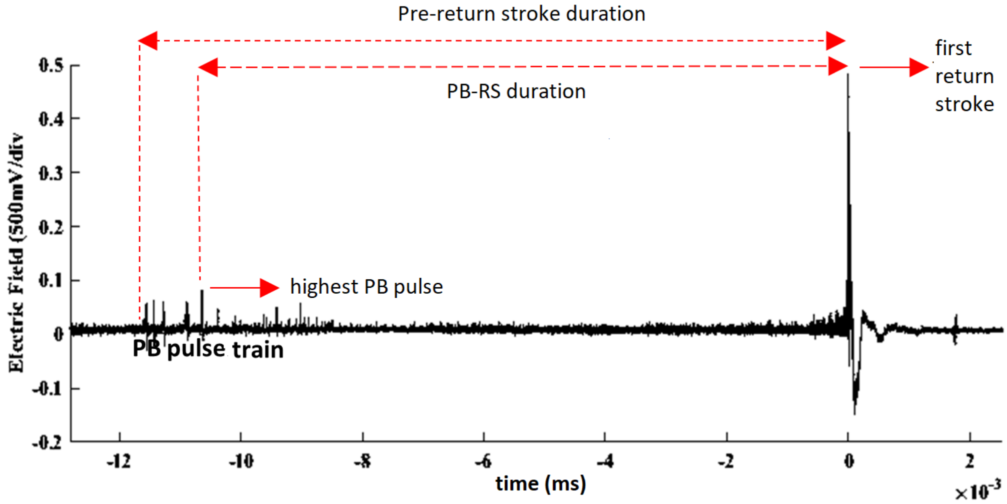

Fig. 4 - Electric radiation field of the of negative preliminary breakdown polarity followed by negative return stroke recorded on 7th November 2019

Further, the terminal point of flat plate antenna was connected to the input of the electronic drive circuit (buffer) to determine electric radiation field (fast field) in such a way that the system allow to operate under lightning frequency operation of hundreds kHz to tens of MHz. To get sufficient frequency operation as mentioned above, the decay time constant of the buffer was set at 17.5 x 10^{-3} s for far lightning distance while close distance was 87.5 x 10^{-6} s. Next, the output of the buffer was fed to the oscilloscope (Lecroy HDO4024) by using 15-metre coaxial cable (impedance=50 W). The recording duration time was set to 2 seconds to ensure the whole event were captured. The sampling, trigger level and pre-trigger duration setting of the oscilloscope were 12.5 Mega Sample per second, 300 mV, 500 ms, respectively.

2.1 Northeast Monsoon

88 samples out of 332 electric fields of lightning flashes data from six different thunderstorms in Melaka, Malaysia (2.1896° N, 102.2501° E) during the Northeast monsoon (6th until 11th November 2019), were selected for the analysis. The Northeast monsoon occurs between November and March and brings more rainfall than other monsoons. The electric fields of negative ground discharge consist of the preliminary breakdown pulses of the same (N=83) and opposite (N=5)

polarity to the subsequent event of the return stroke. The analysis only executed on the negative polarity of the preliminary breakdown of negative ground flashes.

2.2 Southwest Monsoon

The PB/RS ratio percentage and PB-RS duration of negative ground flash during Southwest monsoon was adapted from [6] and compared with the present result. The period of Southwest monsoon begins in May and sustains until September. The weather is relatively drier during this period. The electric field measurement tool used was similar with the present study. The author presents the measurement recorded from April until 2009 of 97 analyzed data during the Southwest monsoon in Johor Malaysia.

3. Result and Discussion

3.1 The Characteristic of the Negative CG Lightning Flashes Under the Influence of the Northeast Monsoon

The PB process is a sequence of channels expending arbitrarily downward step leaders in a seemingly random direction and then bridging with the upward step leader before producing a return stroke [17], [18]. The PB pulse train of negative CG flashes were analysed based on [5], where the electric fields were assumed bipolar. The arithmetic means of the PB/RS ratio of 83 data sets of negative CG flashes were 27.70%, range 7.5 to 191%. Next, the arithmetic means PB-RS duration and pre-RS duration were 27.74 ms (range: 1.84-113 ms) and 28.92 ms (range: 2.3-114), respectively. Note that the arithmetic means of stroke count in this study were 4. This information is a crucial parameter of electrical engineering to design their relay to protect the electrical appliances [19], [13].

3.2 The Comparison of P B/RS Ratio During Northeast and Southwest Monsoons

To investigate the correlation of the PB/RS ratio relative to the influence of monsoon, a comparison of data during the present study and the Southwest monsoon reported by [6] is illustrated in Fig. 5. A comparison of data during Northeast and Southwest monsoon are analysed. The present result shows that only three sets of PB pulse trains of negative CG flashes during the Northeast monsoon exceeded that of the first return stroke (PB/ RS ratio of more than 100%). In other words, only three pronounced preliminary breakdowns during the Northeast monsoon observed. On the other hand, the data during the Southwest monsoon shows a higher percentage of ratios exceeding 100%, indicating pronounced preliminary breakdown more often occurs during the Southwest monsoon. Although the PB/RS ratio in the previous study decreased as the latitude decreased [7], the arithmetic means ratio for both studies is similar (27.7% and 27.8%) despite the influence of different monsoons. Majority of the data shows a weak PB/ RS ratio (<20%). A summary of the PB/RS ratio during Northeast and Southwest monsoons is in Fig. 5.

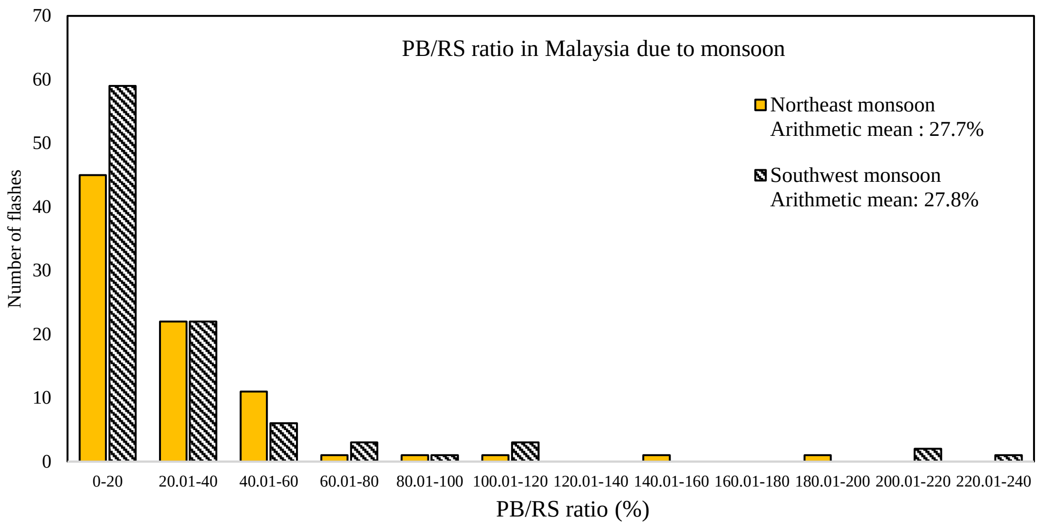

Fig. 5 - The distribution of PB/RS ratio during Northeast monsoon and Southwest monsoon of negative cloud-to-ground flashes in Melaka, Malaysia

3.3 The Comparison of PB-RS Duration During Northeast and Southwest Monsoons

On the other hand, the c omparative study between the Northeast monsoon from the current result and the Southwest monsoon by [6] showed the inconsistency of PB-RS duration, as shown in Fig. 6. The results from the Northeast and Southwest monsoons are inconsistent despite the same latitude of electric field measurement conducted.

The highest percentage of data during the Northeast monsoon has a range of PB-RS duration of less than 20 ms, while non of the event during the Southwest monsoon exhibited a PB-RS duration of less than 20 ms. Next, the results during the Northeast monsoon indicate only 3 data of PB-RS duration than 100 ms, unlike the data from the Southwest monsoon, a higher number of data exceeding 100 ms duration for the PB-RS duration observed. Further, the arithmetic means of PB-RS duration during the Northeast monsoon (27.74 ms) is two factors shorter than during the Southwest monsoon (57.6 ms).

This result implies that the interception process occurs faster during the Northeast monsoon, or it could be due to higher cloud base height during the Southwest monsoon. This result is consistent with [20] who studied the relationship between first return stroke and its preceding in cloud process. The author reported that on average, the negative ground flashes with lower initiation altitude (lower cloud base) and has a shorter step leader duration tend to be followed by stronger first return stroke (see Fig. 7). The author also speculated that the less dense of LPCR might be a favorable condition for producing intense first return stroke.

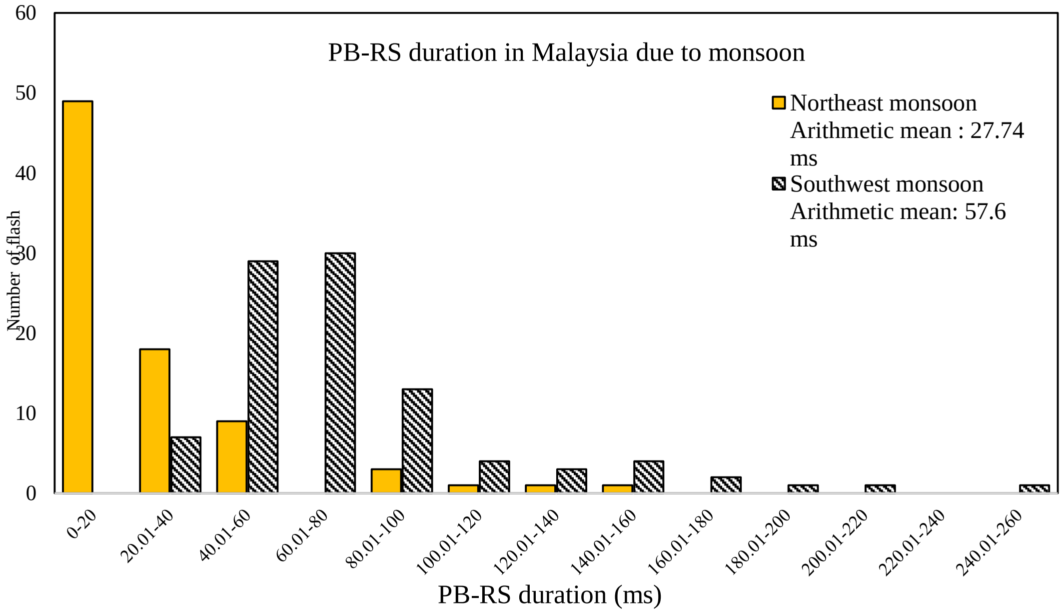

Fig. 6 - The distribution of PB-RS duration during Northeast monsoon and Southwest monsoon of negative cloud-to-ground flashes in Melaka, Malaysia

3.4 The Classification of PB/RS Ratio

The ratio between the highest peak of PB pulses to the first return stroke during the Northeast monsoon is grouped into four, as shown in Table 1. Most of the data exhibit a low PB/RS ratio percentage indicating the strength of the preliminary breakdown in this study, in general, is weak, similar to [19], [21], [22], [23]. Three data with high PB/RS ratio percentages were observed (103%, 145%, and 191%), the arithmetic means of PB-RS duration and pre-RS duration being 20.55 and 21.26, respectively. All three data with the stroke average of 3, exhibiting B, I, L type according to [24] who has sorted out the PB into three successive and distinct discharge processes, termed as breakdown stage (B), intermediate stage (I), and the leader stage (L). The author suggests that B and I are inside the cloud process before launching the step leader (L)).

Table 1 - The classification of PB/RS ratio

PB / RS %	Sample (N)	PB – RS separation (ms)	Pre – return stroke (ms)	Stroke average	BIL type (N)	BL type (N)
>100	3	20.55	21.26	3	3	0
50-100	4	25.59	26.20	4	4	0
20-50	31	17.71	18.45	4	28	3
< 20	45	35.33	36.87	5	37	8

Next, the PB/RS ratio percentages ranged from 50-100% (N=4) and 20-50% (N=31), and the PB-RS duration and pre-RS duration were slightly comparable. The arithmetic means of stroke count for both ranges were 4. Most of data from both ranges exhibited B, I, L type, and only three data of PB/RS ratio range from percentage of 20 to 50 exhibit B, L type. Further, 45 sets of data with a PB/RS ratio of less than 20% demonstrate the highest arithmetic means of PB-RS duration and pre-RS duration: 35.33 ms and 36.87 ms. The result was two factors more than the duration of PB-RS and pre-RS exhibited by other group ranges. The arithmetic means of stroke count for the PB/RS ratio with a range less than 20% is 5. The electric field of negative ground flashes within this range was most exhibit B, I, L type, and only eight data met the description of B, L type.

3.5 The Strength of The PB Process Relative to The PB-RS Duration and Stroke Count

Fig. 7 shows the waveform of negative ground flashes with a PB/RS ratio of 7a) PB (PB-RS duration: 23.33 ms) and 7b) weak PB (PB-RS duration: 58.24 ms). The pronounced PB shows shorter arithmetic means of PB-RS duration than the weak PB pulse train as in Fig. 7.

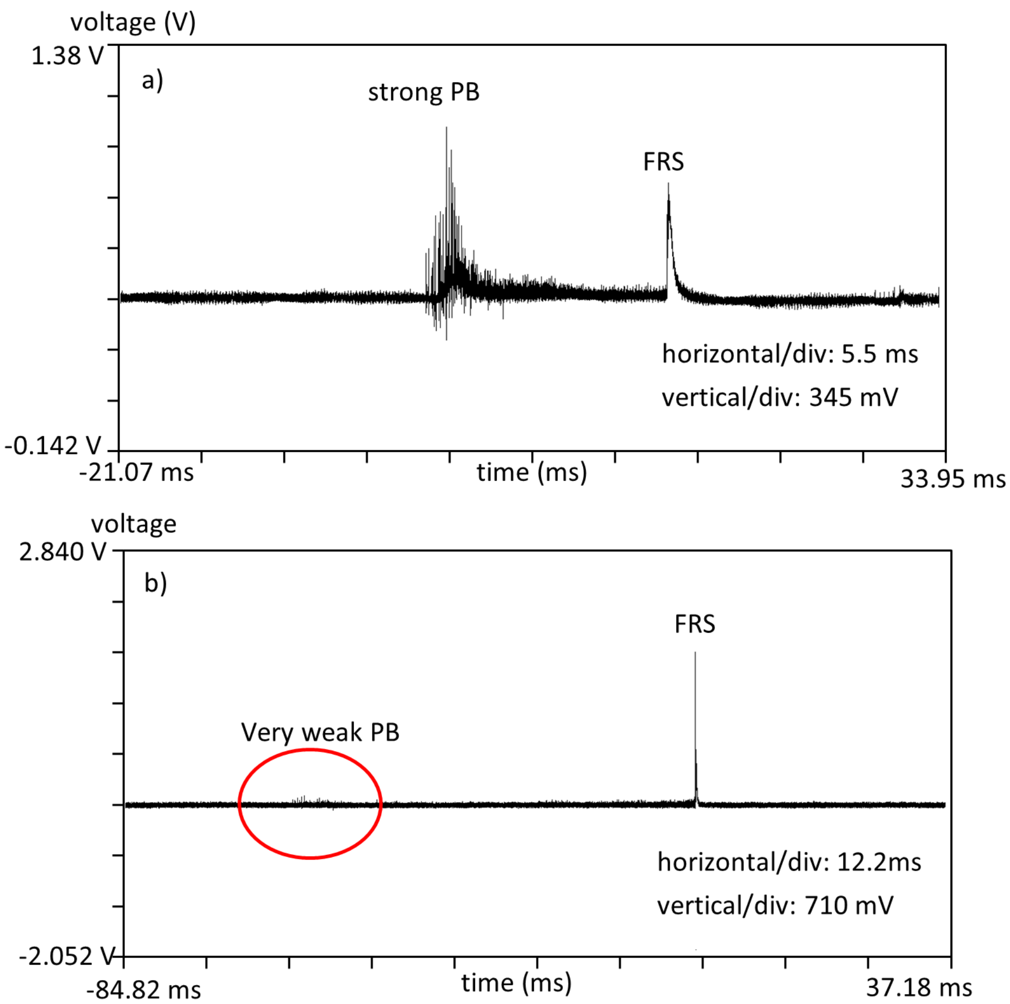

Fig. 7 - The electric radiation fields due to negative ground flashes of (a) pronounced preliminary breakdown recorded on 7 November 2016 and; (b) weak preliminary breakdown recorded on 8 November 2016. The atmospheric electricity sign convention is used here.

Next, the correlation between the PB/RS ratio, PB-RS duration, and stroke count average is in Fig. 8. From Fig. 8, the PB-RS duration, and arithmetic means of stroke count increase with the decrement of the PB/RS ratio. It implies that the stroke average of the negative CG flashes increased with the decrease of preliminary breakdown strength. This result is consistent with the information reported by [11] and [16], as the pronounced PB (PB/RS ratio is higher than 100%) is produced with the presents of dense LPCR and restricting the multiplicity of the return stroke. The information on stroke average is crucial, especially for the electrical circuit breaker setting. Lightning parameter of the return stroke become important for lightning modelling in lightning and protection application [25],[26]. To calculate the electromagnetic fields generated by return strokes, it is necessary to know the spatial and temporal variation of the return-stroke current along the channel [26]. Furthermore, the important parameter of the return stroke such as stroke per flash (multiplicity), stroke average (average in stroke per flash), time intervals (separation time between two strokes) are useful for the setting of relay protection pick-up in the circuit breaker system [27],[28]. [27] urged for the crucial of having multiple sequential of the impulse current test for any protective device (metal oxide varistor or circuit breaker) since typically lightning events produce multiple lightning strokes in nature. Working Group C4.407 [29] concluded the stroke average ranging from 3.4 to 6.4. Further [29] concluded the average of time intervals varied from 60 to 67 ms. In addition, C4.407 summarized that there is no evidence of a systematic dependence stroke average in negative CG that due to geographical location. Similarly, no reliable information on seasonal dependence is available. Thus, at the present time, the available information is not sufficient to confirm or refute a hypothesis on dependence of negative cloud-to-ground lightning parameters on geographical location or season.

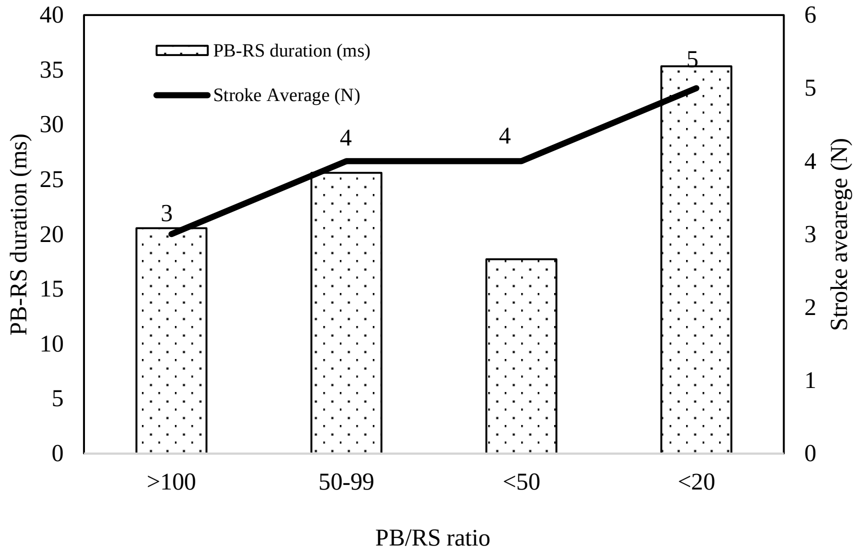

Fig. 8 - The correlation of PB-RS duration to stroke average

3.6 Comparison with The Previous Study

As discussed earlier, the arithmetic means of PB/RS ratio during Northeast monsoon and Southwest monsoon show consistency with one another despite different monsoons of measurement conducted. However, the parameter for PB-RS duration of both monsoons shows dissimilarity as the data during the Southwest monsoon demonstrate two factors longer than the present study (see Fig. 6). To investigate the relation of PB-RS duration of the negative ground flashes associate with monsoons, a comparison of three different monsoons from previous studies of the same region is present.
Table 2 shows the arithmetic means of the PB/RS ratio and PB-RS duration of similar latitudes but different monsoons.

Table 2 - Comparison with the previous study of the same region

Research	Monsoon	Sample Size (N)	PB / RS ratio (%)		PB-RS separation (ms)		Pre- RS duration(ms)	
			Arithetic means	Range	Arithetic means	Range	Arithetic means	Range
Present Study	Northeast	83	27.7	7.5-191	27.74	1.84 -113	28.92	2.3-114
Malaysia, [6]	Southwest	97	27.8	2.6-228.1	57.6	8.3 -227.3	62	-
Sri Lanka, [3]	Northeast & First Inter-monsoon	9	16.5	6.2-26.4	11.9	3.5-25.3	-	-
Padang, [24]	Second Inter-monsoon	100	13	3-37	8.23	3.79-19.08	-	-

The characteristic study of negative ground flashes during the First Inter-monsoon in Sri Lanka by [3] and the Second Inter-monsoon in Padang by [24] shows that the arithmetic means of PB/RS ratio were two factors less than the present study. Overall, the PB/RS ratio reported by [6], [3], [24], and the present study indicates that the preliminary breakdown in the lower region is relatively weak regardless of which monsoon the data measured. The lowest PB/RS ratio in tropics was during the Second Intermonsoon [24]. Overall, the PB/RS ratio between the Northeast monsoon is similar. On the other hand, the PB/RS ratio between the Northeast and Southwest monsoons was higher than during the two intermonsoon.

However, the PB-RS during the Southwest monsoon shows a significantly higher duration than the other monsoon reported by [3] and [24]. Overall, the PB-RS duration during the Northeast monsoon was two factors shorter than during the Southwest monsoon. In contrast, the PB-RS duration between the Northeast and Southwest monsoons was much longer than during the two intermonsoon.

The longer duration of PB-RS of negative ground flashes during the Southwest monsoon compared to the Northeast monsoon, First Inter-monsoon and Second Inter-monsoon indicating the uprising process is affected by the seasons and locations [30], [31], [32], [33], [26]. The air rose into the unstable atmosphere forming a convective cell before the thunderstorms formed. The drier weather during the Southwest monsoon (dry monsoon) might cause the thunderstorm to form at higher altitudes (high cloud base) compared to other monsoons. As result, a higher PB-RS duration occurs.

4. Conclusion

The meteorological state could influence the lightning discharge characteristics. 83 data of negative CG lightning flashes recorded on the 6th to 11th of November 2019, with several parameter of lightning flashes under the influence of Northeast monsoon were analyzed, namely, the PB/RS ratio, PB-RS duration, pre-RS duration and stroke count. The arithmetic means were 27.70%, 27.74 ms, 28.92 ms and 4, respectively. Generally, the preliminary breakdown of negative CG flashes during the Northeast monsoon in the present study is weak and exhibit correlation with the PB-RS duration and stroke average. The stroke average of negative CG flashes increased with the decrease in the PB/RS ratio. The low strength of preliminary breakdown indicating a lower Low Positive Charge Region (LPCR), in which the initial breakdown process only requires low energy to break the LPCR. Compared to the previous study, the PB/RS ratio from the Northeast monsoon (present study), Southwest monsoons, First Inter-monsoon, and Second Inter-monsoon in the same region is considered low despite different monsoons of the data measured. In other words, preliminary breakdown in the lower latitude is relatively weak regardless of which monsoon the data measured. It implies that the meteorological of the tropic region state does not much influence the PB/RS ratio or the strength of the preliminary breakdown of negative ground flashes. However, the PB-RS duration shows an inconsistent result due to monsoon variation. The PB-RS duration of negative ground flashes was longer during the Southwest monsoon compared to the Northeast monsoon, First and Second Inter-monsoon. The inconsistency might be due to a higher cloud base during the Southwest monsoon compared to another monsoon. The present result induced our interest to investigate the temporal characteristic of the PBP train classification in negative ground flashes and see which classes fit well with the temporal characteristic of negative attempted leader (PBP process followed by no return stroke). A similar classification with the negative attempted leader may be used as a tool for the LPCR density indication. We also would like to see the classification pattern of negative ground flashes with other different monsoons supported with a large amount of data which will be discuss in the next publication.

Acknowledgements

I earnestly acknowledge the valuable opportunity by Zamalah Scheme (UTeM Malaysia) for fully funding my PhD research. Also, I would like to mention the measurement facilities, encouragement, and participation during our measurement campaign by the Kementerian Pelajaran Malaysia (MOE) and Pusat Pengurusan Penyelidikan dan Inovasi (CRIM) of Universiti Teknikal Melaka, Malaysia. The acquisition of the measurement equipment was granted by ERGS/2013/FKE/TK02/UTEM/03/01.

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