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Development of GIS-based Ground Flash Density and its Statistical Analysis for Lightning Performance Evaluation of Transmission Lines in Peninsular Malaysia

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ABSTRACT

Malaysia is one of the world's highest lightning regions, making it an ideal location for studying lightning activities, as they cause many power outages on overhead transmission lines. This study presents ground flash density (GFD) mapping and statistical analysis of lightning flash data in Peninsular Malaysia, which will be used to evaluate the lightning performance of transmission lines. Using Geographical Information System (GIS) software, the GFD map and lightning flash data for statistical analysis were extracted. MATLAB was then used to perform statistical analysis and obtain the probability of peak lightning current using the generalized extreme value (GEV) distribution. This study analyzed six years of lightning flash data from 2012 to 2017 recorded by the Lightning Location System (LLS) and used the Peninsular Malaysia base map from the Department of Survey and Mapping Malaysia (JUPEM). Results show that the GFD mapping approach effectively classifies GFD distribution and identifies areas with high lightning activity. 81% of 4,536,380 lightning flashes were negative polarity, with a higher mean peak current magnitude than positive ones. More lightning activity was observed during the Southwest Monsoon (June-September) and the first Inter-Monsoon season (April-May). Pahang had the most lightning flashes due to its large land area. The GFD map overlaid on the transmission line demonstrated how lightning performance on the transmission

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line can be assessed. These findings are useful for utility and protection engineers to improve the performance of transmission lines.

Keywords: Energy, GIS, ground flash density, lightning, statistical, transmission line

INTRODUCTION

Malaysia is a tropical country with a unique location and topography and is known for having high lightning activity, with about 40 strikes per square kilometer per year (Ab-Kadir, 2016; Islam et al., 2019; Rawi et al., 2017). It makes lightning-related outages a major concern for Tenaga Nasional Berhad (TNB), the main electricity provider. TNB has found that 50 – 60% of power outages in their system are caused by lightning (Abdullah et al., 2008). Lightning strikes on phase or shield wires or towers can result in high overvoltage and electrical discharges across insulator strings, causing faults, equipment damage, energy losses, and maintenance costs, especially on 500 kV transmission lines.

To mitigate the impact of lightning on the electricity supply, TNB Research Sdn. Bhd. installed a Lightning Location System (LLS), also known as a Lightning Detection Network (LDN), in Peninsular Malaysia in 1994 (Wooi et al., 2016). The LLS determines the coordinates of cloud-to-ground lightning strikes using the Time of Arrival (TOA) and Magnetic Direction Finding (MDF) principles (Abdullah et al., 2008). The original LLS had 7 lightning sensors but has been upgraded several times (Abdullah et al., 2008; Wooi et al., 2016), as shown in Figure 1. Figure 2 shows the location of the latest upgraded lightning sensors, denoted as 1, 2, 3, 4, and 5, in Peninsular Malaysia as of 2015.

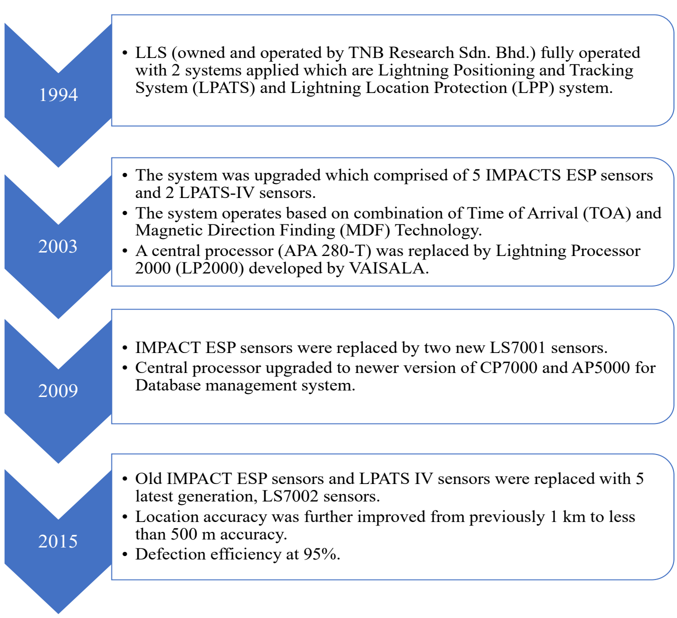

Figure 1. History of lightning location system in Peninsular Malaysia

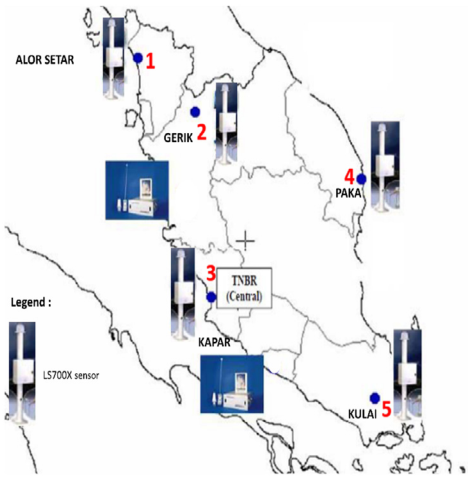

Figure 2. Location of lightning sensors in Peninsular Malaysia (Rawi et al., 2018)

Based on the information shown in Figure 1, the IMPACT ESP lightning sensors in the LLS use TOA and MDF methods to achieve the accuracy and efficiency requirements. With a location accuracy of less than 500 m and a detection efficiency of 95%, The system can detect lightning strikes up to 600 km. In addition, the sensors can reliably differentiate intra-cloud flashes and identify stroke polarity for flashes (Abdullah et al., 2008). The LLS equipment has undergone progressive upgrades to enhance its reliability, which has resulted in improved detection efficiency and location accuracy. Specifically, after a major upgrade in 2015, the LLS has been able to achieve a detection efficiency of more than 95% for cloud-to-ground (CG) lightning activities, with a location accuracy of up to 250 m (Abdullah, 2019).

The LLS is a tool to enhance power line performance and detect electrical failures in the power network. The information from the LLS is leveraged through the Fault Analysis and Lightning Location System (FALLS) software, which the LLS manufacturer developed.

A geographic information system (GIS) is a powerful tool for storing, manipulating, managing, processing, and visualizing geospatial data. Its analytical capabilities, including statistical analysis summaries, calculations, data interrelationships, buffer generation, and overlay function (ESRI, 2010; Javor et al., 2018), make it an even more powerful tool. This technology is widely used in science and industry, providing a foundation for mapping and analysis. With GIS, users can better understand patterns, relationships, and the context of geographic information, leading to better communication and enhanced efficiency, management, and decision-making. It is also observed that there is a growing trend in the use of GIS within the electrical sector (ESRI, 2010; Husain et al., 2012; Kakumoto et al., 2016; Kezunovic et al., 2015; Korir & Ngigi, 2015; Leite et al., 2019; Li et al., 2014; Lin & Xu, 2016; Rahman et al., 2020; Yatim et al., 2019; Yan et al., 2016; Zheng et al., 2021).

Several studies have shown the widespread use and popularity of GIS applications with lightning data (Ali et al., 2018; Biswas et al., 2020; Edirisinghe & Maduranga, 2021; Farukh et al., 2017; Hodanish et al., 2019; Javor et al., 2018; Mammadov et al., 2021; Mishra et al., 2022; Misztal & Siłuch, 2021). However, due to the limitation of information provided by the commercially available LLS, utility found it difficult to work, especially on finding the root cause and correlation of tripping with some other factors such as topography and weather data, thus limiting the research on utilizing GIS for transmission lines' lightning performance evaluation. Our research leverages GIS capabilities to create a GFD map and perform a statistical analysis of lightning flash data to evaluate lightning performance on transmission lines in Peninsular Malaysia and address the gap. The GFD map produced by GIS can also be utilized to analyze past lightning occurrences, known as historical attributes, to assess their impact on TNB assets.

Lightning Performance of Transmission Line

A transmission line is vital in an electricity power system network since it transmits and distributes electrical power along the line. A direct or indirect lightning strike on the transmission line may disrupt supply. TNB's statistics from 2001 to 2013 showed that between 39% and 61% of transmission line outages are caused by lightning every year in Peninsular Malaysia (Rawi et al., 2018).

Similar scenarios were also highlighted in other countries such as Brazil, Indonesia, and China, where line outages due to lightning were reported to be 50 to 70% for 230 kV lines, 66% for 150 kV lines, and 46% for 500 kV lines, respectively (Rawi et al., 2018; Warmi & Michishita, 2018). High outage rates due to lightning activities were also reported in Russia (He & Zeng, 2010). Thus, numerous studies have been conducted on improving the lightning performance of transmission lines. According to Rawi et al. (2018) and Warmi and Michishita (2018), lightning strikes on overhead transmission lines are affected by several factors such as lightning density, tower footing resistance (TFR), soil resistivity (SR), span length of transmission line, terrain characteristics, and monsoon seasons.

The lightning performance of a transmission line is often evaluated based on the flashover rate, expressed as the number of flashovers by 100 km per year. This flashover rate of the transmission line can be further broken down into two important parameters: back flashover rate (BFR) and shielding failure flashover rate (SFFOR). The BFR refers to the annual outage rate on a tower line length basis caused by a back flashover on a transmission line, while the SFFOR is the annual number of flashovers on a tower line length basis caused by shielding failures (IEEE Power Engineering Society, 1997).

GFD is one of the most important parameters that play a significant role in evaluating the exposure of a transmission line to lightning strikes and identifying potential areas for improvement in the line's design or maintenance. This parameter, coupled with others, will contribute towards the overall assessment of the lightning performance of the transmission line and reduce the risk of outages or damage caused by lightning strike failures, as highlighted in this discussion.

Ground Flash Density

The IEC 62858 standard defines ground flash density, N_g, as the number of cloud-to-ground flashes per kilometer squared per year (International Electrotechnical Commission, 2015). This term is often viewed as the primary descriptor of lightning activity (Ab-Kadir, 2016; Bouquegneau, 2014; Phillips, 2004). Ground flash density is one of the fundamental lightning parameters that provide the basis for estimating the frequency of lightning effects on the electrical system. This parameter can be measured from records of lightning flash counters (LFC) or LLS, and it can also be estimated using thunderstorm day or hourly records. Peninsular Malaysia was reported to experience GFD values as high as 28 flashes/km^2/year for about six years between 2004 and 2010 (Abdullah & Hatta, 2012).

Back Flashover Rate (BFR)

As highlighted earlier, GFD is an important parameter for evaluating the lightning performance of transmission lines. Back flashover is a well-known dominant cause of line tripping, and it occurs when lightning strikes the transmission tower or shield wire as opposed to the shielding failure, typically with the lightning current of less than 20 kA, which normally occurs due to failure of the shield wire to protect the phase conductor (Sardi et al., 2008). Therefore, analyzing back flashover is crucial to determine the effectiveness of a transmission line's design and maintenance in withstanding lightning strikes. It can be achieved by examining various parameters, such as the Back Flashover Rate (BFR).

The BFR of the line can be calculated using the Equation 1 (IEEE Power Engineering Society, 1997; Sardi et al., 2008),

$$BFR = 0.6 N_S P(I_C > I_f) \quad [1]$$

where,
Ns is the number of flashes to the line per 100 km per year and is given by Equation 2:

$$N_s = N_g\,(28 h_t^{0.6} + b\,)/10 \quad [2]$$

$P(I_C > I_f)$ is the cumulative probability of the critical back flashover current, I_c exceeding I_f is then given by Equation 3:

$$P(I_C > I_f) = 1/[1 + (\frac{I_C}{I_f})^{2.6}] \quad [3]$$

where N_g is GFD, h_t is the tower height, b is the distance between shield wires, and I_f is the median current of 31 kA.

Monsoon Seasonal Variation of Lightning Activity

Lightning activity in topical countries is reported to be related to the monsoon season (Dewan et al., 2022; Isa et al., 2021; Kamra & Kumar, 2021; Rawi et al., 2017, 2018; Wooi et al., 2016). Peninsular Malaysia has four monsoon seasons: the Northeast Monsoon (December to March), the Southwest Monsoon (June to September), and the two shorter periods of inter-monsoon seasons (April to May and October to November). According to Rawi et al. (2017), the most active periods of lightning are during the inter-monsoon season, which is from April to May and October to November.

Use Cases of Area and Lightning Flashes Data

Peninsular Malaysia is in Southeast Asia, between 1° to 7° North latitude and 99° to 105° East longitude, with a total area of 131,802 km^2. It comprises 11 states and 2 federal territories, grouped into four regions: Northern, East Coast, Central, and Southern. These regions are represented by labels (N1-N4, E1-E3, C1-C3, and S1-S3) in a map shown in Figure 3, and the land areas of each state and federal territory are listed in Table 1.

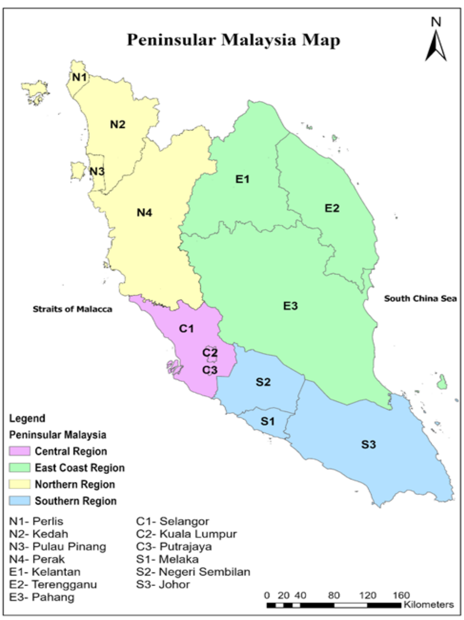

Figure 3. Map of study area replotted using ArcGIS software

Table 1
List of regions in Peninsular Malaysia with respective land areas of state and federal territories

Region	State	Area (km^2)
Northern Region	Perlis, N1	813
	Kedah, N2	9,471
	Pulau Pinang, N3	1,050
	Perak, N4	20,912
East Coast Region	Kelantan, E1	15,030
	Terengganu, E2	12,956
	Pahang, E3	35,944
Central Region	Selangor, C1	7,920
	Kuala Lumpur, C2	243
	Putrajaya, C3	49
Southern Region	Melaka, S1	1,655
	Negeri Sembilan, S2	6,653
	Johor, S3	19,106

This study utilized lightning flashes data provided by the LLS from the period of 2012 up to the year 2017. Although lightning flash data beyond 2018 was not accessible for this study, the data from this 6-year period, which comprises over 4 million records, is still valuable for analyzing lightning patterns and trends. This analysis is essential for developing an effective approach to mitigate lightning damage. Table 2 presents lightning flash data, including date and time, latitude and longitude in decimal degrees, discrimination (type of flash with polarity), and the peak current in kA.

Table 2
Sample of original lightning data

Date and Time	Lat (°)	Lon (°)	Discrimination	Peak Current (kA)
1/1/2017 2:27:17 AM	2.53043	103.686874	CG-	-13
1/1/2017 8:10:12 AM	5.69484	102.118904	CG-	-12
1/1/2017 8:38:46 AM	5.642838	102.334763	CG-	-40
1/1/2017 3:31:31 PM	2.689012	101.49189	CG-	-31
1/1/2017 3:33:55 PM	2.691144	101.486023	CG-	-54

Note. CG- means negative polarity cloud-to-ground flash

METHODOLOGY

The study used ArcGIS software version 10.8.2 to process the data collected from the LLS and the base map from the Department of Survey and Mapping Malaysia (JUPEM). The data was used for statistical analysis and to create a GFD map. The selected transmission line was then assessed using the created GFD map. The procedure for the study is summarized in Figure 4.

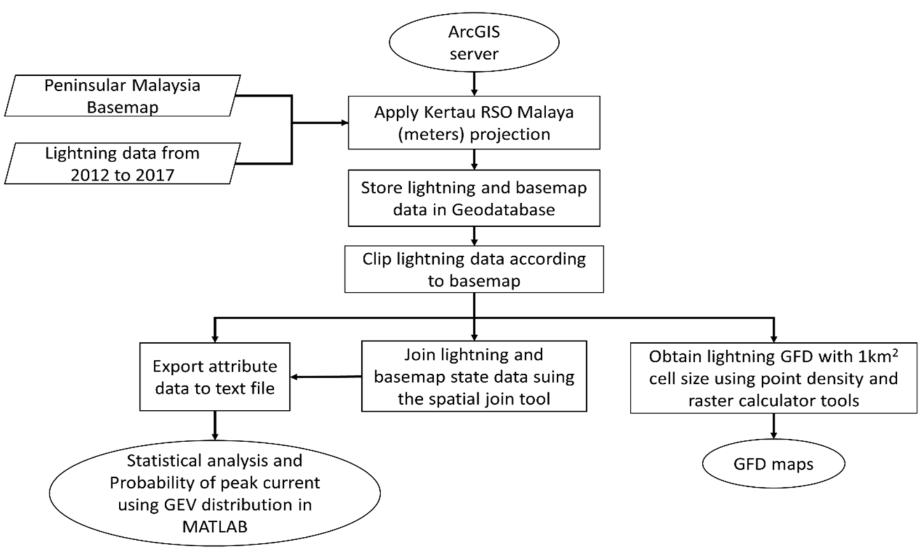

Figure 4. Procedure for statistical analysis and GFD maps

List of definitions for the terms used in Figure 4 are stated as the following (Chang, 2008; Xie et al., 2000; Yao, 2020):

- ArcGIS server serves GIS services such as maps, geodata, and image services. All services provide remote access to a geodatabase through the LAN, WAN, or Internet using an ArcGIS Server.

- Kertau RSO Malaya (Meters) is a projected coordinate system in Malaysia.
- A geodatabase is a set of structured information that can store, manage, and access data.
- Clip is a geoprocessing tool to extract input features overlaid on the clip features.
- Spatial data describes the location of spatial features on the Earth's surface based on a geographic coordinate system with longitude and latitude values.
- Attribute data describes an item or spatial feature in more detail and is stored in tabular format in the geodatabase.
- Spatial join is an analysis to append additional data based on the relative locations of the features in the two layers.
- Point density is a geoprocessing tool to calculate the density of point features around each output grid cell.
- A raster calculator is a geoprocessing tool for performing raster analysis using a Map Algebra expression.

The ArcGIS desktop software was required to create a geodatabase of the lightning and Peninsular Malaysia base map data imported into the software. This geodatabase, or "gdb." enabled users to design, store, and manage spatial and non-spatial data in a single environment. The raw lightning flash data were then clipped to the base map of Peninsular Malaysia to remove all lightning flash data that fell outside the study area.

Statistical Analysis and Peak Current Probability

As shown in Figure 4, the statistical analysis of the clipped lightning flashes data was conducted based on yearly and monthly frequency and seasonal variation during the monsoon. The analysis was performed separately for negative and positive flashes datasets with distinct characteristics. The statistical results for each dataset were calculated, including the maximum and minimum peak value (kA), median, mode, mean, and standard deviation. Additionally, the distribution of lightning flashes by state and region was included in the analysis using the spatial join tool available in ArcGIS software.

The lightning peak current probability density function (pdf) for each data set was also computed using the General Extreme Value (GEV) distribution to describe how often random lightning events happen. GEV distribution was used to represent the probability distribution of lightning flashes' peak current data, as shown in Figure 5. GEV is a family of continuous probability distributions developed within extreme values theory to combine Gumbel, Frechet, and Weibull families or specified as type I, II, and III extreme value distributions, respectively. The GEV distribution is commonly used for representing large-range data such as extreme weather. Previous researchers discovered that using GEV distribution for extreme data was practical, popular, and satisfactory for estimating extreme weather, such as the subtropical monsoon, extreme daily temperatures, and extreme rainfall (Shukla et al., 2010; Yendra et al., 2021).

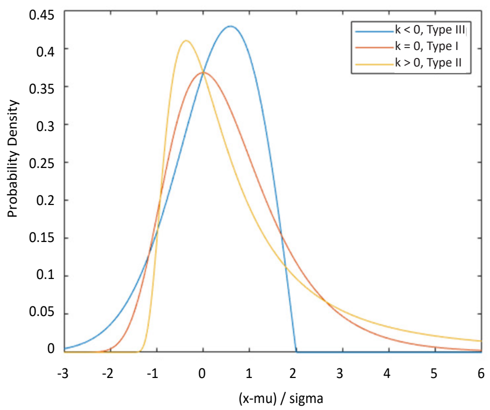

Figure 5. The generalized extreme value distribution (The MathWorks Inc., 2021)

GEV distribution combines the type I, II, and III extreme value distributions into a single family to allow for a continuous range of possible shapes. Type I distribution is normally a distributed curve without skewing, while type II and III are left-skewed and right-skewed, respectively. The curve distribution is filled with a location parameter, mu (μ), a scale parameter, sigma (σ), and a shape parameter, *k*. When $k < 0$, the GEV is equivalent to the type III extreme value. When $k > 0$, the GEV changes to the type II. As *k* approaches 0, the GEV becomes type I in the limit.

The probability density function of the GEV distribution can be expressed as Equation 4 (Provost et al., 2018).

$$f(x;\mu,\sigma,k)=\frac{1}{\sigma}\left[1+k\left(\frac{x-\mu}{\sigma}\right)\right]^{\left(-\frac{1}{k}\right)-1} exp\left\{-\left[1+k\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/k}\right\} \qquad [4]$$

Based on GEV distribution for the lightning data sets, the lightning peak current at 5%, 50%, and 95% occurrence probability for the entire Peninsular Malaysia were determined from 2012 to 2017. The MATLAB software implemented all the statistical analyses and probability peak currents of the lightning flashes method presented here.

Ground Flash Density Map of Peninsular Malaysia

The lightning data for the period 2012 to 2017, imported into the ArcGIS software, were separated into negative and positive polarity data sets. The GFD maps for Peninsular Malaysia were developed using these data sets and the ArcGIS tools of point density and raster calculator, with a 1 km x 1 km grid cell.

RESULTS AND DISCUSSION

Annual Variation and Statistical Analysis for Peninsular Malaysia

According to historical data of lightning events in Peninsular Malaysia, 4,629,881 lightning flashes (including both negative and positive polarities) were recorded by the LLS between 2012 and 2017. However, only 4,536,380 lightning flashes that landed on the land of Peninsular Malaysia were used in this study (i.e., removing flashes that landed in the sea). The summary of findings for the lightning flashes from 2012 to 2017 is shown in Figure 6, with ranges from 371,773 in 2014 to 830,568 in 2017 for negative polarity and from 27,219 in 2014 to 434,416 in 2017 for positive polarity.

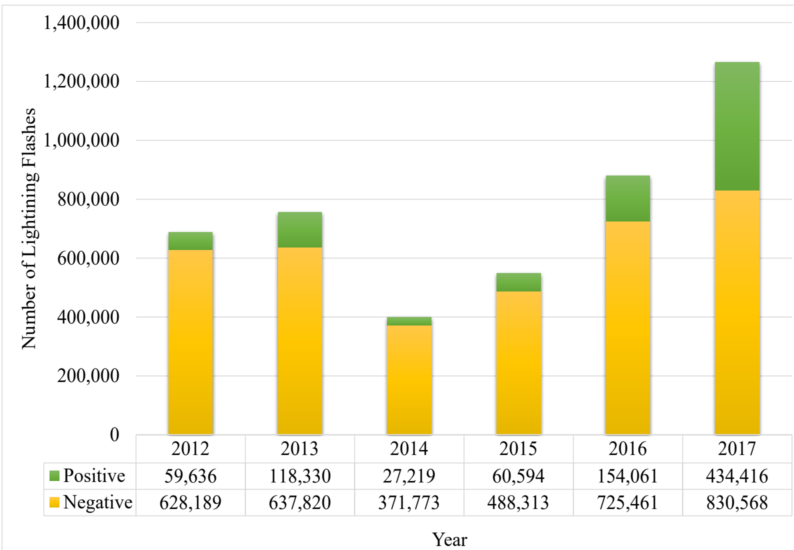

Figure 6. Annual variation of lightning distribution based on polarity from 2012 to 2017

The data shows that negative polarity lightning flashes contributed about 81% of the total flashes from 2012 to 2017, while the remaining were positive. Hence, it is evident that most lightning flashes in Peninsular Malaysia are negative. According to the yearly trend of positive polarity lightning flashes, the percentage of positive polarity lightning flashes has shown an increasing trend from 2014 to 2017, with the recorded percentages being 7%, 11%, 18%, and 34%, respectively. Furthermore, the results showed that there have been more lightning flashes over the last three years studied (i.e., 2015. 2016, and 2017). It could be attributed to the upgraded LLS system, where the detection efficiency and location accuracy improved to 95% and 500 m, respectively. Notably, the system can detect lightning strikes as far as 600 km from the sensors.

A comprehensive statistical analysis and peak current probability were carried out to present the lightning flashes from 2012 to 2017. Tables 3 and 4 show the statistical analysis and peak current probability of negative and positive lightning flashes. Within the 6 years, the highest magnitude of maximum peak currents observed for negative and positive lightning flashes were 508 kA (in 2016) and 427 kA (in 2017), respectively. In contrast, the

Table 3
Statistical analysis and lightning peak current probability of negative lightning flashes

Year	No. of Flashes	Min (kA)	Max (kA)	Median (kA)	Mode (kA)	Mean (kA)	Standard Deviation σ	Peak current Probability		
								95%	50%	5%
2012	628,189	3	290	18	12	21	15.67	6	18	52
2013	637,820	3	444	17	9	21	16.62	6	17	56
2014	371,773	3	221	20	13	24	16.06	8	20	56
2015	488,313	1	322	19	12	24	17.86	7	19	59
2016	725,461	1	508	18	6	22	18.03	5	18	57
2017	830,568	1	426	19	10	25	21.96	5	19	68
2012 - 2017	3,682,124	1	508	18	12	23	18.25	6	18	58

Table 4
Statistical analysis and lightning peak current probability of positive lightning flashes

Year	No. of Flashes	Min (kA)	Max (kA)	Median (kA)	Mode (kA)	Mean (kA)	Standard Deviation σ	Peak current Probability		
								95%	50%	5%
2012	59,636	3	186	8	6	11	10.47	4	8	25
2013	118,330	3	214	8	6	10	9.26	4	8	23
2014	27,219	3	245	9	7	13	13.40	5	9	31
2015	60,594	1	234	8	6	11	10.64	4	8	23
2016	154,061	1	253	6	5	9	8.99	3	6	19
2017	434,416	1	427	7	5	9	8.96	3	7	21
2012 - 2017	854,256	1	427	7	5	9	9.48	3	7	21

lowest magnitude of maximum peak currents observed for negative and positive lightning flashes were 221 kA (2014) and 186 kA (2012), respectively. The median peak current recorded for negative lightning flashes was 17 to 20 kA and 6 to 9 kA for positive lightning flashes. At the same time, the mean peak current recorded for negative lightning flashes was in the range of 21 to 25 kA and 9 to 13 kA for positive lightning flashes.

In previous studies conducted at various locations in Malaysia, several findings were reported, but the available information is limited for comparison. However, our study recorded lightning peak currents comparable to previous studies, as listed in Table 5. It is worth noting that these studies were based on different LLS, with detailed information on the SAFIR 3000 LLS (Chan & Mohamed, 2018; Johari et al., 2021). To further validate these findings, previous studies conducted along the same case line in Peninsular Malaysia using the same LLS system between 2004 and 2015 reported similar results (Rawi et al., 2018). These studies found median peak first stroke currents of 18 kA for negative flashes and slightly higher at 14 kA for positive flashes. Additionally, a high peak first stroke current of 378 kA was reported. It is important to note that the flash peak current corresponds to the peak current of the first stroke in the case of multi-stroke flashes (Diendorfer et al., 2014).

Table 5
Comparison of peak currents reported in previous studies for negative and positive lightning flashes

Year	LLS - reported Peak Currents								No. of Flash	Source
	Negative lightning flash				Positive lightning flash					
	Min (kA)	Max (kA)	Mean (kA)	Median (kA)	Min (kA)	Max (kA)	Mean (kA)	Median (kA)		
2012 – 2017	1	508	23	18	1	427	9	7	4,536,380	
2013 – 2015	1.9	139.6	13.6	13.6	10	86.7	14.2	12.8	572,282	Johari et al. (2021)
2015	1.80	140			1.9	100.5			201,296	Chan and Bin Mohamed (2018)

The analysis of the probability of lightning peak current for the same data set showed that 95% of the time, the peak current occurred in the range of 5 to 8 kA for negative lightning flashes and 3 to 5 kA for positive lightning flashes. Meanwhile, 50% of the time, the peak current was within 17 to 20 kA for negative lightning flashes and 6 to 9 kA for positive ones. Additionally, 5% of the time, the peak current was 52 to 68 kA for negative lightning flashes and 19 to 31 kA for positive ones.

Monthly and Monsoon Seasonal Variation for Peninsular Malaysia

Figure 7 reveals the monthly variation of lightning flashes during 6 years. The highest occurrences of negative lightning, with 616,860 flashes, were recorded in May, while the lowest negative lightning flashes, with 75,602 flashes, were observed in February, and for positive lightning flashes, the month of April had the most lightning, with 156,788 flashes while February had the fewest with 11,928 flashes.

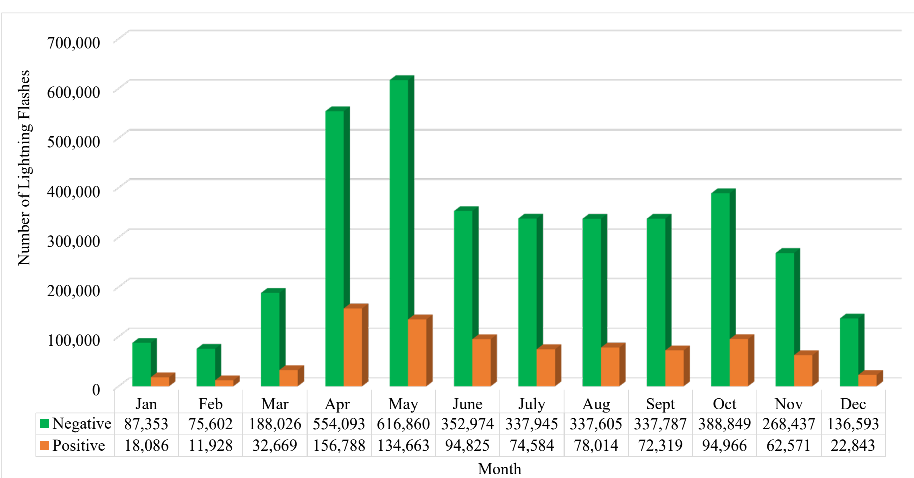

Figure 7. Monthly variation of lightning distribution based on polarity from 2012 to 2017

A statistical analysis of the lightning flashes from 2012 to 2017 for Peninsular Malaysia was carried out according to the monsoon season, as shown in Figure 8 and Table 6, respectively. It is observed that most lightning occurred during the Southwest Monsoon season from May to September, while the lowest was recorded during the Northeast Monsoon season from December to March. During the two Inter-Monsoon periods, from April to May and October to November, there were also higher lightning occurrences compared to the Northeast Monsoon season. These findings are consistent with previous studies that showed higher lightning flashes occurring during the two inter-monsoon periods (Rawi et al., 2017).

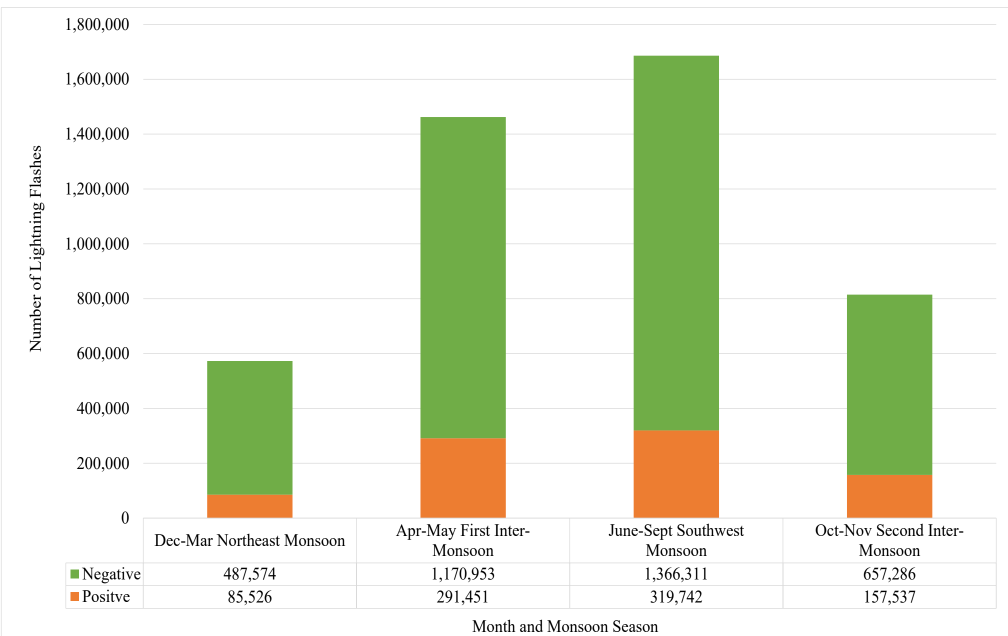

Figure 8. Monsoon season variation of lightning distribution based on polarity from 2012 to 2017

Table 6
Statistical analysis of lightning flashes and peak current probability for Peninsular Malaysia based on monsoon seasons

Negative Polarity											
Monsoon	Period	No. of Flashes	Min (kA)	Max (kA)	Median (kA)	Mode (kA)	Mean (kA)	Standard Deviation σ	Peak Current Probability		
									95%	50%	5%
Northeast	December – March	487,574	1	424	18	12	23.09	17.90	6	18	57
First Inter-Monsoon	April – May	1,170,953	1	348	18	10	23.09	17.90	5	18	56

Table 6 *(Continue)*

Monsoon	Period	No. of Flashes	Min (kA)	Max (kA)	Median (kA)	Mode (kA)	Mean (kA)	Standard Deviation σ	Peak Current Probability 95%	50%	5%
Negative Polarity											
Southwest	June – September	1,366,311	1	508	17	11	21.78	17.18	6	17	55
Second Inter-Monsoon	October – November	657,286	1	444	19	11	24.85	20.05	6	19	64
Positive Polarity											
Northeast	December – March	85,526	1	287	8	6	11.38	11.77	4	8	28
First Inter-Monsoon	April – May	291,451	1	427	7	5	9.11	9.11	3	7	21
Southwest	June – September	319,742	1	265	7	5	8.90	8.73	3	7	20
Second Inter-Monsoon	October – November	157,537	1	299	7	5	9.38	9.40	3	7	21

According to the monsoon seasonal variation, the highest maximum peak current of negative and positive lightning flashes observed were 508 kA (during the Southwest Monsoon) and 427 kA (during the first Inter-Monsoon), respectively. Table 6 shows little variation in the lightning peak current magnitude at 95%, 50%, and 5% occurrence probability when analyzed according to the monsoon seasons.

Lightning Occurrence Distribution by State in Peninsular Malaysia

According to the detected latitude and longitude, the frequency of lightning flashes was plotted on a graph based on state and region, as depicted in Figure 9. The state with the highest negative and positive lightning flashes was E3 (Pahang), with 916,286 and 267,255, respectively. In contrast, C3 (Putrajaya) has the least lightning flashes, with 4,609 negative and 376 positive lightning flashes. In Peninsular Malaysia, the state of Pahang has the largest area, as shown in Table 1, which results in a higher total number of lightning flashes, compared to Putrajaya state, which has the smallest area and the lowest number of lightning flashes.

Ground Flash Density Maps

The GFD maps for Peninsular Malaysia from 2012 to 2017 were produced separately for negative and positive polarity lightning. Figure 10 and Figure 11 compare the negative and positive GFD maps between 2012 and 2017, respectively. These results show that the hotspot areas for negative GFD are within the central region of Peninsular Malaysia (Kuala Lumpur and Selangor). From 2012 to 2015, the highest negative GFD was 45 flashes/km^2/

year. However, in 2016, the highest count increased to 62 flashes/km^2/year, and 73 flashes/km^2/year were reported to be the highest negative GFD in 2017.

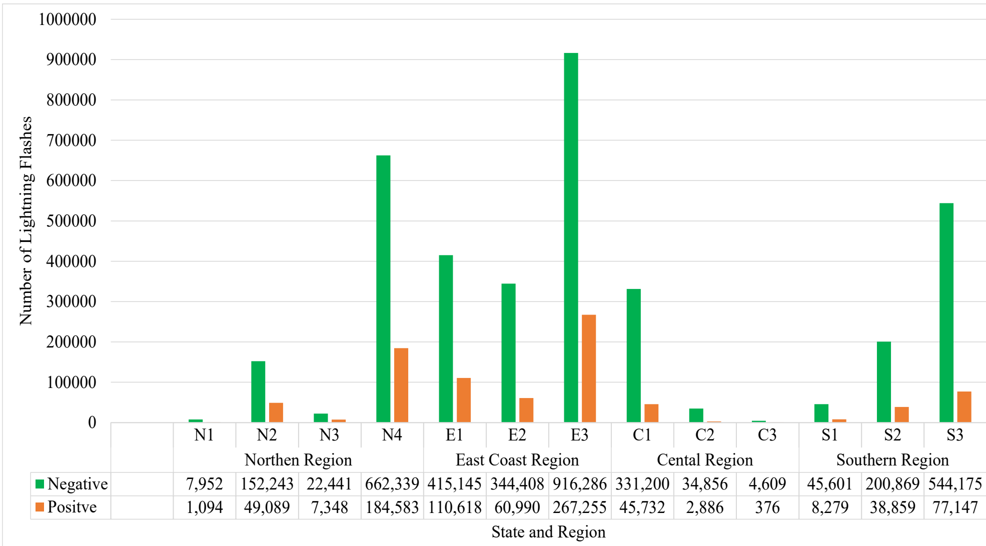

Figure 9. Lightning flash distribution in Peninsular Malaysia from 2012-2017 based on polarity and state

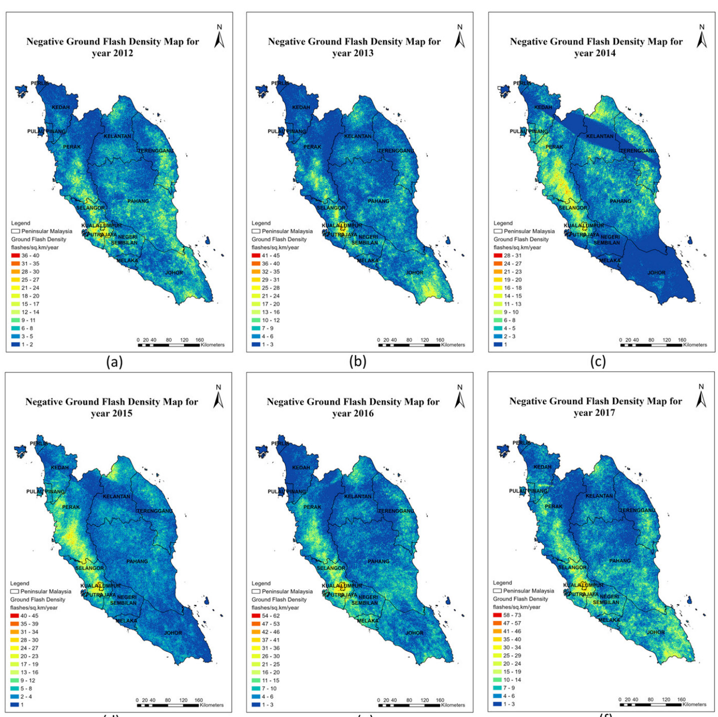

Figure 10. Negative ground flash density in Peninsular Malaysia. (a) 2012; (b) 2013; (c) 2014; (d) 2015; (e) 2016; (f) 2017

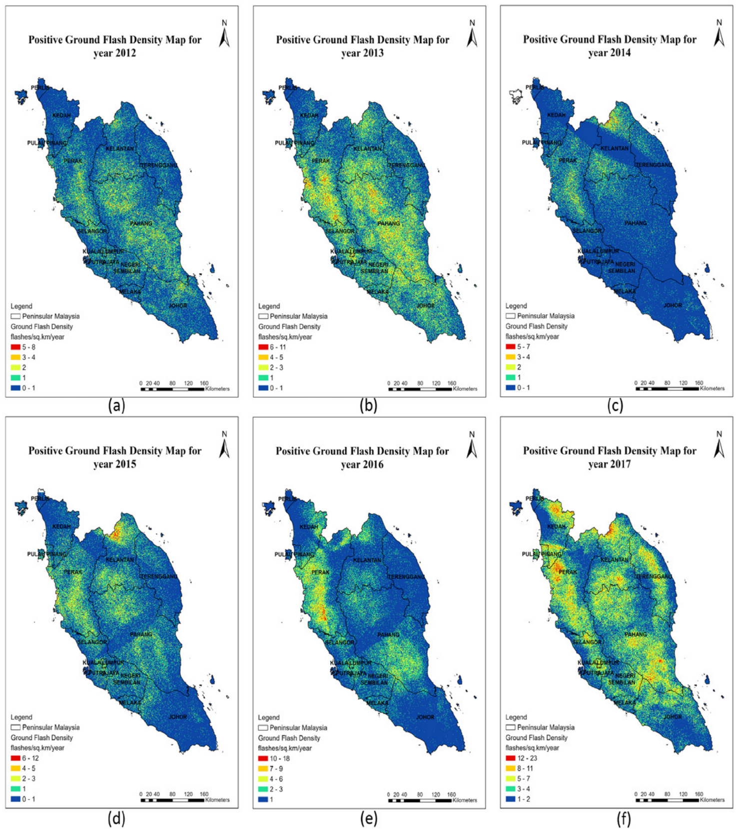

Figure 11. Positive ground flash density in Peninsular Malaysia. (a) 2012; (b) 2013; (c) 2014; (d) 2015; (e) 2016; (f) 2017

Due to the lower occurrences, the maximum recorded value of positive GFD is lower compared to the negative GFD. The positive GFD maps show that the hotspot area is within the Northern region (Perak) and East Coast regions (Pahang and Kelantan). The highest positive GFD of 23 flashes/km^2/year was observed in 2017, 28% more than the highest positive GFD recorded in 2016 and approximately double the highest positive GFD recorded in 2015. Based on the combined lightning flashes from 2012 to 2017, Figure 12 shows the average GFD map for Peninsular Malaysia. It is seen that the Central region is the main hotspot for negative GFD, with the highest average GFD of 38 flashes/km^2/year. Meanwhile, the Northern and East Coast regions are the hotspots for positive GFD, with the highest average GFD of 6 flashes/km^2/year.

Table 7 provides information on the specific locations in Peninsular Malaysia with the highest count of lightning flash density (GFD), determined from the GFD map created in ArcGIS. For instance, the highest count of negative GFD between 2012 and 2017 was recorded in Kuala Lumpur, with a value of 73 flashes/km^2/year in 2017. These 73 negative lightning flashes occurred within a 1 km square area, centered at 3° 04' 02.31" N latitude and 101° 43' 38.44" E longitude. The developed GFD map enables efficient geolocation of lightning incidents within Peninsular Malaysia, which is important for lightning protection design.

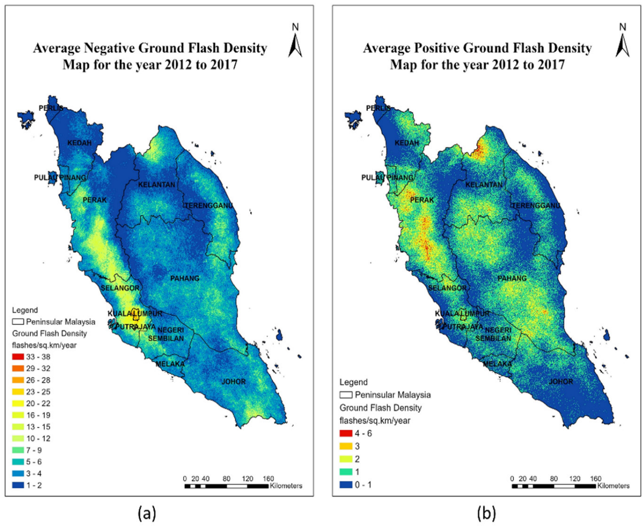

Figure 12. Average ground flash density in Peninsular Malaysia from 2012 to 2017. (a) Negative polarity; (b) Positive polarity

Table 7
Maximum GFD count and the location from the year 2012 to 2017 for both polarities

Year	Coordinates of the central point of a 1 km^2 grid cell (Latitude/Longitude)	State	Max Negative GFD	Coordinates of the central point of a 1 km^2 grid cell (Latitude/ Longitude)	State	Max Positive GFD
2012-2017	N 3° 09' 27.67"/ E 101° 42' 00.50"	Kuala Lumpur	38	N 5°52' 18.40"/ E 101° 58' 24.05015489	Kelantan	6
2012	N 2° 57' 31.89"/ E 101° 45' 48.88	Selangor	40	N 4° 07' 32.91"/ E 101° 49' 58.44" & N 2° 24' 01.64"/ E 103° 30' 33.81"	Pahang & Johor	8
2013	N 3° 10' 32.48"/ E 101° 39' 50.77"	Kuala Lumpur	45	N 4° 31' 12.37"/E 100° 40' 41.80"	Perak	11
2014	N 4° 19' 20.96"/ E 101° 2' 22.12" & N 3° 57' 41.33"/ E 101° 16' 29.53"	Perak	31	N 5° 47' 57.39"/ E 101° 54' 04.49" & N 4° 20' 58.76 / E101° 02' 54.22"	Perak & Kelantan	7
2015	N 3° 13' 47.51"/ E101° 37' 40.72"	Selangor	45	N 5° 48' 30.88"/ E 102° 01' 39.57"	Kelantan	12
2016	N 3° 09' 27.44"/ E 101° 40' 23.32"	Kuala Lumpur	62	N 4° 03' 04.84"/ E 101° 05' 40.02"	Perak	18

Table 7 *(Continue)*

Year	Coordinates of the central point of a 1 km² grid cell (Latitude/Longitude)	State	Max Negative GFD	Coordinates of the central point of a 1 km² grid cell (Latitude/ Longitude)	State	Max Positive GFD
2017	N 3° 04' 02.31"/ E 101° 43' 38.44"	Kuala Lumpur	73	N 5° 04' 52.38"/ E 100° 45' 58.27"/ & N 5° 50' 07.90"/ E 101° 56' 14.26"	Perak & Kelantan	23

Application of GFD Map on Transmission Line Performance Evaluation

The lightning exposure of a selected transmission line can be determined by overlaying the GFD map onto the transmission line and focusing on the lightning flashes data within a 5-km buffer radius of the transmission line's centerline. Figure 13 shows an example of the lightning exposure on a 500 kV transmission line A-B.

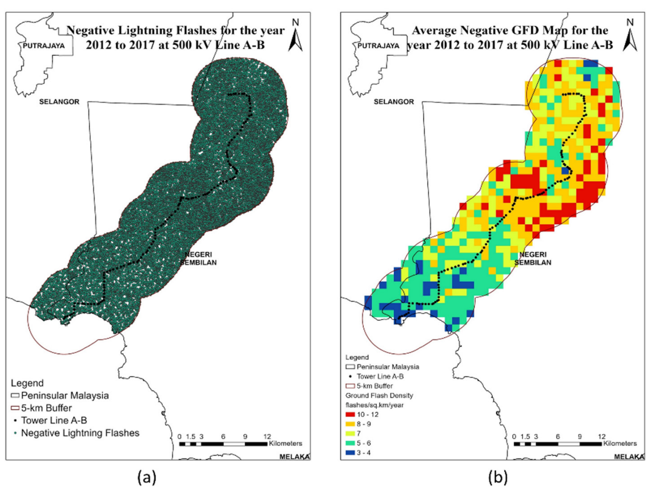

Figure 13. Lightning exposure within a 5-km buffer from the 500 kV Line A-B from 2012 to 2017. (a) Negative lightning flashes recorded data; (b) Negative GFD map

Between 2012 and 2017, the transmission line was exposed to 23,529 negative lightning flashes within a 5-km buffer along the line. The average negative GFD within this buffer was recorded between 3 and 12 flashes/km²/year, with peak current ranging from 2 kA to 278 kA. As demonstrated in Figure 13 (b), the towers located in areas with higher lightning GFD values pose a higher risk of lightning related faults. Therefore, it is crucial to prioritize on monitoring and maintaining these areas. This concern has been previously addressed by other researchers (Hatta et al., 2019; Rawi et al., 2018; Tofani et al., 2018).

Details related to these towers, such as TFR and SR values, ground elevation, and the historical lightning-related tripping incidents, can be extracted by utilizing the GFD map developed in ArcGIS software, as demonstrated in Figure 14. The analysis of the BFR value involved applying Equation (1) to (3). Notably, Figure 14 reveals a crucial parameter for BFR calculation, specifically the average negative GFD, N_g, value of 10 flashes/km^2/year. This information is essential for calculating the BFR value and serves as key metric for evaluating the lightning performance of transmission lines, as highlighted by Ardila et al. (2023).

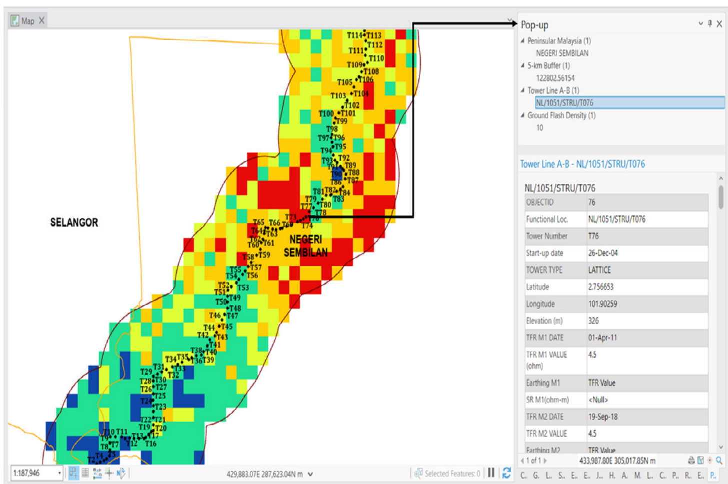

Figure 14. Negative GFD and tower details at one of the towers along the 500 kV Line A-B

By assuming $I_c = 248\ kA$ and given $h_t = 45\ m \;\; b = 2$ m

$$P(I_C > I_f) = 1/[1 + (\frac{248}{31})^{2.6}] = 4.4671 \times 10^{-3}$$

$$N_s = N_g(28h_t^{0.6} + b)/10 = 276.84$$

$$BFR = 0.742 \text{ flashovers/100 km/year}$$

It means that 0.742 back flashovers are to be expected in a year for 100 km.

Therefore, the GFD map developed for transmission lines can evaluate their performance, monitor them, and design appropriate lightning protection systems. This information can help identify high-risk areas and design lightning protection systems, such as installing shield wire, reducing tower footing resistance, increasing insulation levels, and installing arresters to reduce the impact of lightning strikes (Ahmed et al., 2023; IEEE Power Engineering Society, 1997). By implementing lightning mitigation measures, routine maintenance, and inspections of transmission lines, their reliability can be significantly improved.

CONCLUSION

In this study, GFD mapping and statistical analysis were used to assess the impact of lightning on transmission lines. The findings provide valuable information for power companies and researchers. Results show that 81% of the 4,536,380 lightning flashes were caused by negative polarity lightning, which severely impacts transmission lines. The annual lightning flashes increased from 2015 to 2017 due to improved detection by the LLS network after an upgrade in 2015.

The mean peak current of negative lightning flashes was higher than that of positive flashes, in the range of 21 to 25 kA and 9 to 13 kA, respectively. The 95% probability of occurrence for negative and positive lightning flashes was 5 to 8 kA and 3 to 5 kA, respectively. More lightning activity was recorded during the Southwest Monsoon (June to September) and first Inter-Monsoon (April to May) compared to other seasons. The state of Pahang had the most lightning flashes due to its large land area.

The results from the developed GFD map indicate that the Central region was the major hotspot for negative GFD and that the hotspots for positive GFD were in the Northern and East Coast regions. The highest negative and positive GFD were recorded in 2017 at 73 flashes/km^2/year and 23 flashes/km^2/year, respectively. Over the six years studied (2012–2017), the highest average negative and positive GFD were 38 flashes/km^2/year and 6 flashes/km^2/year, respectively.

To summarize, this paper outlines a method for conducting a statistical analysis of lightning flashes and creating GFD maps using GIS to assess lightning performance on transmission lines. For future work, it is recommended to incorporate meteorological data better to understand correlations between lightning distribution and transmission line performance.

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