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ANALYSIS OF APPROACHES FOR ESTIMATING THE LIGHTNING PERFORMANCE OF OVERHEAD TRANSMISSION LINES

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Purpose. A review of the current literature, regarding the existing approaches used to estimate the lightning performance of overhead power lines, was performed. A review of available lightning activity data over India was also performed. **Methodology.** The electro-geometrical model was chosen to analyze the lightning performance of overhead power lines. International normative documents and national standard were used to highlight the main parameters that should to be paid main attention to when estimating lightning performance of overhead power lines. **Results.** Presently, approaches from IEEE and CIGRE guides can be used for analysis of statistical distributions of lightning current parameters. Further studies are required on thunderstorm days, ground flash density and current parameters statistical distributions for different locations, which will be supportive in performing analysis for Indian power lines. **Originality**. To graphically analyze the shielding failure mechanism with a help of electro-geometric model, the sketch of real 220 kV double-circuit transmission line tower was used. Using electro-geometric model it was graphically shown how downward lightning leader that propagate from thunderstorm cloud toward ground can finish its path on the overhead shield wire, phase conductor or ground plane. **Practical value**. Available data on lightning activity over different parts of India are still not enough complete. It is of great importance to obtain reliable statistical data on thunderstorm characteristics in the area of the studied power line route. Measurement techniques based on satellites have limitations in obtaining ground flash density values. Thus, for India there is a need in development of modern lightning detection networks and related studies on lightning characteristics. **Conclusions**. Future efforts should be focused on obtaining not only the positions and number of lightning strikes to the overhead power line, and calculation of lightning flashover rate parameters, but also the statistical distributions of lightning current values and related overvoltage parameters at the overhead wires and different phase conductors. References 21, figures 4.

Key words: lightning performance, overhead transmission line, lightning flashover.

АНАЛІЗ ПІДХОДІВ ДО ОЦІНКИ БЛИСКАВКОЗАХИСТУ ПОВІТРЯНИХ ЛІНІЙ ЕЛЕКТРОПЕРЕДАЧ

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Було виконано огляд сучасної літератури щодо існуючих підходів, що використовуються для оцінки блискавкозахисту повітряних ліній електропередач. Крім того, було проведено огляд наявних даних щодо активності блискавок над Індією. Для аналізу блискавкозахисту повітряних ліній електропередач була обрана електрогеометрична модель. Для виділення основних параметрів, яким необхідно приділити основну увагу при оцінці грозозахисту повітряних ліній електропередач було використано міжнародні нормативні документи та національні стандарти. На даний час для аналізу статистичних розподілів параметрів струму блискавки можна використовувати підходи з посібників IEEE та CIGRE. Потрібні подальші дослідження щодо грозових днів, щільності ударів блискавок на одиницю земної поверхні та статистичних розподілів параметрів струмів для різних місць, які допоможуть у проведенні аналізу для індійських ліній електропередач. Для графічного аналізу механізму неспрацювання грозозахисного тросу за допомогою електрогеометричної моделі було застосовано ескіз реальної дволанцюгової опори лінії електропередачі 220 кВ. Використовуючи електрогеометричну модель, було графічно показано, як низхідний лідер блискавки, який розповсюджуються в напрямку від грозової хмари до землі, може закінчити свій шлях ударом в грозозахисний трос, фазний провідник або поверхню землі. Наявні дані про активність блискавки в різних частинах Індії ще недостатньо повні. Велике значення має отримання достовірних статистичних даних про характеристики блискавки в районі траси досліджуваної лінії електропередачі. Методи вимірювання на основі супутників мають обмеження в отриманні значень щільності ударів блискавок на одиницю земної поверхні. Таким чином, для Індії існує потреба в розробці сучасних мереж виявлення блискавок і пов'язаних з ними дослідженнях характеристик блискавки. Подальші зусилля мають бути зосереджені на отриманні не тільки положень і кількості ударів блискавки в повітряну лінії електропередачі та розрахунку параметрів грозових перекриттів, а й статистичних розподілів значень струму блискавки та відповідних параметрів перенапруги на грозозахисних тросах та різних фазах.

Ключові слова: блискавкозахист, повітряна лінії електропередачі, перекриття внаслідок блискавки.

PROBLEM STATEMENT. Overhead transmission line failures are most commonly caused due to lightning strokes to either an overhead ground wire or a phase conductor. This appears to be a significant characteristic for design and protection of overhead transmission lines. The lightning performance of an overhead transmission line is typically evaluated by the number of lightning flashovers per 100 kilometers per year or per 100 miles per year [1]. The lightning performance of the power line (lightning flashover rate) is the sum of the following terms [2]: direct strikes flashover rate; nearby strikes flashover rate; flashover rate from failures of protective equipment. The estimation of transient overvoltage events requires knowledge on lightning discharge currents statistical distributions for all conductors of overhead power line separately, both for direct and indirect strikes. The modern procedures of power lines lightning performance estimations usually include: generation of random numbers (Monte Carlo methods) to obtain input parameters of the lightning stroke and the overhead power line (phase voltages) having random nature; application of an incidence model to determine the point of impact of every lightning stroke; calculation of the transient overvoltage generated by each stroke, depending on the point of impact; and computation of the lightning flashover rate parameters [3, 4]. Among these parameters are: the lightning flashover rate (LFOR) of a transmission line, the back flashover rate (BFOR) and the shielding failure flashover rate (SFFOR) [3]. The BFOR is the annual outage rate on a tower-line length basis caused by back flashover on a transmission line and the SFFOR is calculated as the annual number of flashovers on a tower-line length basis caused by shielding failures [1]. Moreover, the shielding failure rate (SFR) is the annual number of lightning events on a tower-line length basis, which bypass the overhead ground wire and hit directly the phase conductor. This lightning event may or may not result in a flashover. There are a lot of scientific and technical publications and guides on the topic, recommendations are varied in different countries, and the issue is continuously developing [5, 6]. Thus, for performing the discussed estimation of lightning performance of overhead transmission or distribution power lines it is important to overview existing approaches.

The aim of this work is to overview the existing approaches used for estimating lightning performance of overhead power lines.

MATERIAL AND RESULTS. The conventional existed methods for assessing lightning performance of overhead lines are based on analytical methods where the overvoltage equation computation must be completed by means of numerical methods in which their accuracy becomes in some way questioned as the integrations are needed to solve the corresponding equations. Traditionally, the electro-geometric model (EGM) based on a concept of striking distance has been used for many years to determine the estimated maximum lightning current peak value that can bypass the overhead shield wire and hit directly the phase conductor [1, 7, 8]. It can be also applied for computation of the number and position (point) of the lightning incidents. The idea of EGM is that it considers the downward lightning leader (typically negative), while neglecting events when the upward leader (typically positive) is initiated first from the structure [2, 3]. The EGM-based analysis depends on lightning current parameters, and lightning and striking distance relations. The statistics of the stroke-current distribution is needed to compute the SFR. According to [1], the cumulative probability $P(I)$ that the lightning current will exceed the given value I is determined by equation (1).

$$P(I) = \frac{1}{1+\left(\frac{I}{31}\right)^{2.6}} . \qquad (1)$$

In formula (1) probabilities $P(I)$ are expressed as real numbers ranging from 0 to 1; peak value of lightning current I is expresses in kA. Median current value of first return stroke is 31 kA. Formula (1) is applied for peak current values of first return stroke in the interval between 2 and 200 kA [1]. This cumulative statistical distribution of lightning peak currents, giving probability of cases exceeding given lightning current peak value is shown in Fig. 1.

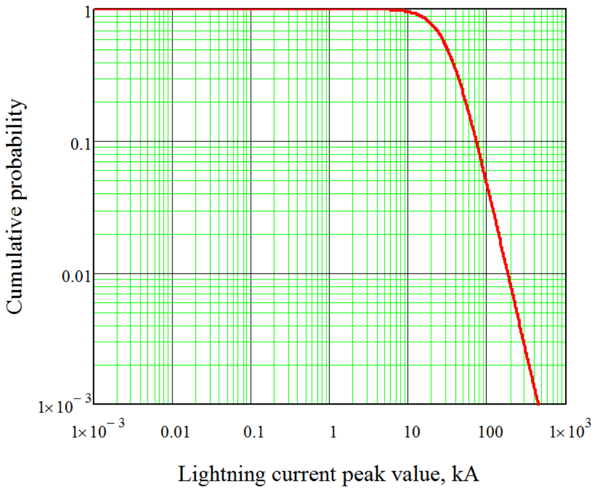

Figure 1 – Cumulative distribution of lightning current peak value in logarithmic scale on both axes

According to [1], the SFR is obtained by integrating the exposure width $D_c(I)$ for each current times the probability of that current on each side for all possible currents up to maximum current value, which determined by equation (2).

$$SFR = 2N_g L \int_0^{I_{max}} D_c(I) f_1(I) dI . \qquad (2)$$

In formula (2): N_g is the number of lightning flashes to ground per square kilometer per year; L is the length of overhead power line (usually calculations are performed for 100 km of line length) and $f_1(I)$ is the density function of the lightning current amplitude distribution [1]. The value of maximum possible current I_{max} is limited by power line geometry and determined from EGM approach.

According to [1], if measurements of the ground flash density for the area under consideration are not available, then this parameter can be estimated with a help of common formula:

$$N_g = 0.04 T_d^{1.25} . \qquad (3)$$

In formula (3), T_d is number of thunderstorm days for area under consideration.

According to [1, 9], the striking distances to conductor (r_c) and to ground (r_g) can be estimated through the rolling sphere radius r. For simplicity it is often assumed that the two radii are equal:

$$r_c = r_g = r = 10 I^{0.65}. \quad (4)$$

Assumption defined by formula (4) corresponds to the rolling sphere version of EGM.

At higher power line voltages, a shielding failure with a low peak value lightning current may not necessarily result in a flashover [10]. The minimum or critical lightning current value I_c required for flashover can be estimated by following equation [1, 10]:

$$I_c = \frac{2CFO}{Z_{surge}}. \quad (5)$$

In formula (5): CFO stands for the critical flashover voltage and Z_{surge} is the conductor surge impedance under presence of corona [1, 10]. CFO denotes the peak value of the impulse wave which, under specified conditions, results in a flashover through the surrounding medium on 50% of the applications [1].

Formula (6) represents the number of shielding failures at the power line having length L per unit time (typically per year) that results in flashovers (SFFOR) [1, 10]:

$$SFFOR = 2 N_g L \int_{I_c}^{I_{\max}} D_c(I) f_1(I) dI. \quad (6)$$

The idea of EGM assumes that the downward leader channel is approaching the ground and that the lightning flash will strike the tower if its prospective ground termination point lies within the attractive radius r_c, as it shown for common 220 kV power line tower in Fig. 2.

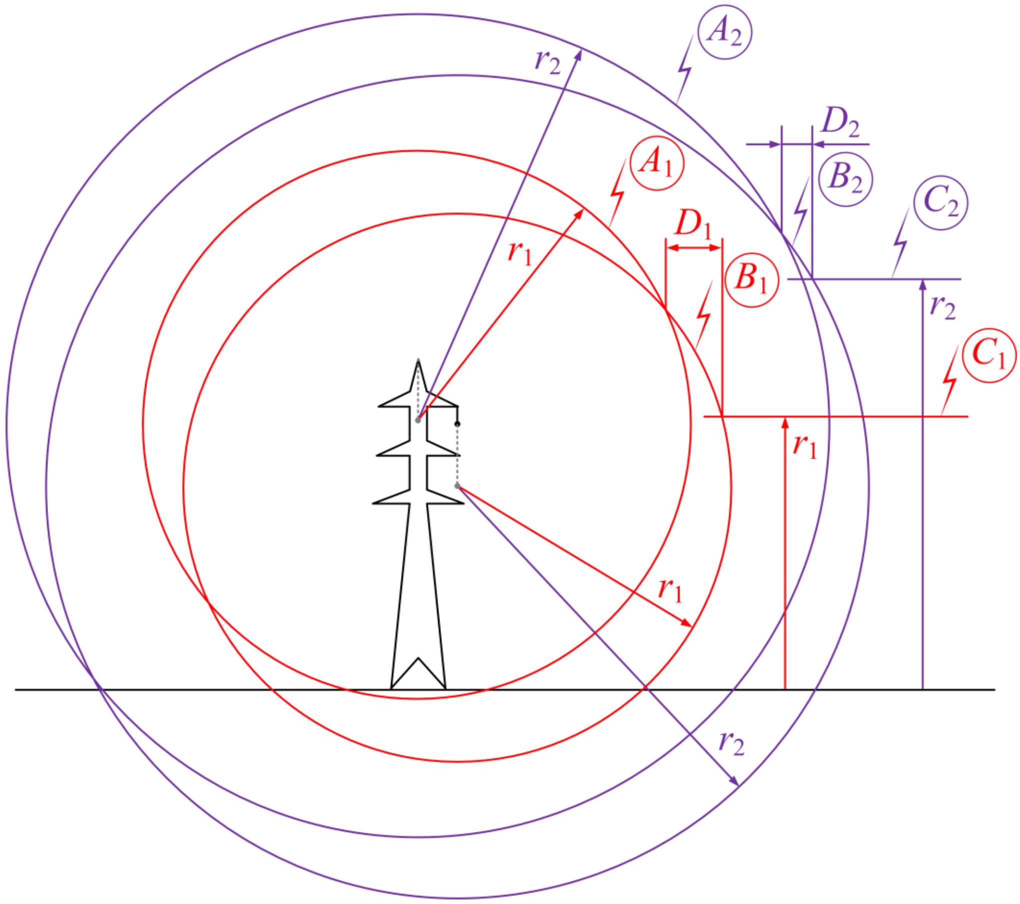

Figure 2 – Application of electro-geometric model for 36 m tall double circuit 220 kV power line tower (visualization for overhead shield wire and one phase conductor)

The dotted lines show the sagging of the conductors of power line. According to electro-geometric model concept, downward lightning leaders that propagate from thunderstorm cloud toward ground and marked as A_1 and A_2 in Fig. 2, will finish their path on the overhead shield wire. Lightning leaders marked as B_1 and B_2 will finish their path on the phase conductor. These two flashes denoted by lightning symbols touch the uncovered area, the area, which is not protected by overhead shield wire. Rest of lightning leaders marked as C_1 and C_2 will finish their path on the ground plane.

In Fig. 2 visual representation of the lightning shielding failure arc used in EGM is drawn for two peak current magnitudes I_1 and I_2, when $I_1 < I_2$. Striking distances and exposure width for first current are denoted as follows:

$$r_c^{(1)} = r_g^{(1)} = r_1; \; D_c^{(1)} = D_1.$$

Analogously, for second current:

$$r_c^{(2)} = r_g^{(2)} = r_2\,;\; D_c^{(2)} = D_2\,.$$

With the increase of lightning current I, the exposure width D_c (and lightning shielding failure arc) of transmission lines will decrease gradually, as shown in Fig. 2, where $D_1 > D_2$. The attractive radius depends on several factors, such as: charge of the downward leader, its distance from the structure, type of structure (vertical mast or horizontal conductor), structure height, nature of the terrain (flat or hilly), and ambient ground field due to cloud charges [2].

When lightning hits an overhead phase conductor, the current large magnitude and its high-frequency nature are causing voltage surges propagating in both directions from the point of a lightning strike. Since overhead transmission lines are usually shielded by several overhead ground wires, lightning overvoltage can be caused by strikes to either a shielded wire or a phase conductor. This type of strike produces a flashover if the back flash overvoltage exceeds the insulator electrical strength. Overvoltage transients caused by a shielding failure, are more dangerous, while their frequency is low due to shielding provided by overhead shield wires [1, 2]. It is considered that if a direct lightning strike occurs on a power line, then in the vast majority of cases this will cause insulation flashover [11].

Though, observations show that many of the lightning-related outages of low-insulation lines happened due to lightning that hits the ground in proximity of the power line [12, 13]. The induced overvoltage transients are not much considered for transmission lines as compared to distribution lines due to large voltage insulation levels and heights of the towers.

Some of the recent models such as upward connecting leader, leader progressive model, leader inception and propagation model are based on simulations of upward connecting leader development. According to leader progressive model (LPM) [14], the flashover mechanism comprises of three stages: corona inception, streamer propagation and further leader propagation. The total flashover time is the addition of the corona inception time, the streamer propagation time and the leader propagation time [14]. The snapped data of natural lightning discharge exposes that the lightning leader has a noticeable effect of branching and tortuosity, which can be defined by fractal mathematics [9]. Hence the fractal approach model can be used in analyzing the progression patterns of leaders.

A self-consistent leader inception and propagation model (SLIM) also can be applied to study lightning attachment to different grounded structures, which include conductors and towers of power transmission and distribution lines [5, 14]. In the model, the corona inception is estimated by using the well-known streamer inception criterion; however the total charge in second or successive corona burst determines the transition from streamer to leader [5]. SLIM, which is based on the physics of the transition from streamer to leader, dynamically evaluates the inception of ascending positive leaders, taking into account the change in time of the electric field created by descending stepped leaders and the space charge associated with streamers and interrupted leaders formed before that the stable leader inception takes place [5].

The estimation of lightning performance parameters for the given power line is carried out by a stepwise procedure which is considering the available data and approach of study. This stepwise procedure includes the following items, listed below.

1) Collection of data related to lightning activities from locations under study: thunderstorm days T_d, thunderstorm hours T_h, power line structure parameters, voltage level, grounding resistance).

2) Estimation of lightning parameters: ground flash density N_g, probability distribution of return stroke current peak values $P(I)$, probability distribution of current steepness values $P(S)$, etc.

3) Action of strikes on the overhead power line (direct/indirect, shield wire and phase conductors, induced overvoltage transients, positive or negative).

4) Application of the incidence model to determine point of lightning impact.

5) Analysis by EGM and/or LPM approach, additional leader models on the generated data.

6) Calculation of interception points, currents and overvoltage distributions.

7) Calculation of lightning flashover rate parameters SFR, LFOR, BFOR, SFFOR.

Lightning performance of overhead power lines always includes analysis of related overvoltage transients and their comparison to characteristics of high-voltage insulation. Lightning surges at power lines are fast-front transient voltages mainly caused by the impact of lightning strikes directly to lines and to ground or other objects in their vicinity. Calculation of lightning performance of overhead power lines is based on consideration of thunderstorm activity and lightning occurrence data and statistical distributions of lightning parameters. These calculations can be done according special procedures, varied in some countries, for example, according to documents [1, 15]. Since authors are interested to perform lightning performance analysis for Indian power lines, it is required to perform overview available data on lightning activity over India.

India has a wide variety of climate zones such as hot-dry coastal, island, hilly, interior and oceanic [16]. Lightning safety for human, buildings, structures and air navigation requires the knowledge on thunderstorm activity in different parts of India and related lightning characteristics that becomes all the more essential. In Indian topology, the climatic activity is studied on basis of longitude and latitudes, regions, and seasonal variations. The Indian annual thunderstorm days count is ranging from 1 to 103 as recommended by national standard [17]. In [18] it was found that the ground flash density N_g for conditions of India can be calculated from the formula (7).

$$N_g = 0.026 T_d^{1.274}\,. \qquad (7)$$

Above expression derived for use under conditions of India instead of generalized expression (3).

The measurement of lightning data was done in past using radars and weather stations located in different ranges of distances. After the invention of satellite technology, the data were recorded with the help of remote sensing centre. The advanced progress in optical and image processing field resulted in the measurement task become simpler. The thunderstorm data were obtained from Indian observatory stations and optical transient detector system (OTD). The combination of OTD and lightning imaging sensor (LIS) on board of the tropical rainfall measuring mission (TRMM) satellite are used in recent studies. The calculation range are based on optical detection, hence, it is required to have regional database to relate the optical data with the ground measured values [16, 19].

The geographical areas of Eastern region and Western region of India, which are demarcated by the 79°E longitude line drawn from south to north were selected for study in [16, 19]. The data from these articles were additionally analyzed by authors. The corresponding illustrations for the Western region are shown in Fig. 3, and for the Eastern region are shown in Fig. 4.

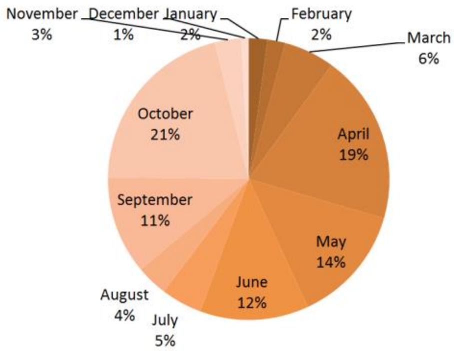

Figure 3 – Percentage of lightning flash count over Western region

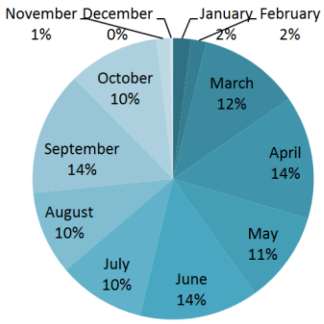

Figure 4 – Percentage of lightning flash count over Eastern region

The annual mean of lightning flash count of Eastern region is noticeably higher than that of the Western region in monsoon season (lasts from June to September). The winter season shows almost same amount of variation. Only during the post-monsoon season (lasts from October to December), the flash count of Western region is higher than that over Eastern region. The changes in thunderstorm activities are remarkable in both regions. The seasonal thunderstorm days have significant values in pre-monsoon and increasing more in monsoon. For winter the values are comparatively lesser as compared to total count.

More recent study of lightning activity was performed over the Arabian Sea and the Bay of Bengal of Indian coastal region using monthly satellite-based lightning flash count grid data for a 10-year period [20]. It was found the annual variation in flash rate density with the first peak occurring in May and the second in October. The amplitude of the first maximum (May) observed to be 11.5 for the Arabian Sea and 28 for the Bay of Bengal. The second maximum (October) was observed as 9 for the Arabian Sea and 10 for the Bay of Bengal. The lightning activity shows a minimum range of flash rate density during winter months [20].

The lightning activity data are mainly gathered with the meteorological radars and ground stations, optical transient detector (OTD) system, lightning imaging sensor (LIS), and lightning detection networks (LDN). From the reviewed observations it can be resolved as follows. Analyzing data obtained from LDNs, such as [21], it can be seen that N_g for the Eastern region is in the range of 4 to 32 and in some areas of the North-Eastern region it is raising up to 64. For the Western region, it has variation from 4 to 16 in South-West coast and varies from 2 to 16 in the Arabian Sea.

From some optical studies, the annual mean of lightning flash count and ground flash density of Eastern region is found larger by 20% than that of the Western region. In monsoon season it is twice larger. The calculation of ground flash density N_g from satellite optical observations is not always accurate and requires additional validation for different regions.

CONCLUSIONS. Available data on lightning activity over different parts of India are not enough complete. Measurement techniques based on satellites, such as optical transient detector system and lightning imaging sensor, have limitations in obtaining ground flash density values. Thus, for India there is a need in development of modern lightning detection networks and related studies on lightning characteristics.

Presently, approaches from IEEE and CIGRE guides can be used for analysis of statistical distributions of lightning current parameters. Further studies are required on thunderstorm days, ground flash density and current parameters statistical distributions for different locations, which will be supportive in performing analysis for Indian power lines.

The lightning performance of overhead power lines estimation procedure is based on the selected interception model (electro-geometric model, to leader progressive model and others), available lightning characteristics, the transmission line structure and voltage levels, type of overvoltage transients and other characteristics under study.

For this procedure, various traditional and recent models are applied, which consider both the deterministic and stochastic features of downward and upward lightning leader. The new methods for simulation of lightning interception (like to leader progressive model, fractal models) and for estimations of lightning performance of power lines are utilizing more physics and statistics approaches, and hopefully will result in more accurate results. These to be validated by field studies supported by novel instrumentations. Of course, as before, it is of great importance to obtain reliable statistical data on thunderstorm characteristics in the area of the studied power line route. Future efforts should be focused on obtaining not only the positions and number of strikes to the overhead power line, and calculation of lightning flashover rate parameters, but also the statistical distributions of lightning current values and related overvoltage parameters at the overhead wires and different phase conductors.

REFERENCES

1. IEEE Std 1243-1997. IEEE Guide for improving the lightning performance of transmission lines. pp. 1–44. DOI: https://doi.org/10.1109/IEEESTD.1997.84660.
2. Nucci, C. A. (2010). A survey on CIGRE and IEEE procedures for the estimation of the lightning performance of overhead transmission and distribution lines. *2010 Asia-Pacific international symposium on electromagnetic compatibility*. pp. 1124–1133. DOI: https://doi.org/10.1109/APEMC.2010.5475698.
3. Martinez-Velasco, J. A, Corea-Araujo, J., Bedoui, S. (2018). Lightning performance analysis of transmission lines using parallel computing. *Ingeniare. Revista chilena de ingenieria*. Vol. 26. No. 3. pp. 398–409.
4. Shariatinasab, R, Tadayon, P., Ametani, A. (2016). A hybrid method for evaluating of lightning performance of overhead lines based on Monte Carlo procedure. *Journal of electrical engineering*. Vol. 67. No. 4. pp. 246–252. DOI: https://doi.org/10.1515/jee-2016-0036.
5. Cooray, V., Becerra, M. (2010). Attractive radius and the volume of protection of vertical and horizontal conductors evaluated using a self consistent leader inception and propagation model – SLIM. *2010 30th International conference on lightning protection (ICLP)*. pp. 1–7. DOI: https://doi.org/10.1109/ICLP.2010.7845802.
6. Li, J., Yang, Q., Sima, W., Sun, C., Yuan, T., Zahn, M. (2011). A new estimation model of the lightning shielding performance of transmission lines using a fractal approach. *IEEE Transactions on dielectrics and electrical insulation*. Vol. 18. No. 5. pp. 1712–1723. DOI: https://doi.org/10.1109/TDEI.2011.6032843.
7. IEEE Std 1410-2004. Revision of IEEE Std 1410-1997. IEEE Guide for improving the lightning performance of electric power overhead distribution lines. pp. 1–50. DOI: https://doi.org/10.1109/IEEESTD.2004.94577.
8. Shostak, V., Tyulyukov, V. (2014). Statistical distributions of current amplitudes and lightning incidence number to structures of various configurations. *2014 International conference on lightning protection (ICLP)*. pp. 1472–1478. DOI: https://doi.org/10.1109/ICLP.2014.6973362.
9. International standard IEC 62305-1:2010 (Edition 2.0). Protection against lightning – Part 1: General principles. pp. 1–137. ISBN 978-2-83220-604-1.
10. IEEE Working Group Report. (1993). Estimating lightning performance of transmission lines. II. Updates to analytical models. *IEEE Transactions on power delivery*. Vol. 8. No. 3. pp. 1254–1267. DOI: https://doi.org/10.1109/61.252651.
11. Procopio, R. (2018). Lightning performance and protection systems. *2018 IEEE Symposium on electromagnetic compatibility, signal integrity and power integrity (EMC, SI & PI)*. pp. 1–32. DOI: https://doi.org/10.1109/EMCSI.2018.8495220.
12. Sirad, M. A. H., Rais, M., Djalal, M. R., Putri, A. N. (2018). Optimization of grounding resistance to minimize transient currents at 150 kV SULSELRABAR system. *2018 International conference on information and communications technology (ICOIACT)*. pp. 572–578. DOI: https://doi.org/10.1109/ICOIACT.2018.8350685.
13. Hadi Sirad, M. A., Taha, S. (2018). Performance optimization of 150 KV transmission tower in Jeneponto steam power plant using GIS analysis. *2018 2nd Borneo international conference on applied mathematics and engineering (BICAME)*. pp. 203–206. DOI: https://doi.org/10.1109/BICAME45512.2018.1570501193.
14. Becerra, M., Cooray, V. (2006). A self-consistent upward leader propagation model. *Journal of physics D: Applied physics*. Vol. 39. pp. 3708–3715. DOI: https://doi.org/10.1088/0022-3727/39/16/028.
15. CIGRE WG 33.01. (1991). Guide to procedures for estimating the lightning performance of transmission lines. *Technical brochure 63*. pp. 1–61.
16. Nath, A., Manohar, G. K., Dani, K. K., Devara, P. C. S. (2009). A study of lightning activity over land and oceanic regions of India. *Journal of earth system science*. Vol. 118. No. 5. pp. 467–481. DOI: https://doi.org/10.1007/s12040-009-0040-7.
17. Indian Standard IS 2309:1989 (Second revision). (2007). Protection of buildings and allied structures against lightning – code of practice. pp. 1–64.
18. Trotsenko, Y., Dixit, M., Mykhailenko, V. (2021). Expression for calculation of lightning ground flash density for conditions of India. *2021 IEEE International conference on modern electrical and energy systems (MEES)*. pp. 1–5. DOI: https://doi.org/10.1109/MEES52427.2021.9598780.
19. Manohar, G. K., Kesarkar, A. P. (2004). Climatology of thunderstorm activity over the Indian region: II. Spatial distribution. *MAUSAM*. Vol. 55. No. 1. pp. 31–40.
20. Tinmaker, M. I. R., Aslam, M. Y., Chate, D. M. (2014). Climatology of lightning activity over the Indian seas. *Atmosphere-ocean*. Vol. 52. No. 4. pp. 314–320. DOI: https://doi.org/10.1080/07055900.2014.941323.
21. Vaisala. (2021). Lightning like never before. Annual lightning report 2020. pp. 1–25. Ref. B212260EN-A.

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