International Journal of Electronics and Communication Engineering (IJECE)
ISSN(P): 2278-9901; ISSN(E): 2278-991X
Vol. 2, Issue 5, Nov 2013, 195-204

International Academy of Science, Engineering and Technology
Connecting Researchers; Nurturing Innovations

LIGHTNING PROTECTION SYSTEM: A COMPARATIVE ANALYSIS OF FOUR MODIFIED MODELS

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ABSTRACT

This paper develops and modifies the current and the attractive radius analytical expressions used in modeling a lightning protection system (LPS). The modified expressions are used as a performance and measurement tool. The tools are used to carry out a comparative analysis of four popular LPS models. The models are implemented with data collected from the Nigeria Meteorological Service (NMS) and isokeraunic level respectively in the North-East Zone of Nigeria. The modified LPS model is applied to the Improved Electro-geometric models (IEGM); the Self-consistent Linear Model; Eriksson Collection Volume Model (CVM), and Petrov-and-Water (CVM). These models are converted into a computer simulation model by using Microsoft Excel (Ms Excel) spreadsheet. The mean of the area of exposure and the probability of the mean number of lightning hit per year for a period of twelve years are analyzed with the template developed with the MSExcel template. The paper found out that the area of exposure of the LPS system increases with increase in height of the tower while the probability of the mean number of hits per year decrease with an increase in the correction factor. The result of the analysis presented SLIM model as the best model, and the Petrov and Waters CVM model as the worst model.

KEYWORDS: LPS, Model, NMS, Nigeria, North, East Zone

INTRODUCTION

For centuries, thundercloud and the lightning flickers accompanying it had been attributed to the Demy gods. Previous woks on LPS [1, 2] pointed out that lightning strikes have been erroneously attributed to the manifestation of the wrath of the Supreme Being against the wicked or evil doers. Lives are being wrecked and property worth millions of Naira is being destroyed by Lightning strike [2, 3, 4]. Ancient civilizations in the Mediterranean and northern Europe, Middle and Far East, Africa and America were of the opinion that the gods are responsible for thunder and lightning [1, 5, 6]. On the contrary, there are direct measurements focusing on the engineering principles; expert knowledge; standard organizations; isokeraunic map; meteorological services, experimentation and computation which predicted precisely a high level of lightning strike in some regions of the globe. In the North-East zone of Nigeria, for instance, a high frequency of lightning strike has been recorded by the NMS and the isokeraunic map [6, 7, 8, 9, 10, 11].

LIGHTNING GENERATION AND LIGHTNING PROTECTION SYSTEM

Lightning originates from a charged cloud and then progresses directly to any structure, points above the ground or directly to the ground [8]. As it progresses downward towards a point, it develops a potential gradient and field intensity near the point. The induced potential gradient causes points such as trees, towers, tall structures and as well as the earth to develop upward streamers [12]. The downward leader and the upward streamer travel in opposite directions through the ionized path formed [8, 12]. Thus, a collision occurs frequently in the path. At the point of inception between the upward streamer and downward leader, charge neutralization occurs and a bright luminosity travels in different directions [13]. Before the occurrence of the luminosity, invisible negative charges are drifting towards the earth. In some cases subsequent strokes may occur after a short interval, thus a continual generation of current of varying luminosities may occur depending on the field intensity [12]. To avoid the destructive effects of lightning strikes on the transceivers mounted on a tower, an installation of a Lightning Protection System (LPS) important. The LPS intercepts effectively lightning current directed to the tower and conduct the same from the point to the ground without causing damage to it.

An LPS is defined as the complete system of conductors and other electrical components used in protecting a structure. It prevents points from receiving the injurious or damaging effects of current discharged by lightning. An LPS also reduces drastically the risk of loss of human life, interruption services render to the public and the loss of the economic values of the devices used for these services [14]. Electrocution of animals and cost reduction in breakdown equipment are also reasons for installing LPSs. [15, 16, 17, 14, 18].

The essence of any LPS is to protect both persons and structures from the effects of the current discharged by lightning current [19]. To achieve this aim, the provision of an efficient lightning conductor above a structure is needful. The intended purpose of the lightning conductor is to divert lightning strike preferentially to the elevated conductor, which shunts the lightning current to the ground without wreck major on the structure [7,9, 15, 19, 20, 21,].

MODEL DESCRIPTION AND METHODOLOGY

Tall structures such as communication towers are frequently hit by lightning [22]. The hit is as a result of leader current from a lightning strike. A tall structure exceeding 100 m is commonly affected by the return stroke without any visible downward leader activity [22, 23]. Classical research papers employ the Electro-geometric Model (EGM) to determine the striking distance of lightning strike. Conversely, the EGM technique has limitations. It does not account for the physical basis of the upward leader interception process, the height of the structure and the geometry of the launching point [7, 9, 21, 22]. However, recent works on LPS are not satisfied with the EGM model. This gives rise to several modifications of the EGM model [21, 24, 25].

Some popularly modified EGM include the Improved EGM (IEGM), Linear Progression Model (LPM), Self-consistent Leader Interception Model (SLIM), and Collection Volume Model (CVM) [7, 9, 21, 22 23, 24] etc. The main reason for the modifications is to develop an effective and efficient LPS system. Therefore, this paper compares four popular LPS models analytically and determines the best model suitable for application in the tower mounted in the North-East zone of Nigeria. Equation (1), the waveform of current is adopted from a research paper [24, 25] and the mean of the current waveform is computed from equation (2).

The analytical expression of the attractive radius of the LPS is formulated by using equation (3). The current waveform fall interval is developed from the recursive model depicted by equations (4-7). Equation (4-7) is established on the concept of adiabatic equilibrium condition. The equilibrium condition states that the sum of the flow rate of the downward and upward current attracted or diverted in a time interval specified by an LPS in an enclosed atmosphere (adiabatic) is zero. In other words, the downward leader current discharged by the LPS is equal to the quantity of the upward streamer (also known as return stroke) it dissipated to the atmosphere.

The return current stroke is simulated based on the following assumptions stated by [26]:

- The leader approaches from a give direction

- An upward return stroke is developed from the top of the rod towards the charge cloud center of the leader current
- The interception of the return stroke and the leader current result in lightning

Recall that the normalization of a probabilistic system such as the current fall time model sums up to one. This is illustrated analytically by equation (8-9). By making the invisible current fall time (I_{10}) subject of the formula of equation (9), the model of the idle period of the invisible current fall time is expressed as shown in equation (10). When equation (10) is substituted into equation (5) and the resulting expression further substituted into equation (1), the final expression of current waveform is obtained in equation (11) agrees with the one presented in the published a paper [24]. By applying equations (3 & 11) to the IEGM, CVM and SLIM model separately established by Eriksson; Petrov and Waters; and Bacera and Cooray respectively, the modified results of the attractive radius expression changes to the result delineated by equations (12-15) after some algebraic manipulation.

The probability of the total number of lightning strikes of a given tower is presented as the product of the area of exposure of the electronic device and the number of thunder strike per year of a geographical location where the tower is mounted [21,]. The number of lightning strikes per year on a structure is formulated as shown by equations (16- 19). Equation (19) is the common platform used for determining the number of lightning strikes on the tower per year in the North-East zone of Nigeria. Equations (12-15) are substituted into equations (18 &19) to formulate the expressions of the area of exposure and the probability of the mean of thunderstorm days per year IEGM, CVMs and SLIM analytical expressions used for the comparison. The probability of the mean of thunderstorm days per year of the IEGM, CVMs and SLIM models are presented in equations (20-23) respectively. These equations were modeled and simulated with Microsoft Excel 2007 spreadsheet. The model is run and statistical data were collected at the end of the simulation.

$$I = \frac{I_p}{\eta} * \frac{1}{1+\left(\frac{t}{\tau_2}\right)^c} * I_{1k} \tag{1}$$

Where,

I_p = Current return stroke

η = correction factor

c= current steepness factor

$$mean\ (\bar{I}) = \frac{\sum_{i=1}^{M} I_i}{M} \tag{2}$$

$$R_s = a * i_t^{\ b} * h^k \tag{3}$$

Where,

a, b, k = constants

i_t = instantaneous lightning current

h = height of structure

$$\left.\begin{aligned} I_{1n}\tau_{1n} &= \frac{I_{1(n-1)}t}{n} \\ I_{1n} &= \frac{I_{1(n-1)}t}{n\,\tau_{1n}} \end{aligned}\right\} \tag{4}$$

Where,

I_{1n}= current fall time

τ_{1n} = inter-arrival time constant

t= lightning strike period

n= 1, 2, 3…k are the states of the current fall time

$$I_{1k} = \frac{I_{10}}{k!}\frac{t^k}{\tau_{11}\tau_{12}\ldots\tau_{1(k-1)}\tau_{1k}} \tag{5}$$

$$\tau_1 = \tau_{11} = \tau_{12} = \tau_{13} = \tau_{14}\ldots = \tau_{1k} \tag{6}$$

$$I_{1k} = \frac{I_{10}}{k!}\left(\frac{t}{\tau_1}\right)^k \tag{7}$$

$$I_{10} + I_{11} + I_{12}\ldots + I_{1k} + \ldots = 1 \tag{8}$$

$$I_{10}\left(1+\sum_{k=1}^{\infty}\frac{1}{k!}\left(\frac{t}{\tau_1}\right)^k\right) = 1 \tag{9}$$

$$I_{10} = \frac{1}{\sum_{k=1}^{\infty}\frac{1}{k!}\left(\frac{t}{\tau_1}\right)^k} \tag{10}$$

$$I = \frac{I_p}{\eta} * \frac{1}{1+\left(\frac{t}{\tau_2}\right)^c} * \frac{\frac{1}{k!}\left(\frac{t}{\tau_1}\right)^k}{1+\sum_{i=1}^{\infty}\frac{1}{k!}\left(\frac{t}{\tau_1}\right)^k} \tag{11}$$

Eriksson’s IEGM model of the attractive radius of an LPS system

$$R = \left(\frac{I_p}{\eta} * \frac{1}{1+\left(\frac{t}{\tau_2}\right)^c} * \frac{\frac{1}{k!}\left(\frac{t}{\tau_1}\right)^k}{1+\sum_{i=1}^{\infty}\frac{1}{k!}\left(\frac{t}{\tau_1}\right)^k}\right)^a * 0.84h^{0.4} \tag{12}$$

Where,

$$a = 0.7h^{0.02}$$

$$R = 0.84I^{0.74}h^{0.6}$$

Eriksson’s CVM model of the attractive radius of an LPS system

$$R_a = 0.84\left(\frac{I_p}{\eta} * \frac{1}{1+\left(\frac{t}{\tau_2}\right)^c} * \frac{\frac{1}{k!}\left(\frac{t}{\tau_1}\right)^k}{1+\sum_{i=1}^{\infty}\frac{1}{k!}\left(\frac{t}{\tau_1}\right)^k}\right)^{0.74} * h^{0.6} \tag{13}$$

Petrov and Waters CVM model of the attractive radius of an LPS

$$R_a = (0.56)\left((h+15)\left(\frac{I_p}{\eta} * \frac{1}{1+\left(\frac{t}{\tau_2}\right)^c} * \frac{\frac{1}{k!}\left(\frac{t}{\tau_1}\right)^k}{1+\sum_{i=1}^{\infty}\frac{1}{k!}\left(\frac{t}{\tau_1}\right)^k}\right)\right)^{2/3} \tag{14}$$

Bacera and Cooray's SLIM model of the radius of an LPS

$$R = 1.86\left(\frac{I_p}{\eta} * \frac{1}{1+\left(\frac{t}{\tau_2}\right)^c} * \frac{\frac{1}{k!}\left(\frac{t}{\tau_1}\right)^k}{1+\sum_{i=1}^{\infty}\frac{1}{k!}\left(\frac{t}{\tau_1}\right)^k}\right)^{a} * h^{0.1746} \tag{15}$$

Where,

I_p= return stroke peak current

R_a=radius of attraction

$$a = -1.617*10^{-3}h + 0.6417h^{0.0932}$$

$$N = \pi R^2 * N_g\left(\overline{T}_d\right) * Cd * 10^{-6} \tag{16}$$

$$N_g(\overline{T}_d) = 0.023\overline{T}_d^{\,1.3} \tag{17}$$

$$\overline{T}_d = \frac{\sum_{i=1}^{K}(T_d)_i}{K} \tag{18}$$

$$N = \pi R^2 * 0.023\overline{T}_d^{\,1.3} Cd * 10^{-6} \tag{19}$$

Where,

$N_g(\overline{T}_d)$ = mean of ground flash density of North-East Zone of Nigeria

$\overline{T}_d$ = The mean of thunderstorm days per year or isokeraunic level of the region

C_d = location factor

R_a= radius of attraction

i = 1, 2, 3 …K

$$N=\pi\left(\frac{I_p}{\eta}*\frac{1}{1+\left(\frac{t}{\tau_2}\right)^c}*\frac{\frac{1}{k!}\left(\frac{t}{\tau_1}\right)^k}{1+\sum_{i=1}^{\infty}\frac{1}{k!}\left(\frac{t}{\tau_1}\right)^k}\right)^{2a}*0.84h^{0.8}*0.023\overline{T}_d^{\,1.3}*Cd*10^{-6} \tag{20}$$

$$N=0.7056\pi\left(\frac{I_p}{\eta}*\frac{1}{1+\left(\frac{t}{\tau_2}\right)^c}*\frac{\frac{1}{k!}\left(\frac{t}{\tau_1}\right)^k}{1+\sum_{i=1}^{\infty}\frac{1}{k!}\left(\frac{t}{\tau_1}\right)^k}\right)^{1.48}*h^{1.2}*0.023\overline{T}_d^{\,1.3}*Cd*10^{-6} \tag{21}$$

$$N=\left[\left(0.56\pi(h+15)\right)\left(\frac{I_p}{\eta}*\frac{1}{1+\left(\frac{t}{\tau_2}\right)^c}*\frac{\frac{1}{k!}\left(\frac{t}{\tau_1}\right)^k}{1+\sum_{i=1}^{\infty}\frac{1}{k!}\left(\frac{t}{\tau_1}\right)^k}\right)^{0.74}*h^{0.02}\right]^{4/3}*0.023\overline{T}_d^{\,1.3}*Cd*10^{-6} \tag{22}$$

$$N=3.4596\pi\left(\frac{I_p}{\eta}*\frac{1}{1+\left(\frac{t}{\tau_2}\right)^c}*\frac{\frac{1}{k!}\left(\frac{t}{\tau_1}\right)^k}{1+\sum_{i=1}^{\infty}\frac{1}{k!}\left(\frac{t}{\tau_1}\right)^k}\right)^{2a}*h^{0.2392}*0.023\overline{T}_d^{\,1.3}*Cd*10^{-6} \tag{23}$$

RESULTS AND DISCUSSIONS

The mean number of the thunderstorm days of the North-East of Nigeria is computed based on the measurement done by the NMS [40]. Precisely the major towns in the zone comprise Bauchi, Yola, Potiskum, Maiduguri, Nguru, Wukari, Gombe, Jos, Mubi, Jalingo Bui and Damaturu . The mean of thunderstorm days of these towns over a period of twelve years is computed with the aid of equation (18). Equation (18) is substituted into equation (12-15). Further, the area of the exposure of the LPS is calculated from the attractive radius depicted in equations (12-15) and the equations are applied to the formula (πR^2). Figures 1 and 2 are the graph of the area of exposure of the LPS against height.

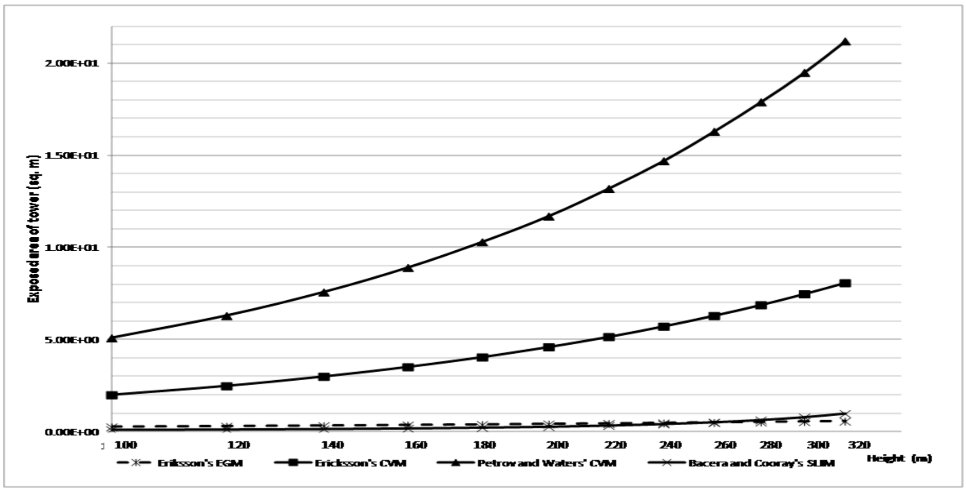

Figure 1: Exposed Area of Tower vs. Height of Tower

The height of the structure varied from 100-320m in steps of 20m while constant following parameters are used : the mean value of the NMS and the isokeraunic level thunderstorm ($\overline{T}_d$) = 65.33 days per year and 89.42 days per year respectively; the current st. epness (c)=1; $t/\tau_{.}$ =0.9; t/τ_2=1; $\bar{I}_p/\eta$=0.2kA. The exposed area increases with increase in height. The exposed area of Figure1 shows that the SLIM and IEGM models are very insensitive to increase in height of the LPS whereas the CVMs models are very sensitive to increase in height. Between the ranges of 100-220m, the SLIM model gives the best protection level. Figure 1 reveals that only about 0.33sqr.m of the tower is exposed to lightning strikes when the height of the tower is 220m for both IEGM and SLIM models while 5.15sqr.m of the tower is exposed lightning strike by Eriksson's CVM model. The area of exposure of Petrov and Waters CVM model is 13sqr.m when the height of the tower is 220m. Within the range of 260-320m the IEGM model provides the best protection as depicted by Figure. It was closely followed by the SLIM model while Petro and Waters CVM model gives the worst protection.

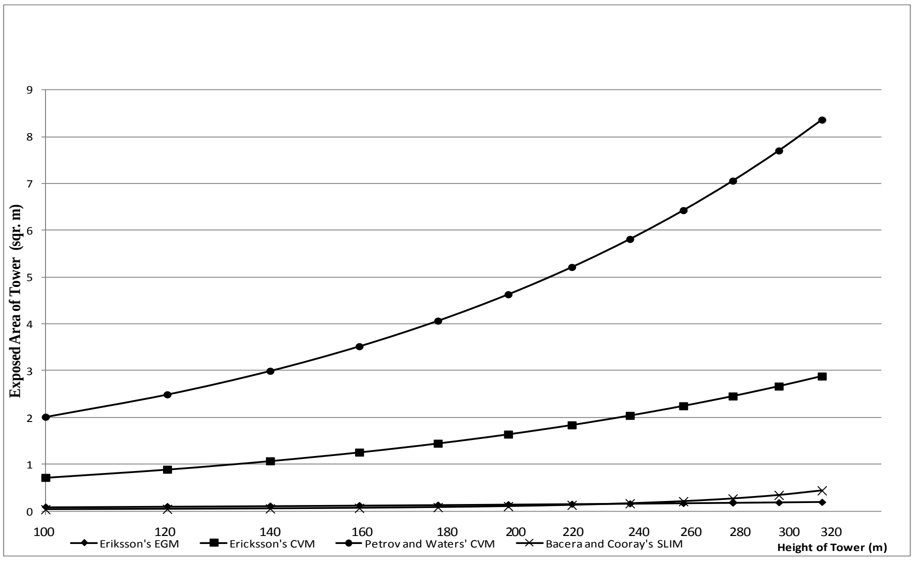

Figure 2: Graph of Exposed Area of Tower against Height of the Tower

Figure 2 is also the graph of the area of exposure against varying height with all parameters remaining the same except that $t/\tau_1=t/\tau_2=0.9$. The area of exposure is reduced and a remarkable improvement is obtained. When the height of the tower is between 100-180m, the SLIM model possesses the best protection level. At a range of height of about 100-200m, the IEGM and SLIM models have approximately equal protection level. It is clear from Figure 2 that above 260m IEGM is the best model. The exposure area of the IGM is only 0.19sqr.m at 300m while that of SLIM, Eriksson CVM, and Petrov and Waters CVM model are 0.4, 2.8 and 8.4sqr.m respectively.

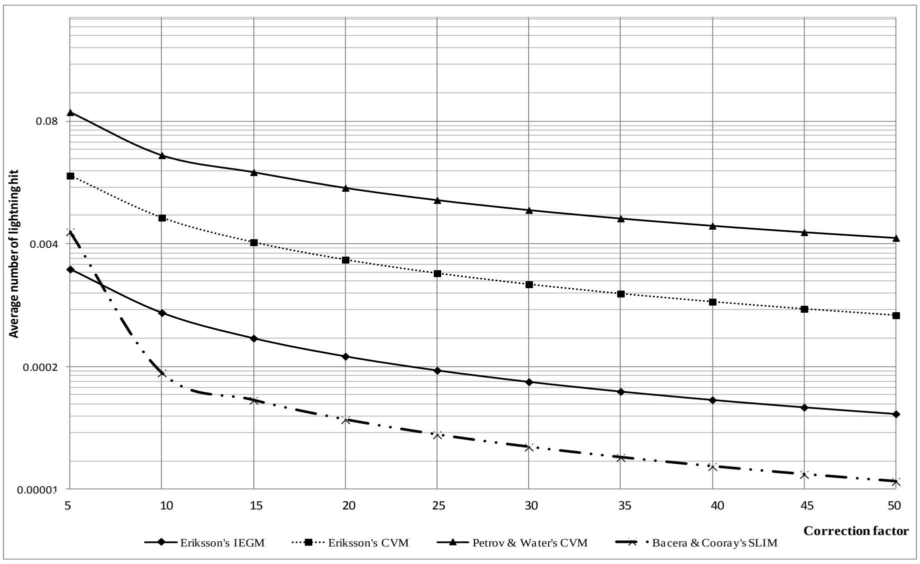

Figure 3: Graph of Average Number of Lightning Hit against Correction Factor

Figure 3 depicts the graph of the probability average number of lightning hit against correction factor. The graph of Figure 3 is plotted by implementing equations (20-23) and the mean value of the NMS thunderstorm days per year is computed from equation (18). The parameters of the model reckoned at the end of the experiment are as follows: mean of the current ($\bar{I}$) =15kA; the steepness of the current (c) =1; quantity of ionize charge (k) =4; t/τ_1=0. 09; t/τ_2=0. 002 and mean of NMS thunderstorm =63. 5 days per year. Figure 3 shows that the probability of the mean number of lightning hit decreases with an increase in the correction factor (η) in all the models.

The SLIM and IEGM models are presented, as shown in Figure 3, as excellent models; they comply with the Eritech IEC 62305 standard [11]. The probability of the mean number hit of the SLIM model decreases from $5.3*10^{-9}$ to $12*10^{-11}$ as the correction factor increases from 5 to 50. The probability of the mean number of hits of the IEGM, Eriksson CVM and Petrov and Waters CVM decrease from $2.2*10^{-9}$, $2.1*10^{-8}$, and $1*10^{-7}$ to $6.3*10^{-11}$, $8.2*10^{-10}$ and $4.6*10^{-9}$ respectively with an increase in the correction factor from 5 - 50.

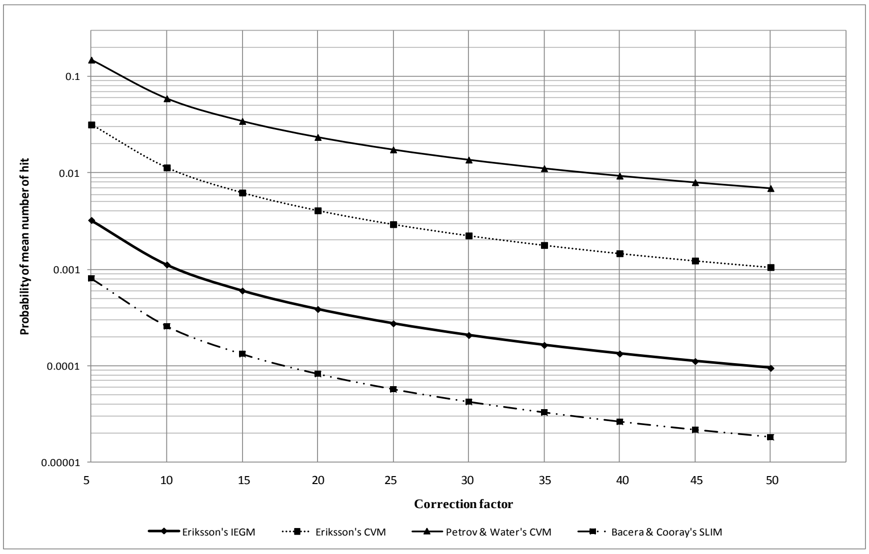

Figure 4: Graph of Probability of Mean Number of Lightning Hit against Correction Factor

The graph of Figure 4 is also obtained from equations (18, 20-23). All the parameters utilized in Figure 3 are retained except the mean of thunderstorm values. The thunderstorm value is obtained from the isokeraunic map of the North-East zone of Nigeria. From equation (18), the average thunderstorm computation is equal to 89.42 per year. The graph of Figure 4 shows that the number of hits decreases with increase in correction factor.

The SLIM model shows a decrease in the probability of the mean of lightning hit from $8.1*10^{-10}$ to $1.8*10^{-11}$ with increase in correction from 5-50. Similarly, the IEGM model recorded a decrease in the probability of the mean lightning hit from $3.2*10^{-9}$ to $9.4*10^{-11}$. Eriksson, and Waters and Petrov CVM models also recorded a decrease from $3.8*10^{-8}$ and $1.4*10^{-8}$ to $1.1*10^{-9}$ and $6.9*10^{-9}$ respectively when the correction increases from 5-50.

CONCLUSIONS

The result of the analysis presented clearly that Bacera and Cooray's SLIM model is the best model suitable for implementing the LPS system in the North-East zone of Nigeria. This is closely followed by Eriksson's IEGM model. The worst model is the Petrov and Waters CVM model. This work is concluded by suggesting either the SLIM or IEGM model should be improved on. Further works will look at LPS with respect to both horizontal light strike and the atmospheric layer on IEGM technique.

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