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Comparison of lightning return stroke channel-base current models with measured lightning current

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ABSTRACT

Electromagnetic pulse radiation produced around the lightning stroke channel has caused the disturbance to the microelectronic industry, especially to disturbance of high frequency to electronic systems. Lightning channel-base current function (CBC) characteristics and parameters determine lightning electromagnetic field (LEMF) results obtained on the basis of the used models. This paper evaluated and compared the measured lightning current and six lightning current-based channels models namely Bruce and Golde, Heidler, Diendorfer and Uman, Nucci, Pierce and Cianos and new current-based current (NCBC) models. In terms of the waveshape, among all the six lightning channel-based current models discussed, the models developed by Javor, Nucci and Diendorfer and Uman have showed a good agreement compared to the measured lightning current. In terms of 10-90% risetime and full width half maximum time (FWHM) comparison, NCBC and Nucci models have showed compatible comparison. However, Nucci model is not easily adjustable to different desired pulse-current waveshapes. On the other hand, NCBC model can be simplified, the values of lightning peak current and risetime can be chosen arbitrarily and independently from other parameters, and there is no need for the peak-correction factor, so that reduces the number of parameters. Therefore, the NCBC model was suggested to be used in the future in order to simulate much accurate return stroke model. This knowledge will contribute to the development of a new accurate and efficient return stroke model.

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1. INTRODUCTION

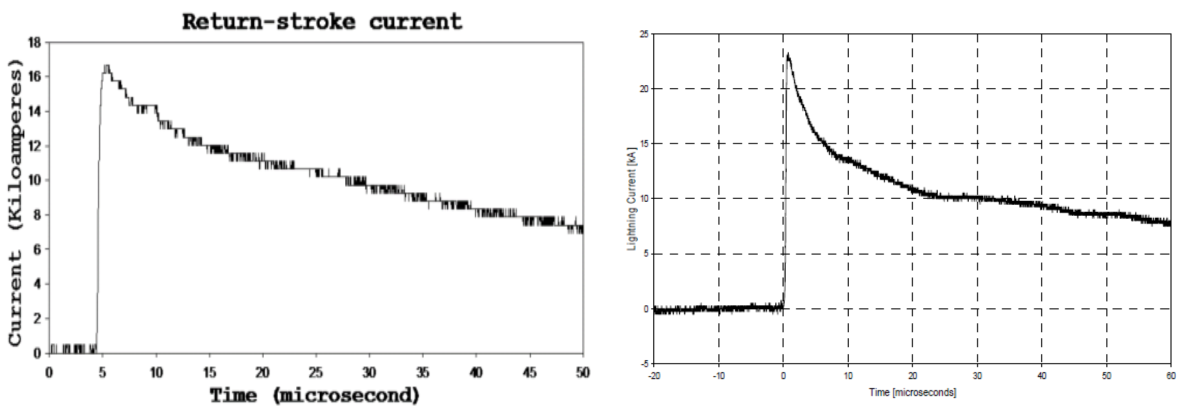
Lightning is one kind of huge scale electrostatic discharge where it may cause the global mortality rate to be around 1,000 per year [1]. When lightning happens several MV of voltage and tens thousands of Amperes current can be drawn from cloud to ground. This cloud-to-ground channel normally named as lightning channel or return stroke channel. The electromagnetic pulse radiation is produced around the stroke channel. Since the microelectronic industry was growing rapidly, the loss caused by lightning electromagnetic pulse were increased every year. The lightning current is often used as input function to many types of lightning models since it is the source of lightning electromagnetic pulses. Modelling the return stroke current and its lightning electromagnetic pulses are one of the most important aspect to further understand the lightning characteristic and hence further improve the lightning protection. The channel base current of lightning stroke is the base to research the distribution of current along the channel and the lightning electromagnetic pulse generated by the channel. There are two components of lightning return stroke current waveform, considered in developing a current model. The two components are the return stroke current functions in the channel base and the space-time variation of return stroke current along-the channel. The estimation of the two components is done separately. In the evaluation of the first part, several functions are expressed based on measured values of the natural and triggered lightning measurements on the first and subsequent return strokes.

Lightning channel-base current are usually measured [2, 3] or assumed based on typical measurements [4-6]. However, other than these two methods, lightning channel-base current can also be approximated by a mathematical function [7, 8] having usually a few adjustable parameters. It is preferably as less parameters as possible in the mathematical function, but the mathematical function able to produce desired characteristic. Recently the research on various lightning current models has been discussed and compared extensively [9, 10]. However, chosen channel-base current function (CBC) characteristics and parameters determine lightning electromagnetic field (LEMF) results obtained on the basis of the used model, so as the computation possibilities. Therefore, this paper aimed to evaluate and compare the measured lightning current and six lightning current-based channels models.

2. EXPERIMENTAL OBSERVATION ON LIGHTNING CURRENT

Most of the measurements of the return stroke current have been made at ground level, so the measured data are only for the base current of the return stroke. Furthermore, the measurements were either made on triggered lightning or on lightning strikes to tall towers [11]. In the former case, the extent to which the triggered lightning corresponds to its natural counterpart was still not fully understood, whilst in the latter case it is obvious that the tall conducting structure of the tower will influence the lightning stroke in many ways. These measured currents, therefore, may be different from those of lightning to flat terrain.

Therefore, a mathematical model for lightning return strokes is needed: 1) to suggest the return stroke currents from the measured electromagnetic radiation; 2) to predict the electric and magnetic fields at very close distances where the field measurements are highly impractical to be done; and 3) to acquire a better understanding of the nature of lightning and related phenomena [9]. A return stroke model can be defined as a mathematical construction, interpreted verbally, numerically or graphically, that can represent the observed properties of the lightning return stroke. If a model is to be considered to be acceptable, it should be able to describe at least some of the experimentally obtained data pertinent to the lightning return stroke such as the temporal variation of both the channel base current and its derivative, the velocity of the return stroke tip, and the electromagnetic fields at distant points [9]. Figure 1 showed the waveform of measured current at vertical lightning return-stroke channel from two research articles.



(a) (b)

Figure 1. Waveform of measured current at the vertical lightning return-stroke channel shown by, (a) Díaz Cadavid, et al. [2], (b) Djalel, et al. [3]

3. LIGHTNING CURRENT-BASED CHANNEL MODELS

There are five basic models normally used to calculate the channel-base current. They are namely Bruce and Golde model, Heilder model, Diendorfer and Uman model, Nucci model, and Pierce and Cianos model. In year 2011, Javor and Rancic [8] proposed a new lightning return stroke current model which could be used in lightning return-stroke models to approximate different channel-based currents, they named it as New Channel-Base Current model (NCBC). Due to the reason that it can be difficult for a common user to adjust parameters to the desired waveshape, parameters suggested by researchers in respective developed models have been used in this study.

The first model for a lightning channel-based current was Bruce and Golde model [7]. Their model has the advantage of simplicity and had been widely used in early days [11]. In the Bruce-Golde model, the channel current was assumed uniform below the return-stroke wavefront. Above the wavefront, the current is zero. The current is discontinuous at the wavefront [11]. Bruce and Golde model was exhibited in Figure 2 given (1) and with the lightning parameter as in Table 1 where I0 is the amplitude of the channel base current, α is a constant factor, β is a constant factor as well.

$$I_{first}(0,t) = I_0(e^{\alpha t} - e^{\beta t}) \quad (1)$$

Table 1. Typical value for Bruce and Golde channel base current [7]

Parameters	Return Stroke
I_0 (kA)	30
α (1/s)	4.4×10^4
β (1/s)	4.6×10^5

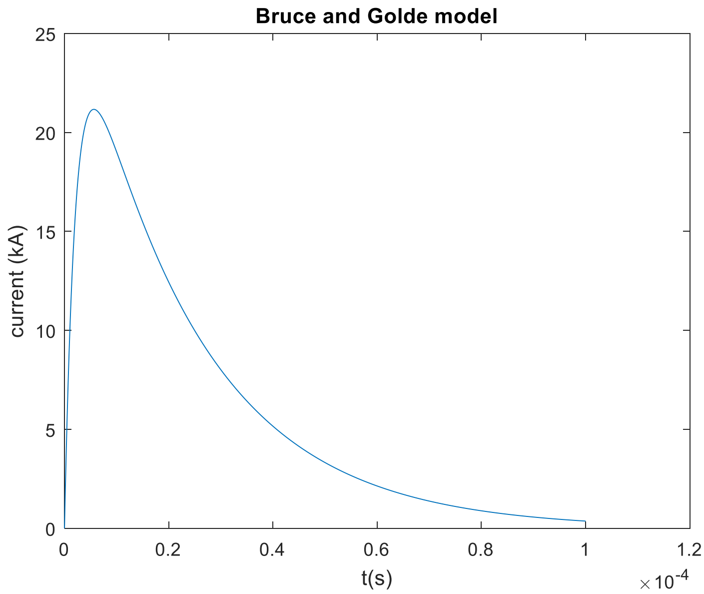


Figure 2. Bruce and Golde model for channel base current

Next was the function of channel-base current presented by Heidler [12, 13] which was defined by (2) and with the parameters considered as in Table where i_o is the amplitude of the channel base current, τ_1 is the front time constant, τ_2 is the decay time constant, n is the amplitude correction factor.

$$\text{i(0,t)}=\frac{i_0}{\eta_1}\,\frac{(\frac{t}{\Gamma_1})^n}{1+(\frac{t}{\Gamma_1})^n}\exp(\frac{-t}{\Gamma_2}) \quad (2)$$

where $\eta = \exp[-(\frac{\Gamma_1}{\Gamma_2}) \times \left(n\frac{\Gamma_2}{\Gamma_1}\right)^{\frac{1}{n}}]$

Heidler's function reproduced concave rising part and the second-order derivative equal to zero at $t=0^+$. It could be difficult for a common user to adjust parameters to the desired waveshape. Fourier transform of the Heidler's function is approximately given by Heidler and Cvetić [14], and analytically by Andreotti, et al. [15]. One pulse function was proposed by Feizhou and Shanghe [16] with the calculated analytical integral, but it also included calculation of the peak-correction factor from the expression involving other three parameters, as for the Heidler's function. The sum of two Heidler's functions was proposed by Rachidi et al. [17] for the subsequent return-stroke channel-base current. For the first return stroke, the expression of two Heidler's functions was proposed by Nucci and Rachidi in [18], and the parameters were chosen according to the experimental data from Rachidi, et al. [17]. For representing the first positive, and the first and subsequent negative short-stroke currents, Heidler's function was used in the International Standard IEC 62305-1[19]. In Figure 3 is Lightning channel-base current waveform of Heidler model.

Table 2. Typical value for Heidler channel base current [17]

Parameters	Return Stroke
i_o (kA)	28
τ_1 (μs)	1.8
τ_2 (μs)	95
n	2

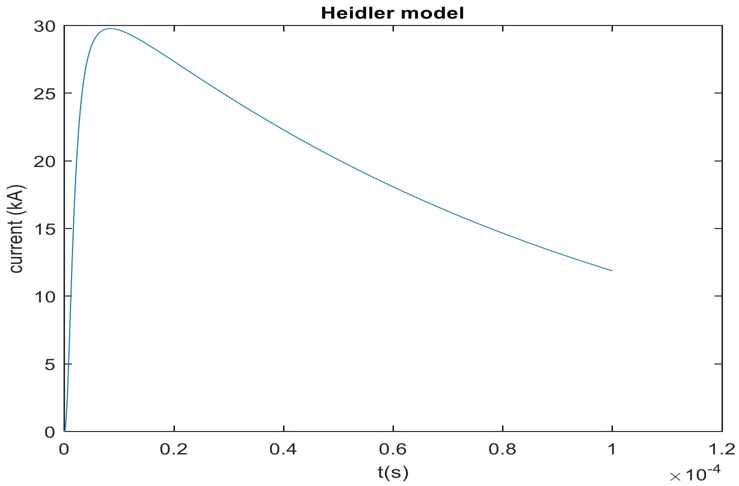


Figure 3. Lightning channel-base current waveform of Heidler model

Diendorfer and Uman [20] extended Heilder model and they presented the current at the ground level by the sum of two expressions, given by (3). Their model of channel base current was shown in Figure 4 with the parameters tabulated in Table 3 where i_{01} and i_{02} are the amplitude of the channel base current. $\tau_{11}$and τ_{12} are the front time constant, τ_{21} and τ_{22} are the decay time constant, $n_1$and n_2 are exponent (2~10) and η_1, η_2 are the amplitude correction factor.

$$i(0,t)=\frac{i_{01}}{\eta_1}\frac{(\frac{t}{\Gamma_{11}})^{n_1}}{1+(\frac{t}{\Gamma_{11}})^{n_1}}\exp(\frac{-t}{\Gamma_{12}})+\frac{i_{02}}{\eta_2}\frac{(\frac{t}{\Gamma_{21}})^{n_2}}{1+(\frac{t}{\Gamma_{21}})^{n_2}}\exp(\frac{-t}{\Gamma_{22}}) \quad (3)$$

Table 3. Typical value for Diendorfer and Uman channel base current [17, 21]

Parameters	Return Stroke
i_{01} (kA)	10.7
i_{02} (kA)	6.5
τ_{11} (μs)	0.25
τ_{12} (μs)	2.5
τ_{21} (μs)	2.1
τ_{22} (μs)	230
n_1	2
n_2	2

In addition, Nucci, et al. [22] also extended the Heilder model and presented the current at the base channel using the sum of two expressions given in (4). Nucci model was considered as double-exponential function (DEXP). His model of channel base current was shown in Figure 5 with parameters listed in Table 4 where i_{01} and i_{02} were the amplitude of the channel base currents, τ_1 and τ_3 were the front time constant, τ_2 and τ_4 were the decay time constant, n was an exponent (2~10) and η was the amplitude correction factor. The DEXP function is simple and integrable, but the main drawback is physically non-realistic convex waveshape in the rising part, with the too large maximum current derivative at $t=0^+$, making great problems in LEMF calculations. It was found that the DEXP function is not easily adjustable to different desired pulse-current waveshapes.

$$i(0,t)=\frac{i_0}{\eta}\,\frac{(\frac{t}{\Gamma_1})^n}{1+(\frac{t}{\Gamma_1})^n}\exp(\frac{-t}{\Gamma_2}) + i_{02}(\exp(\frac{-t}{\Gamma_3}) - \exp(\frac{-t}{\Gamma_4})) \quad (4)$$

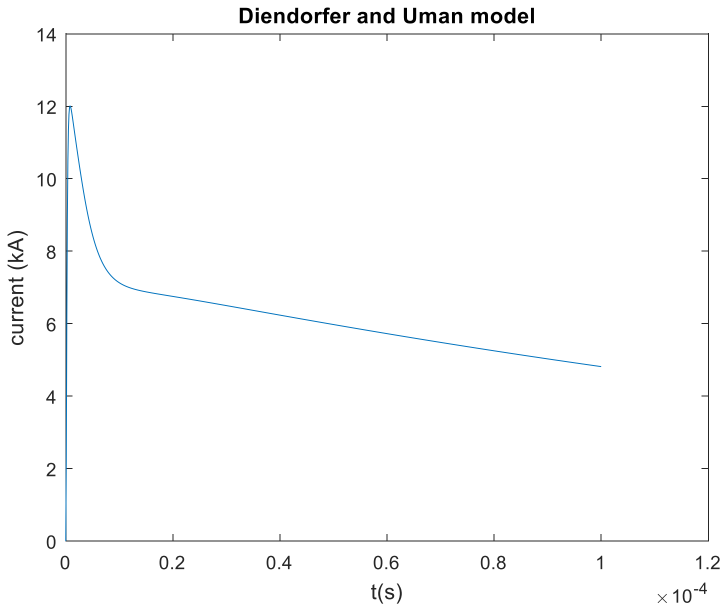


Figure 4. Lightning channel-base current waveform of Diendorfer and Uman model

Table 4. Typical value for Nucci channel base current [24]

Parameters	Return Stroke
i_{01} (kA)	9.9
i_{02} (kA)	7.5
τ_1 (μs)	0.072
τ_2 (μs)	5
τ_3 (μs)	100
τ_4 (μs)	6
n	2
η	0.845

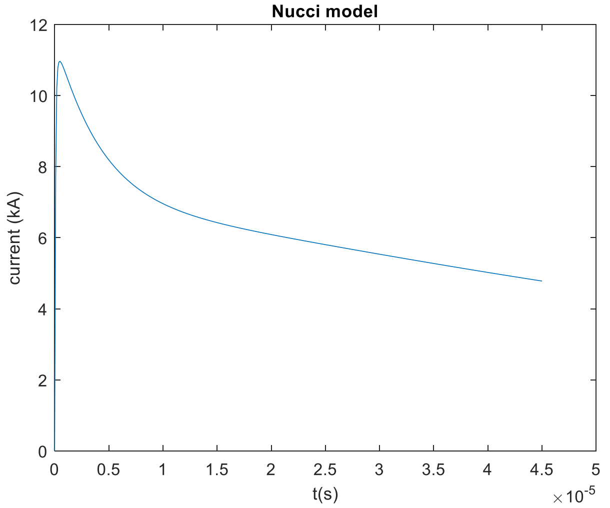


Figure 5. Lightning channel-base current waveform of Nucci model

Pierce and Cianos model as expressed by (5) was used to calculate the channel base current [23]. The waveform was shown in Figure 6 with the parameters are as in Table 5. In this model, Pierce and Cianos have shown how the parameters i_0, α and β can be defined from the information of time to peak current, full width half maximum time and the peak current.

$$I(0,t) = i_0\left(e^{\alpha t} - e^{\beta t}\right) + i_{01}\left(e^{-\gamma t} - e^{-\sigma t}\right) \quad (5)$$

Table 5. Typical value for Pierce and Cianos [25]

Parameters	First Return Stroke
i_0 (kA)	20
i_{01} (kA)	2
α (1/s)	2×10^4
β (1/s)	2×10^6
γ (1/s)	1×10^3
σ (1/s)	1×10^4

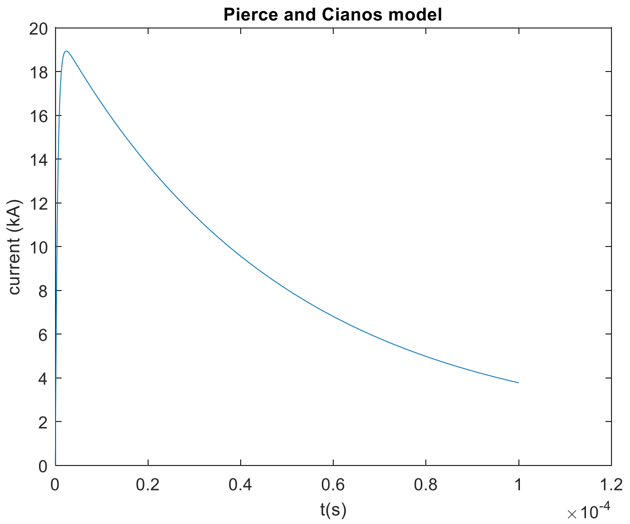


Figure 6. Lightning channel-base current waveform of Piece and Cianos model

For all the aforementioned functions, the maximum current value needed the peak-correction factor, and the corresponding time to maximum current value was not the parameter that could be easily chosen in advance. For the new channel-based current (NCBC) function developed by Javor and Rancic [8], the values of I_m and t_m could be chosen arbitrarily and independently from other parameters, and there was no need for the peak-correction factor, so that reduced the number of parameters as shown in (6).

$$i(0,t)=\begin{cases} I_m \tau^{a} \exp[a(1-\tau)],\ 0 \le \tau \le 1 \\ I_m \sum_{i=1}^{n} c_i \tau^{b_i} \exp[b_i(1-\tau)],\ 1 \le \tau \le \infty \end{cases} \quad (6)$$

where a and b_i are the parameters, c_i is the weighting coefficients so that n=1, c_i=1, $\tau=t/t_m$ is the normalized variable, t_m is the risetime to the maximum current value I_m , and n is the chosen number of expressions in the decaying part.

For n=1, c_1=1 and b_1=b, the NCBC function reduced to the simplified NCBC having four parameters: I_m, t_m, a, and b. Parameter a of the NCBC function determined the waveshape of the rising part. The choice of b_i and c_i determined the decaying, independently from the rising part. The procedure of choosing parameters was based on the analysis of their influence on waveshape characteristics. From the explanation of Javor and Rancic [8], simplified NCBC with parameter 0<a<1 has a convex shape so as the DEXP function in the rising part, but very high values of the first derivative at $t=0^+$ result in unrealistic spikes in numerical results for the field.

The NCBC gave the shape of the function similar to the measured lightning channel based signal by Zhang, et al. [24] and Qie, et al. [25] with the parameters given in the Table 6. The NCBC function for n=2 could be also used successfully for other faster or slower decaying waveshapes. More terms in the decaying part of the NCBC function gave better approximations without losing any of the function advantages. The parameters of the CBC function were given according to the Standard IEC 62305–1 [19]. The parameters of the CBC were the same no matter what the lighting protection level is so as for the Heidler's function. The correction factor was not needed; therefore, any other maximum values could be easily obtained by multiplication of the CBC function with the corresponding current value. In Figure 7 is lightning channel-base current waveform of new channel-based current model.

Table 6. Typical value for NCBC [25]

Parameters	First Return Stroke
I_m (kA)	11
t_m (μs)	0.472
a	1.1
b_1	0.16
c_1	0.34
b_2	0.0047
c_2	0.66

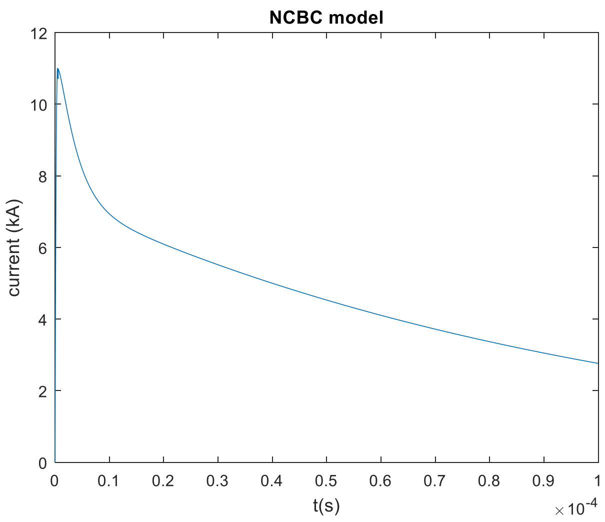


Figure 7. Lightning channel-base current waveform of new channel-based current model

3.1. 4.0 COMPARISON BETWEEN THE SIX MODELS OF LIGHTNING CHANNEL-BASE CURRENT MODELS AND THE MEASURED LIGHTNING CURRENT

The six-lightning channel-based current models discussed in this paper had their own parameters to follow in order to show a good agreement with realistic lighting current waveform. In order to compare the waveshape of each lightning channel-based current, normalization process has been carried out and the results were shown in Figure 8 with the measured current replotted from Djalel, et al. [3]. Among all the six lightning channel-based current models discussed, lightning channel-based current model developed by Javor and Rancic [8], Nucci [22] and Diendorfer and Uman [20] have showed a good agreement to measured lightning current in Figure 1. As far as the current waveshape was concerned, other models have no similarity with the measured return stroke current waveshape. Comparing the six lightning channel-based current models, the Bruce and Gold and the Pierce and Cianos model have the setback of getting a discontinuity in the derivative of current at t=0 [26]. It is noteworthy to mention that the Diendorfer and Uman [20] model which is the modified Heidler functions have a good agreement with measured current in contrast to the original Heidler function [12].

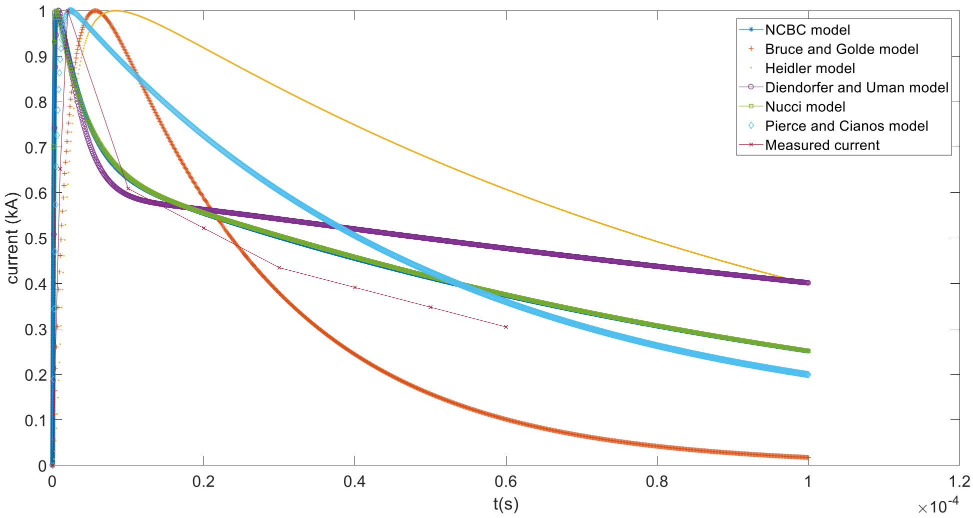


Figure 8. NCBC, Bruce and Golde, Heidler, Diendorfer and Uman, Nucci, Pierce and Cianos models and measured current in the first 100 µs normalized to maximum values

In addition, the 10-90% risetime and full width half maximum time (FWHM) of various lightning-channel based models were measured with the measurement methods presented in Figure 9 and the results was tabulated in Table 7. The Bruce and Golde and Heidler models have similar 10-90% risetime, while the rest of the models have shorter risetime. The shortest risetime observed was obtained from Nucci model, while the longest risetime was obtained from Heidler model. On the other hand, Bruce and Golde model, Nucci model and New Channel-Base Current (NCBC) model showed a consisted FWHM result and shorter time compared to the other three models in this paper.

Table 7. Time domain analysis on the lightning-channel based model

Models	10-90% Risetime (µs)	FWHM (µs)
Bruce and Golde model	3.0	22.5
Heidler model	3.3	75.8
Diendorfer and Uman model	0.4	45.1
Nucci model	0.16	29.4
Pierce and Cianos model	0.994	39.8
New Channel-Base Current (NCBC) model	0.29	29.7
Measured return stroke [26]	0.52	23.8
Measured return stroke [27]	2.0	23.7

From the obtained result, the difference results of measured 10-90% risetime and the FWHM time of the lightning could be affected by the different amount of charges bought by lightning from cloud to ground. Compared to measured triggered lightning from Zhang, et al. [24] and Qie, et al. [25], NCBC and Nucci models showed the very similar results among the six lightning models. However, Nucci model is not easily adjustable to different desired pulse-current waveshapes. On the other hand, NCBC model can be simplified, the values of lightning peak current and risetime can be chosen arbitrarily and independently from other parameters, and there is no need for the peak-correction factor, so that it reduced the number of parameters. Nucci model was denoted with square in Figure 8, it has faster decaying after the maximum value and later slower in comparison to the Heidler model. Therefore, the NCBC model was suggested to be used in future in order to simulate much accurate return stoke model.

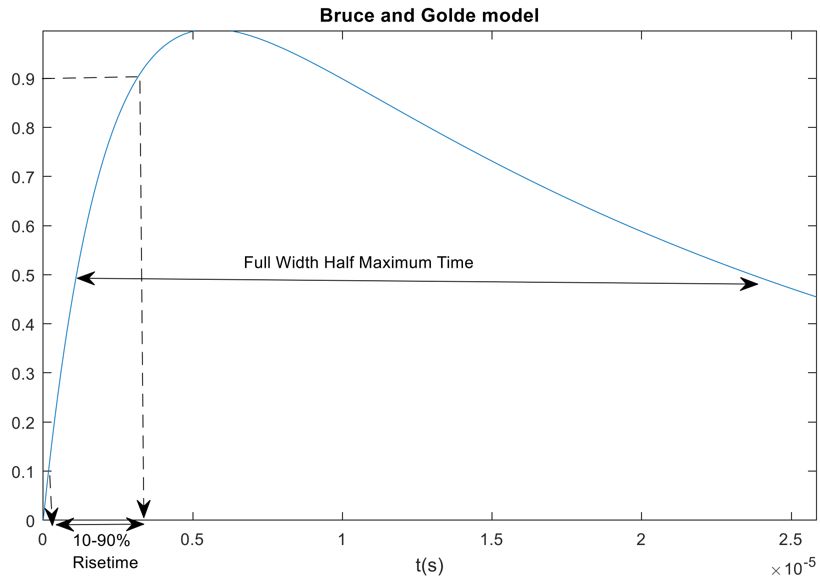


Figure 9. Normalized Bruce and Golde model with 10-90% risetime and full width half maximum time labeling

4. CONCLUSION

The function chosen for lightning return-stroke channel-base current approximation was continuous, simple, analytically differentiable, and integrable. In the rising part of the function, it can be concave-to-convex, or just convex. It can have the desired current steepness and different shapes of the decaying part, the exact chosen rising time and the chosen maximum current value without peak correction factor. In this study, it was found that NCBC model showed the best results among the six lightning models with similar waveshape with measured lightning current signal and compatible risetime and FWHM time of lightning current signal. NCBC model can be simplified and the values of lightning peak current and risetime can be chosen arbitrarily and independently from other parameters. The function can also be used in different lightning return-stroke models.

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