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Variations in Return Stroke Velocity and Its Effect on the Return Stroke Current along Lightning Channel

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***Abstract*— A direct lightning strike to a tall structure can impart high impact damage to electrical equipment that may be installed within and around the structure. This is due to the behaviour of the lightning return stroke current which generates a lightning electromagnetic field (LEMF) and consequently creates an induced voltage (LIV) on the electrical equipment. The lightning return stroke current along the channel is influenced by the parameters of the return stroke velocity (RSV). The return stroke velocity can be determined by measurement. Mostly, this value is considered as the average value in the range c/2 to 2c/3 for the first hundred metres of channel height, which should be taken into account when calculating the LEMF. Hence, the result of the evaluation of lightning return stroke current behaviour will inherently influence the evaluation of the lightning protection that is required for the electrical equipment surrounding the tall structure. However, when performing measurements, the return stroke velocity shows a changing trend value for different channel heights. In this paper, this trend will be used to evaluate the return stroke current at different heights along a channel. Thus, modelling of a lightning current along a channel was undertaken. Also, the return stroke velocity for different channel heights was calculated by considering the initial delay time. The results indicate that the lightning current along the channel has a significant effect on the changes in the return stroke velocity profile.**

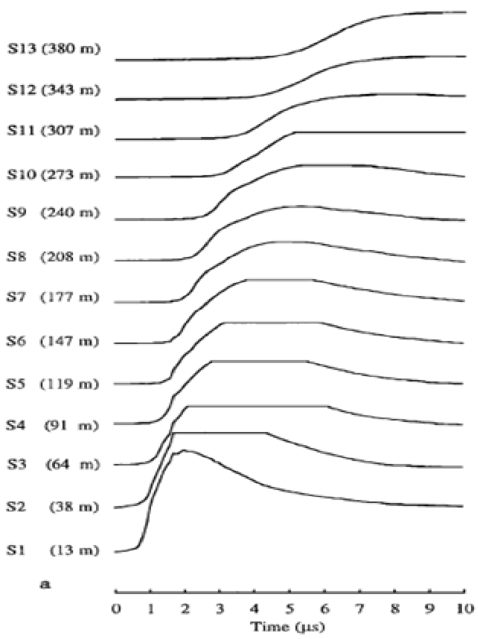
Keywords-component;*lightning, return stroke velocity, return stroke current*

I. INTRODUCTION

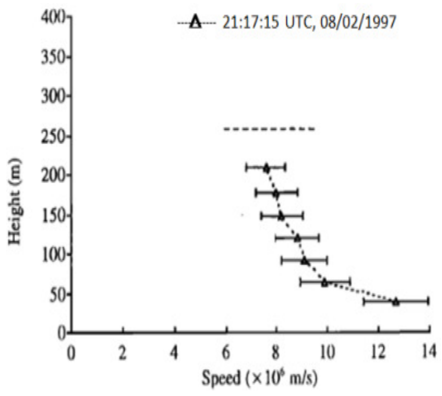
A lightning strike direct to a tall structure may cause physical and internal damage to equipment that may be installed within and around the structure [1, 2]. This may be caused by the lightning return stroke current that generates a LEMF and consequently produces a LIV on the equipment [3, 4]. The lightning return stroke current along the channel is influenced by the RSV parameter [5-7]. According to references [8, 9], the RSV parameter is assumed to be the average value in the range c/2 to 2c/3 for the first hundred metres of channel height, where *c* is the speed of light. It has become a typical value that is used in observing as well as in determining the lightning return stroke current behaviour and LEMF. Thus, it may contribute to the inherent result when deciding the appropriate level of lightning protection during the evaluation of the lightning return stroke current behaviour, and the LEMF when the average RSV is considered. Moreover, the RSV in measurement work represents a different value for different channel heights [10, 11]. The RSV shows an increasing trend for the first few hundred metres of channel height, reaching the maximum trend of RSV and showing a decreasing trend for increasing channel height [10-12]. However, consideration of these trends is not given much attention in modelling the lightning return stroke current along a channel in the presence of a tall structure. Hence, the aim of this paper is to evaluate the effect of changes in the return stroke velocity on the lightning return stroke current in the presence of a tall structure. Some basic assumptions are made such as 1) the lightning channel is a vertical strike to a tall structure, without any branches and 2) the tall structure is a monopole tower.

II. LIGHTNING RETURN STROKE MEASUREMENT

The lightning RSV is an important parameter which may influence the evaluation of the lightning return stroke current, the lightning electromagnetic field as well as the induced voltage. According to the literature [10], the RSV can be determined through an observation pattern during an optical intensity measurement. Each position height of the channel is considered with respect to the peak of time as shown in Fig. 1(a) and the determination of the lightning RSV as graphed in Fig. 1(b). Moreover, a typical measurement of lightning RSV was actively carried out through experimentation using natural and triggered lightning. In the case of natural lightning, the two and three dimensional return stroke speed was recorded which was based on the average speed of the visible part of the channel. A photoelectric device was used with streak camera equipment to capture and measure the lightning RSV. Table I shows the RSV for natural lightning measured by various authors and given as the average value. It can be seen that the lightning RSV increases and reaches a maximum value with increasing channel height. For the triggered lightning, the measured lightning RSV was completed at different channel heights with respect to the single and multiple strokes. Table II shows the triggered lightning RSV measured by various authors. The behaviour of the lightning RSV is viewed as an increasing trend for the first few hundred metres of channel height, which reaches a maximum value, then shows a decreasing trend with respect to the increasing height of the channel. Thus, the trends of these measurements show that the RSV is changing with respect to the different heights of the channel, whereby it is not an average value of the RSV as described before. Hence, this trend will be considered in this paper in order to evaluate the lightning return stroke current along the channel.



(a)



(b)

Figure 1. The return stroke (a) Optical intensity (b) speed of the return stroke [10]

TABLE I THE MEASURED LIGHTNING RSV FOR NATURAL LIGHTNING [12-14]

References	**Channel Height (m)**	**Velocity (m/s) × 10^8**	
		Mean	
		Two-dimensional velocity	**Three-dimensional velocity**
Jay & Langum	466.70	0.40	1.55
	956.82	0.86	1.75
	1539.35	1.39	1.78
Mach & Rust	Short channel (<500 m)	1.9±0.7	1.4±0.4
	Long channel (>500 m)	1.3±0.3	1.2±0.3
Idone & Orville	400-500	1.4	-
	1000-2000	1.1	-

TABLE II THE MEASURED LIGHTNING RSV FOR TRIGGERED LIGHTNING [10, 11, 15]

References	Channel Height (m)	Velocity (m/s) × 10^8				
		Stroke order				
		1	2	4	5	6
Olsen & Jordon	7-63	1.34	1.19	1.19	1.24	1.24
	63-117	1.62	1.81	1.83	1.78	1.58
	117-170	1.70	1.22	1.50	1.61	1.47
Wang & Takagi	Less than 60	1.30	1.50	-	-	-
	Greater than 70	0.5	0.40	-	-	-
Hussein & Janischewskyj	30-63	0.7	-	-	-	-
	63	0.7 to 1.44	-	-	-	-
	63-90	1.44	-	-	-	-
	90-120	0.43	-	-	-	-
	120	0.43 to 0.55	-	-	-	-
	120-144	0.55	-	-	-	-
	144-180	0.50	-	-	-	-

III. LIGHTNING RETURN STROKE MATHEMATICAL MODELLING

The behavioural trend measurement for changes in the lightning RSV with respect to different channel heights can be expressed by mathematical modelling as presented in Eq. 1 [16, 17] whereby v_1, v_2, v_3, λ_1, λ_2, λ_3 and λ_4 are the parameter constant values which depend on the peak of current as tabulated in Table III. In this paper, the RSV value for each channel height of 10 m, 20 m, 30 m, 40 m and 50 m is estimated from the plotted graph in Fig. 2 which is based on the profile RSV for the peak of lightning current at 9 kA, 12 kA and 15 kA. Also, an average RSV value is calculated and it is constant for all channel heights. In addition, the profile of the RSV changes along the channel is considered in the presence of a tall structure as illustrated in **Fig. 3**.

$$v(z') = \begin{cases} v_1 + \left(\frac{v_2}{2}\right)\left\{2 - \exp\left(\frac{-(z'-1)}{\lambda_1}\right) - exp\left(\frac{-(z'-1)}{\lambda_2}\right)\right\} & 1 \le z' \le 50 \\ v_3 \exp\left(\frac{-z'}{\lambda_3}\right) - v_4 \exp\left(\frac{-z'}{\lambda_4}\right) & z' \ge 50 \end{cases} \quad (1)$$

TABLE III RETURN STROKE VELOCITY PROFILE PARAMETERS FOR DIFFERENT CURRENT PEAKS [17]

I_p	Velocity, 10^8 m/s				λ,m			
(kA)	v_1	v_2	v_3	v_4	λ_1	λ_2	λ_3	λ_4
9	0.95	1.34	0.687	1.60	1.4	7.4	320	2000
12	1.02	1.35	0.711	1.66	1.4	7.4	400	2100
15	1.07	1.37	0.488	1.95	1.2	8.0	330	2000

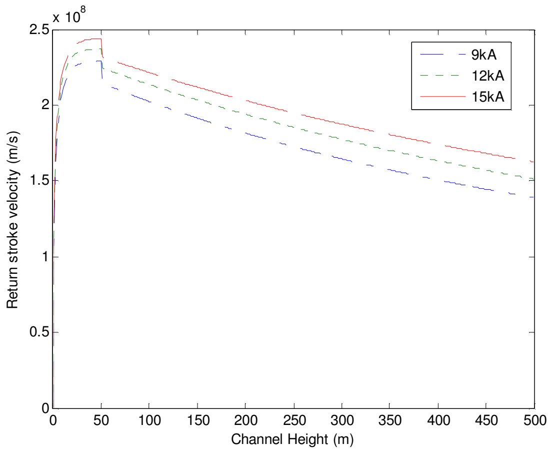


Figure 2. Return stroke velocity for different channel heights with respect to 9 kA, 12 kA and 15 kA peak current

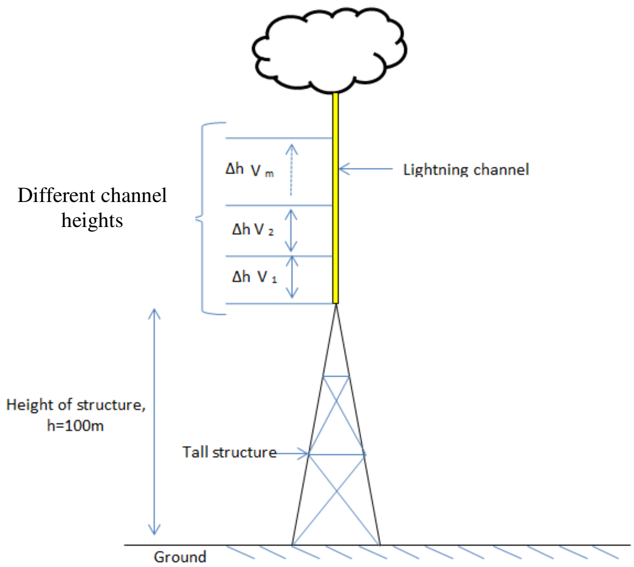


Figure 3. Illustration of a lightning strike to a tall structure and the profile of RSV changes along the channel height

The different RSVs at different channel heights will contribute to different amounts of time that are needed for the current to reach a certain height of the channel as expressed in Eq. 2 [17, 18]. In addition, Eq. 3 describes the lightning current along the channel in the presence of a tall structure by considering the RSV changes.

$$t_m^{S_n} = \sum_{m=1}^{S_n} \frac{\Delta h}{v_m} \quad (2)$$

where S_n is the number of the Δh along the channel and v_m is the RSV for each height.

$$i(z',t) = \begin{bmatrix} P(z'-h)i_o(h, t - t_m^{S_n}) - \rho_t i_o\left(h, t - \frac{z'-h}{c}\right) \\ +(1-\rho_t)(1+\rho_t)\sum_{n=0}^{\infty} \rho_g^{n+1}\rho_t^{n} i_o\left(h, t - \frac{z'+h}{c} - \frac{2nh}{c}\right) \end{bmatrix} \quad (3)$$

where ρ_t and ρ_g are the top and ground current reflection coefficients respectively, n is the number of reflection currents inside the tower, h is the tower height, i_o is the channel base current, c is the speed of light, v is the return stroke velocity and $P(z'-h)$ is the return stroke current models.

IV. RESULT AND DISCUSSION

In order to consider the effect of changes in the RSV on the peak current along the channel, the sum of two Heidler current functions was used as the channel base current. Also, the current model of the Modified Extended Transmission Line with decay Exponential (MTLE) was considered. The results were generated according to 1) different channel heights and the average channel height and 2) different peaks of current for the RSV profile. The results are discussed accordingly. Table IV shows the peak of lightning current along the channel for the RSV profile at 12 kA peak current. The lightning currents are evaluated for RSV changes with respect to channel heights of 10 m, 20 m, 30 m, 40 m, and 50 m and at the RSV average with respect to average channel heights of 100 m, 500 m and 1000 m. The result shows that the peak current for the RSV changes and the RSV average tend to significantly decrease with respect to an increasing channel height. However, the peak current for the RSV changes is much higher than the peak current arising from the RSV average. Also, different peak currents are presented for different channel heights for the RSV changes as compared to the RSV average at the first channel height of 100 m. Thus, the changes in RSV have a strong effect on the value of the peak current. Therefore, when evaluating the lightning return stroke current along the channel, the changes of RSV on the peak current needs to take account since, it may affect the evaluating of lightning electromagnetic (LEMF) as well as lightning induced voltage (LIV).

TABLE IV PEAK OF LIGHTNING CURRENT ALONG THE CHANNEL FOR (a) RSV CHANGES AND (b) RSV AVERAGE

$z'_{changes}$ (m)	$I_{peak,changes}(kA)$
10	8.79
20	8.73
30	8.66
40	8.59
50	8.52

(a) RSV changes

$z'_{average}(m)$	$I_{peak,average}(kA)$
100	8.05
500	7.73
1000	6.67

(b) RSV average

In addition, Table V represents the percentage difference between the peak current due to the RSV changes with the peak current due to the RSV average. The result shows that there is at least a less than a 10% percentage difference found in the first channel height at 100 m as compared with the RSV changes for the first channel height of 50 m. However, this percentage difference increases as the RSV average increases for a channel height of 500 m and 1000 m. The percentage difference is calculated by: $\frac{I_{peak,RSV changes}-I_{peak,RSV\ average}}{I_{peak,RSV\ average}} \times 100\%$. Hence, the result indicates that for first of 100 m of channel length, the current peak only have been less affected by the changes of RSV. However, for those who are working on the evaluating of LEMF for channel length more than 100 m, the changes of RSV on the current peak for each height of channel length should be considered. The percentage differences are high as increase the channel length height. In addition, the RSV changes react with the profile of the RSV which is dependent of the peak current as graphed in Fig. 2. Three types peak current are selected to see the effect of the RSV change profile on the peak current. Fig. 4 indicates the peak current that is generated by applying the different profile RSV changes. It shows that the peak current is slightly reduced as the channel height increases. However, the peak current is seen to be highest for the profile RSV changes, 15 kA. Also, there is at least a 20 % difference between the peak current at an RSV profile of 12 kA and at 15 kA. Thus, the profile RSV changes significantly affect the peak current, which may contribute to the effect evaluating the LEMF as well as the LIV.

TABLE V PERCENTAGE DIFFERENCE BETWEEN THE PEAK CURRENT DUE TO THE RSV CHANGES AND RSV AVERAGE

$z'_{changes}$ (m)	Percentage difference (%) at $z'_{average}$ (m), $100m$	Percentage difference (%) at $z'_{average}$ (m), $500m$	Percentage difference (%) at $z'_{average}$ (m), $1000m$
10	9.19	13.71	31.78
20	8.44	12.94	30.88
30	7.58	12.03	29.84
40	6.71	11.13	28.79
50	5.83	10.22	27.73

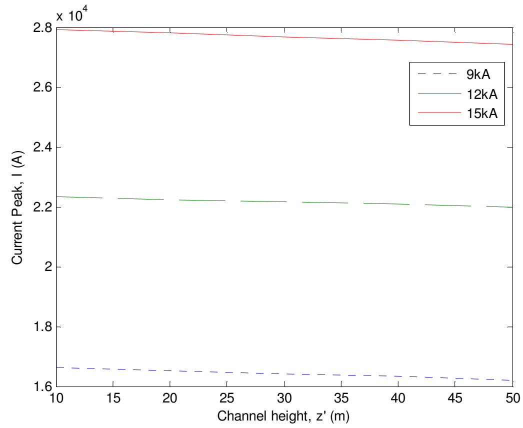


Figure 4. Peak current for the different RSV profiles

Moreover, Fig. 5 shows the waveform of the lightning return stroke current for the RSV changes as well as the RSV average. The result indicates that the initial time with respect to the RSV changes show an increasing time as the channel height increases. However, it is less than the initial time derived from the RSV average. The initial time for the RSV average is dependent on the average channel height selected. As the average channel height increases, the initial time also increases.

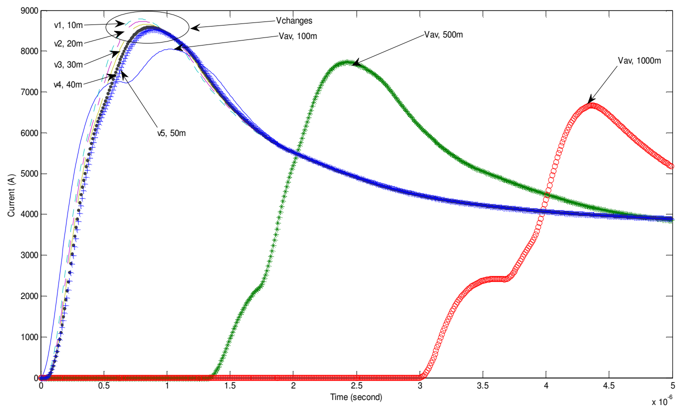


Figure 5. Lightning return stroke current for RSV changes and RSV average at profile RSV, 12 kA

V. CONCLUSION

The effect of changes in the return stroke velocity on the value of the lightning return stroke current has been considered and discussed accordingly. The results show that the peak current along the channel is significantly affected by RSV changes as well as the difference of RSV profile for increasing of channel heights. However, the peak current of RSV average is seen to significant effect on the average of first 100 m channel height. Hence, the changes peak current along the channel is dependent on the RSV changes, RSV profile as well as at the first 100 m channel height average. All these changes are suggested to be taken into account when considering the evaluation of LEMF, since it if the effect on the evaluation of the LIV. An appropriate result in evaluation LIV as well as protection system may generate with considering the changes peak current.

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