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An Extension of the Guided Wave M-Component Model Taking into Account the Presence of a Tall Strike Object

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***Abstract*— We present in this paper an extension of the guided-wave M-component model of Rakov et al. considering the presence of a vertically elevated strike object. The tall object is represented as a lossless, uniform transmission line. Expressions for the current distribution along the channel and along the strike object are derived. Simulation results for the electric field are presented. The results show that, for very tall structures and fast M-component waves, the presence of a tall strike object can result in a sharp peak superimposed on the M-component electric field. For slow M-component waveforms or for moderately tall structures, the presence of the tall strike object can be disregarded in the M-component field calculations.**

Keywords—M-component; tall objects; current; electric fields

I. Introduction

The M-component mode of charge transfer occurs during the continuing current stage in downward lightning [1]. M-component-like processes also occur during the initial stage of upward lightning initiated by tall structures or in rocket-triggered lightning. More information on the M-component mode of charge transfer to ground can be found in Section 4.8 of [2], pages 107-111.

Instrumented towers (e.g., [3]-[9]) are used to obtain information on lightning currents and the associated electromagnetic fields in their vicinity. Experiments using rocket-triggered lightning (e.g., [10]-[12]) also provide an important source of information to investigate the physics and characteristics of various stages in a lightning discharge, including subsequent return strokes and M-components.

In upward discharges, pulses superimposed on the initial continuous current (ICC pulses) were investigated by Wang et al. [12] who noted similarities between some of the ICC pulses and M-components in downward lightning. The mechanism involved in the formation of the ICC pulses in tower-initiated lightning was also studied by Miki et al. ([13]-[14]) and Flache et al. [15]. Zhou et al. ([6], [16]) proposed a classification of ICC pulses into mixed mode pulses and classical M-component mode pulses according to the height of the junction point between a newly formed branch or a reactivated branch and the ICC channel. Different types of current pulses in upward lightning were investigated and analyzed by Azadifar et al. [17] and He et al. ([18]-[20]).

M-components and ICC pulses occurring in upward flashes initiated by tall towers are usually modelled by neglecting the transient processes along the tower. This assumption is, in general, justifiable because of the relatively slow risetimes of M components. However, in case of very tall structures such as the CN Tower (553 m) in Toronto (e.g., [3]-[4]) or the Tokyo Skytree (634 m) in Tokyo [8], and for M-components with relatively fast risetimes, the effect of the tower might be of importance.

The aim of this paper is to present an extension of the guided-wave M-component model of Rakov et al. [21], considering the presence of a vertically elevated strike object.

The paper is organized as follows. Section II briefly presents the classical M-component model in absence of any tall structure. The extension of the M-component model considering a tall strike object is presented in Section III. Section IV presents simulation results and a discussion on the effect of the height of the tall structure on M-component-generated fields. The paper ends with general conclusions presented in Section V.

II. Classical Guided-Wave M-Component Model

In the model proposed by Rakov et al. [21], the M-component is represented as a superposition of two propagating current waves: a downward incident current and an upward current reflected at the bottom of the lightning channel.

Fig. 1 illustrates the M-component model in which an M-component wave $i_H(t)$ is injected at a point located at a height H and travels downward with a speed v. At time H/v, when the incident current wave reaches the ground, a reflected wave travels upward at the speed of the original downward wave v (see Fig. 1). The reflection coefficient depends on the characteristic impedance of the channel and the impedance of the ground (Z_{ch} and Z_g). Assuming a perfect reflection off the ground, the distribution of the current along the vertical channel is written as

$$i(z,t)=\begin{cases} i_H\left(z,t-\dfrac{H-z}{v}\right) & if\quad t<\dfrac{H}{v} \\ i_H\left(z,t-\dfrac{H-z}{v}\right)+i_H\left(z,t-\dfrac{H+z}{v}\right), & if\quad t\geq\dfrac{H}{v}\end{cases} \quad (1)$$

III. M-Component in the Presence of a Tall Vertical Strike Object

The geometry of the problem is presented schematically in Fig. 2. We consider the strike object as a lossless uniform transmission line of length h, with a characteristic impedance Z_t. The reflection coefficients at the ground ρ_g and at the tower top ρ_t are shown in Fig. 2. The incident current wave reaches the tower tip at the time of H_a/v, and it is partially reflected upward at the same speed of the original downward wave. The transmitted wave is assumed to propagate downward along the tower at the speed of light.

As shown in Fig. 2, multiple reflections and transmissions will occur along the tower. In the next subsections, we will derive equations describing the current distribution along the channel and the strike object, following a procedure used for return strokes by Rachidi et al. [23]-[24]. In the derivation, we will disregard any reflections from the top of the channel.

A. *Current distribution along the lightning channel*

The current distribution along the lightning channel can be written as a time sequence

$$\begin{aligned} i(z,t) &= i_H\left(H,t-\frac{H-z}{v}\right)u\left(t-\frac{H-z}{v}\right) \\ &-\rho_t i_H\left(H,t-\frac{H+z-2h}{v}\right)u\left(t-\frac{H+z-2h}{v}\right) \\ &+(1+\rho_t)(1-\rho_t)\rho_g i_H\left(H,t-\frac{H+z-2h}{v}-\frac{2h}{c}\right)u\left(t-\frac{H+z-2h}{v}-\frac{2h}{c}\right) \\ &+(1+\rho_t)(1-\rho_t)\rho_g^2\rho_t i_H\left(H,t-\frac{H+z-2h}{v}-\frac{4h}{c}\right)u\left(t-\frac{H+z-2h}{v}-\frac{4h}{c}\right) \\ &.... \end{aligned} \quad (2)$$

Regrouping the terms, we obtain

$$\begin{aligned} i(z,t) = \Bigg\{ & i_H\left(H,t-\frac{H-z}{v}\right)u\left(H,t-\frac{H-z}{v}\right) \\ &-\rho_t i_H\left(H,t-\frac{H+z-2h}{v}\right)u\left(H,t-\frac{H+z-2h}{v}\right) \\ &+(1-\rho_t)(1+\rho_t)\sum_{n=0}^{\infty}\rho_g^{n+1}\rho_t^{n} i_H\left(t-\frac{H+z-2h}{v}-\frac{2nh}{c}\right)u\left(t-\frac{H+z-2h}{v}-\frac{2nh}{c}\right)\Bigg\} \end{aligned} \quad (3)$$

where n is an index representing the successive multiple reflections occurring at the two ends of the strike object and v is the M-component wave propagation speed in the channel. The first term in (3) is the incident (downward) wave, the second term is the reflected (upward) wave from the top of the strike object, and the summation term corresponds to multiple transmitted waves from the strike object.

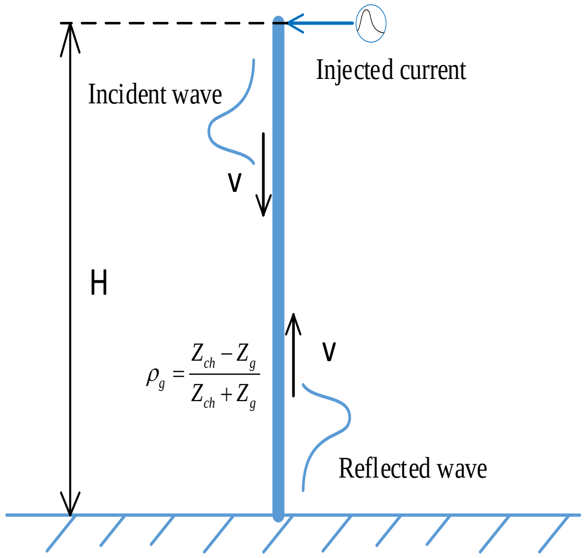

Figure 1. M-component model for a flat ground without a tall object.

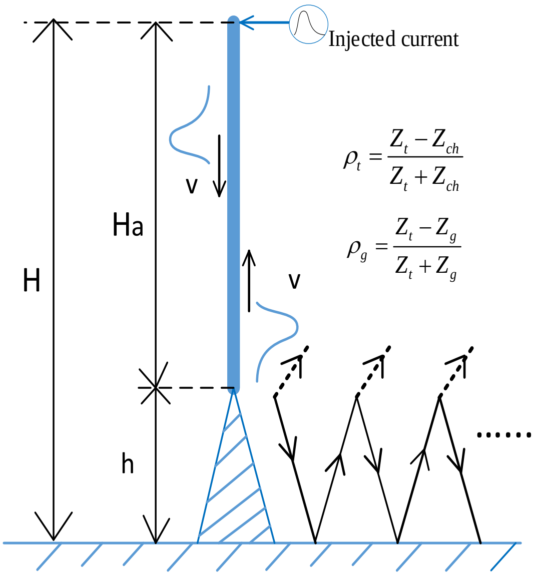

Figure 2. M-component model associated with a tall object.

Note further that when only the first pair of terms (n=0) of the sum is retained, and assuming $\rho_g=1, h=0, \rho_t=0,$ $H=H_a$, (3) reduces to (1).

B. *Current distribution along the strike object*

The current distribution along the tall object is given by

$$
\begin{aligned}
i(z,t) = & (1-\rho_t) i_H\left(H, t-\frac{H-h}{v}-\frac{h-z}{c}\right) u\left(t-\frac{H-h}{v}-\frac{h-z}{c}\right) \\
& +(1-\rho_t)\rho_g i_H\left(H, t-\frac{H-h}{v}-\frac{h-z}{c}-\frac{2h}{c}\right) u\left(t-\frac{H-h}{v}-\frac{h-z}{c}-\frac{2h}{c}\right) \\
& +(1-\rho_t)\rho_g \rho_t i_H\left(H, t-\frac{H-h}{v}-\frac{h-z}{c}-\frac{2h}{c}\right) u\left(t-\frac{H-h}{v}-\frac{h-z}{c}-\frac{2h}{c}\right) \\
& +(1-\rho_t)\rho_g^2 \rho_t i_H\left(H, t-\frac{H-h}{v}-\frac{h+z}{c}-\frac{4h}{c}\right) u\left(t-\frac{H-h}{v}-\frac{h+z}{c}-\frac{4h}{c}\right) \\
& ....
\end{aligned} \tag{4}
$$

Regrouping the terms, we obtain

$$
\begin{aligned}
i(z,t) = & (1-\rho_t)\left\{ \sum_{n=0}^{\infty} \rho_g^{\,n} \rho_t^{\,n} i_H\left(t-\frac{H-h}{v}-\frac{h-z}{c}-\frac{2nh}{c}\right) u\left(t-\frac{H-h}{v}-\frac{h-z}{c}-\frac{2nh}{c}\right) \right. \\
& \left. +\sum_{n=0}^{\infty} \rho_g^{\,n+1} \rho_t^{\,n} i_H\left(t-\frac{H-h}{v}-\frac{h+z}{c}-\frac{2nh}{c}\right) u\left(t-\frac{H-h}{v}-\frac{h+z}{c}-\frac{2nh}{c}\right) \right\}
\end{aligned} \tag{5}
$$

IV. Simulation Results and Analysis

A. Simulation parameters

Two different waveforms for the M-component wave, represented using Heidler's function [25] and shown in Fig. 3, were considered in the analysis. The selected waveform parameters (risetime and full width at half maximum (FWHM)) are in the range of the observed values of the M-component-type pulses measured at the Säntis tower [19]. The current parameters for the two considered waveforms are shown in Table I. The current magnitude was set to 1 kA for the two adopted waveforms. The asymmetrical waveform coefficient (AsWC) [1] for the two selected waveforms are, respectively, 0.79 and 0.58, satisfying the criterion for an M-component mode of charge transfer [19]. Furthermore, the 10-90% risetimes are 11.0 μs and 404.0 μs, both satisfying the criterion of Flache et al. [15], in which ICC pulses with higher-than-8 μs risetimes were ascribed to the M-component-type of charge transfer. The risetime of the fast M-component waveform is within the range of measured M-components of rocket-triggered lightning [11] and of natural negative cloud-to-ground lightning measured in Morro de Cachimbo [26]. The 10-90% risetime of the slow waveform agrees well with the data reported by Thottappillil et al. [27].

Two different heights for the tall object are considered: (i) 124 m, corresponding to the Säntis Tower in Switzerland, and (ii) 553 m, corresponding to the CN Tower in Toronto, Canada. The ground and tower top reflection coefficients were assumed to be, respectively, 1 and -0.8 in all the considered cases.

The junction point height between a newly formed branch or a reactivated branch and the ICC channel was assumed to be 2 km and the M-component wave speed was set to 1×10^8 m/s (see Uman and Rakov [28], page 182).

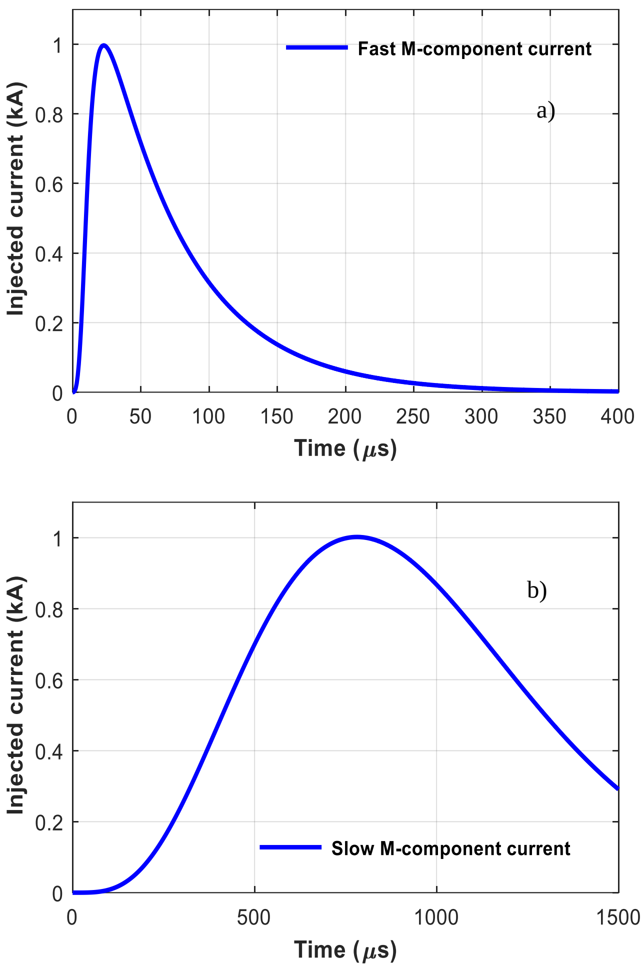

Figure 3. Injected current. (a) Fast waveform. (b) Slow waveform.

TABLE I
Parameters of the M-component injected current

	I(kA)	τ_1(μs)	τ_2(μs)	n	10-90% risetime (μs)	AsWc
Fast Waveform	1.02	12	60	3	11.0	0.79
Slow Waveform	0.77	2000	200	4	404.0	0.58

B. Electric fields

The electric field was evaluated at a distance of 15 km using closed-form expressions considering a perfectly-conducting ground [29]-[30]. The simulation results are shown in Fig. 4.

As expected, it can be seen that for the slow waveform, the electric field is not affected by the presence of the tall

[1] A fully symmetrical pulse is characterized by an AsWC equal to 1/2, while waveforms characteristic of return strokes or mixed modes have AsWCs close to 1.0. According to *He et al*. [19], if AsWC for a pulse superimposed on the ICC is lower than 0.8, the pulse is classified as an M-component-type ICC pulse.

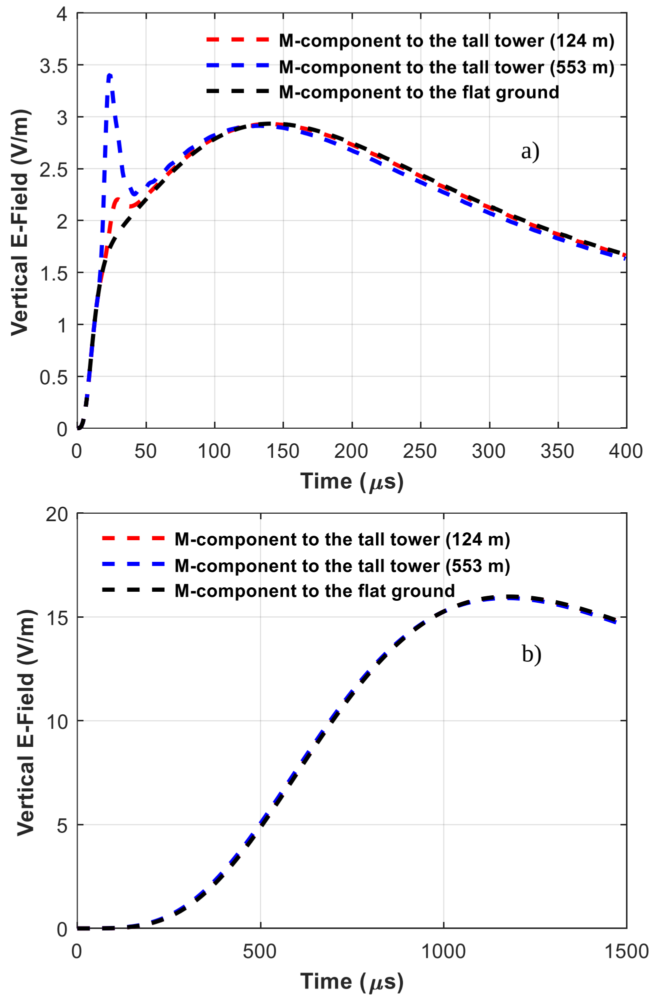

Figure 4. Electric fields at 15 km. (a) Fast M-component current waveform. (b) Slow M-component current waveform. H=2 km and v=1 × 10^8 m/s.

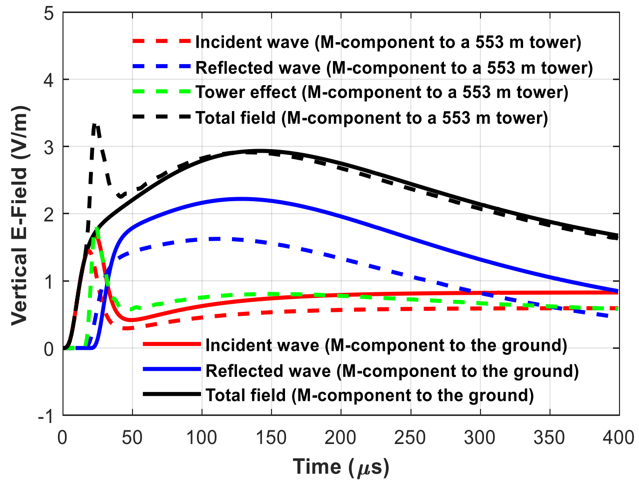

Figure 5. M-component electric field at 15 km. Fast M-component current waveform, 553-m tall strike object, H=2 km and v=1 × 10^8 m/s.

strike object. However, for the fast waveform, the 553-m tall tower cannot be regarded as an electrically short object and its presence results in the appearance of a sharp peak.

In Fig. 5, we have presented the contribution of the channel and the tower to the total electric field. It can be seen that the sharp peak is the result of the contribution of the current along the tower, which travels at the speed of light.

The sharp peak in Fig. 4a should not be confused with the microsecond-scale pulse due to the junction process of an in-cloud leader and the current-carrying channel (Rakov et al., [31]), a process disregarded in the present model and occurring in the electric fields prior to the slower pulse corresponding to the M-component wave propagation along the tower.

V. Conclusions

We presented in this paper an extension of the guided-wave M-component model of Rakov et al. considering the presence of a vertically elevated strike object.

The tall tower was represented as a lossless, uniform transmission line. Expressions for the current distribution along the channel and along the strike object were derived. Simulation results for the electric field at a distance of 15 km were presented.

The results show that, for very tall structures and fast M-component waves, the presence of a tall strike object can result in a sharp peak superimposed on the rising portion of the M-component electric field. For slow M-component waveforms or for moderately tall structures, the presence of the tall strike object can be disregarded in the M-component field calculations.

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