Return-stroke radiation by a branched channel: a transmission-line discharge model

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23 May 2024

RETURN-STROKE RADIATION BY A BRANCHED CHANNEL: A TRANSMISSION-LINE DISCHARGE MODEL

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Abstract: This paper is concerned with the effects of branching in the lightning channel on the radiated fields of the return stroke. To model the current on the channel, we employ some recent results on the discharge of a transmission line that simulates the channel discharge. The effect of branches on the upward traveling return stroke pulse appears as a pulse-driven release of charge from the branch into the main channel. For the sake of simplicity, far-field radiation is obtained employing the modified transmission line (MTL) approximation for pulse propagation on the channel, which yields closed-form radiation.

1. Introduction

Modeling of lightning return stroke is important for application to channel current reconstruction, for understanding some basic physical phenomena, and to provide reliable and simple models for the assessment of the fields produced by lightning in EMC and other endeavors (e.g. see the review in [1]).

While most of the work on this subject has been concerned with straight channel models, the observed electromagnetic field radiated by lightning discharges often shows a "fine structure" that deviates from the smooth shape obtained with the assumption of radiation from a straight channel.

Irregularities of the channel are naturally thought of as one of the reasons of the irregularity in field waveforms, because of the channel geometry influence on both the channel current, and on the radiation processes. It is therefore important to assess the effect and relevance of complexities in the channel model, considering in detail a realistically tortuous and branched geometry.

Recent work on the fine structure of the lightning discharge fields [2,3,4,5...] has added to a few previous publications (e.g. [6,7,8]) on this subject. The effect of channel tortuosity was analyzed in [2,3,4], employing a transmission-line model for the current on the channel and its (far) radiation.

The effect of channel «kinks» was shown to give rise to time-localized glitches in the field waveform that, taken all together, build up the fine structure of the waveform itself.

In the first works by the authors, the focus was on the effect of *tortuosity* of the *main* channel, and branching was not considered.

Branching can be included in this kind of approach, providing a model for the current behavior at branching points. It has been done this in more recent works by the authors [5,9], which extended the so-called modified transmission line (MTL) model, considering exponential altitude decay [13], to current partition at branches, based upon transmission line theory and a model for the channel and branch characteristic impedances.

On the other hand it was shown in [3,4,10] that return stroke formation and propagation (on a straight channel) can be considered as parts of the same model describing self-consistently the *discharge* of an initially *charged* lossy transmission line.

This kind of approach gives results that can be brought into congruence with all terms of the Masters-Uman-Lin-Standlers [11] (MULS) current model (except for the uniform current, that could however be introduced), and recovers the MTL predictions as the asymptotic early-time approximation. In particular, the results for pulse propagation up the channel yield a clear interpretation in terms of a charge-release process that is driven by the upward propagation of the front of the breakdown pulse.

The potential of the considered approach is apparent in connection with its extension to branched lightning, since it allows a more direct modeling of the transient current phenomena at branching points. In fact in this case the current «partition» is replaced by a release process of the charge stored in the branch that is more physically appealing, yet being completely described by the transmission line equations of the model.

In view of the above, the present work addresses the analysis of the effect of branching considering the channel current obtained from the charged transmission

line model applied to a branched channel.

As discussed in [1], all models based on transmission lines (TL) - termed «distributed RLC» in [1] - miss some part of the boundary-value problem for the Maxwell equations that describe the (macroscopic) problem of channel radiation; at the same time, as recognized in the cited work, TL-based models afford a simple, «engineering» model, that has also the potential to shed some light on the channel current behavior and radiation phenomena.

This constitutes one of the rationales of the present work, especially in the presence of the complications added by the presence of a non-straight, branched channel.

In addition, we remark that thin, conducting wire antennas can be viewed as (uniform or non-uniform) slanted bi-conical lines, as originally done in the works by Shelkunoff. Lastly, it should be noted that the present approach is based on a complete, self-consistent treatment of lossy transmission lines, which is not standard.

In order to obtain simple radiation fields, our results are then approximated to employ radiation from MTL; this does not constitute a limitation of the technique proposed here, and work is presently under way to determine the radiated field from the complete results of the present model.

2. Current modeling on the branched channel

The geometry of the channel is obtained as described in [5], starting from a (stochastic-based) procedure that simulates the stepped-leader phase and generates a branched, tree-like discharge path; this is then simplified into a tree-like structure with straight segment between branching points (as opposed to tortuous portions of channel between branches).

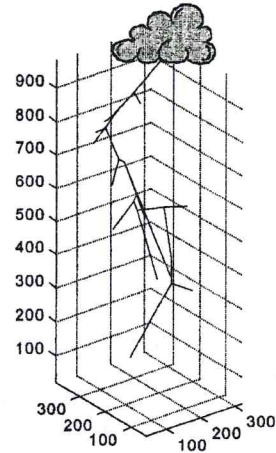The results shown here refer to the geometry in Fig.1.

Figure 1: Geometry of the branched channel considered here.

The basic model for current on the branched channel is that of a network of *charged* transmission lines, whose discharge on the ground termination generates the return-stroke currents. In our model, each segment of the main channel, and all the segment of the branches, are modeled as lossy transmission lines, and the model self-consistently accounts for both the base pulse formation and the subsequent propagation of the transient current on the entire branched channel. As an example, Fig.2 shows such a circuit for the single case
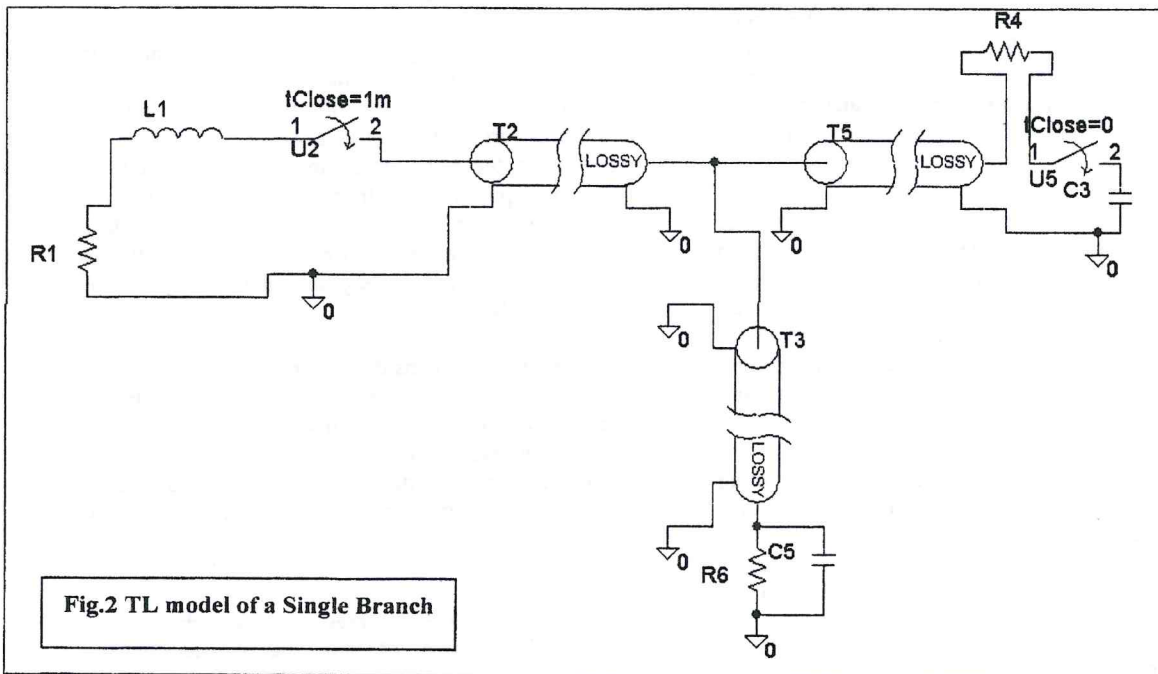

Fig.2 TL model of a Single Branch
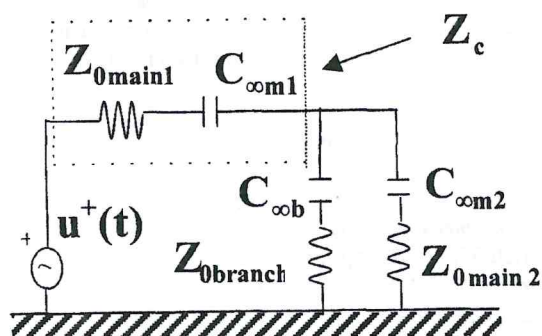
of a single-branch channel.

Figure 3: Equivalent circuit

As already mentioned in the Introduction, the rationale for the model and the interpretation of the results is as detailed in [2,3,10] for the straight channel; here we will summarize only what specifically pertains to the branched case.

We begin by noting that the model is completely specified once the geometry of the channel and all the characteristic p.u.l. parameters, C', L', R' of the lines are specified.
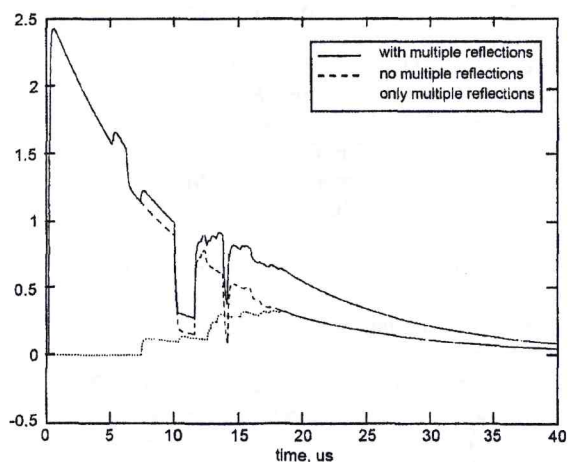

Figure 4: Electric radiated field, present model.

The transmission lines are lossy RLC (no shunt loss conductance, see [2,3]), and the p.u.l. parameters C', L', R' can be obtained starting from the characteristic impedance Z_0 and phase velocity v of the corresponding lossless transmission line, and the high-frequency limit of the p.u.l. attenuation; the latter is the MTL frequency-independent decay length, here called L_c.

The phase velocity is here assumed constant everywhere and $v=c/3$ in order to compare the different approaches,

even if more physical results have been obtained by the authors considering different phase velocities in the different sections, i.e. in the branches and in the main channel, due to the different physical phenomena involved.

The characteristic impedances of the lossless lines can be either obtained via the slanted biconical-line model (SBM) in [5], or employing a heuristic scaling between the main channel and the branches [5].

The entire current evolution of the return stroke discharge is modeled in this way, but on each segment the current is given by dispersive, lossy propagation terms that do not allow to find the transient radiated fields in closed-form expressions. On the other hand, the MTL model affords simple, «engineering» closed-form results for far radiation; in order to retain this simplicity, with the associated possibility of interpretation, the current on line has not been considered to its full extent.
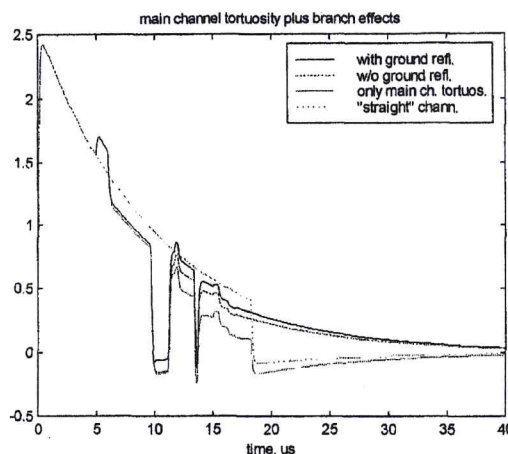

Figure 5: Electric radiated field, previous model

Only the early-time (i.e. MTL-like) part of the solution has been retained for calculation of the lightning radiation; in our model, this entails a simplified circuit in which:

1. propagation between two discontinuities (i.e. between any two branch points) is described by the MTL approximation (undistorted pulse propagation plus attenuation)

2. at each branching the discontinuity effect on the incident traveling pulse is evaluated using the equivalent circuit representation of the incident pulse, and the characteristic impedance Z_c of the lines is substituted for its early-times RC equivalent circuit, as derived in [2,3,10]:

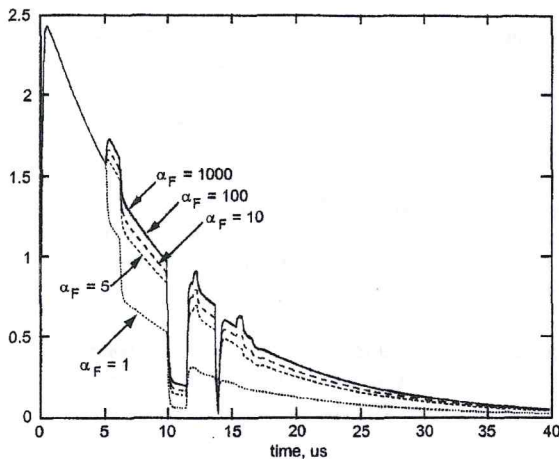$$Z_c(\omega) \approx Z_0 + 1/(j\,\omega\,C_\infty),$$

Fig. 6 Electric radiated field new model, scaling parameter sensitivity.

$$C_\infty = C' L_c$$

as shown in Fig. 3

For the first branch, at height h_{b1}, the incident, triggering voltage pulse $u^+(t)$ is the MTL-propagated early time approximation of the voltage at the base of the channel,

$$u^+(t) = u_0^+(t - h_b/v) \exp(-h_b/L_c) ,$$

$$u_0^+(t) = V_0 - a \exp(-t/t_r) - b \exp(-t/t_f)$$

where t_r and t_f are the rise and fall times [10], and a and b are coefficients depending on t_r, t_f and V_0 is the initial voltage.

At the branch, the circuit is solved and voltage and currents transmitted across the discontinuity are taken as incident for the next branch, and so on. This way, the effect of branches on the upward traveling return stroke pulse turns out to be modeled as a release of charge from the branch into the main channel, triggered by the passage of the upward traveling wavefront (analogous to the breakdown pulse of the MULS model).

3. Results

Typical results are shown in Fig. 4, that refer to the channel geometry shown in Fig. 1. In the shown results, the (frequency-dependent) impedance of the branches is obtained from that of the main channel as

$$Z_{c\,branch} = \alpha_F \, Z_{c\,main}$$

and Fig. 6 reports the effect of this scaling parameter, which appears weak. The results are also compared to those obtained with the model in [5], reported in Fig.5.

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