Calculation of Lightning-Induced Voltages with RUSCK's Method in EMTP Part I: Comparison with Measurements and Agrawal's Coupling Model

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Abstract - **This paper discusses the computation of lightning-induced voltages on a transmission line with a phase and neutral conductor, using an implementation of Rusck's theory in the Electromagnetic Transients Program EMTP. The results obtained are compared with measurements and with equations for the estimation of the maximum induced voltage, for an experimental distribution line subjected to rocket triggered lightning flashes. In this comparison good agreement is found among the EMTP-RUSCK method, measurements on the experimental line, and the equation for the estimation of the maximum induced voltage based on the Agrawal coupling model.**

Keywords: EMTP, Induced Voltage, Lightning, Rusck's Theory.

I. INTRODUCTION

Lightning flashes nearby electric power lines induce overvoltages which can cause faults and disturbances in electrical and electronic devices [1], [2]. It is important to understand and analyse these induced overvoltages, in particular because new equipment with power electronic devices is generally sensitive to such overvoltages.

This paper deals with voltages induced by nearby lightning using Rusck's theory implemented in the Electromagnetic Transients Program EMTP. The effects of lightning in the vicinity of lines are evaluated so that they can be taken into account in the design and protection of lines [3], [4], [5].

The results obtained from the EMTP-RUSCK method are compared with measurements on an experimental distribution line, which was subjected to nearby triggered lightning flashes [6] and with calculations using Agrawal's coupling method [7].

Triggered-lightning flashes provide important parameters that are extremely useful for engineering applications, since the likelihood of obtaining these same parameters from natural lightning is low and would also require an extended period of time to get a meaningful database. With experiments it is possible to measure the major factors involved in the lightning stroke itself as well as the induced voltage on the experimental line. Despite many discrepancies between triggered and natural lightning flashes, Fisher believes that " *the leader-return stroke sequences in triggered lightning are believed to be very similar to those constituting the subsequent strokes of natural cloud-to-ground lightning"* [7]. Other researchers come to the same conclusion [8], [9], [10], [11].

II. RUSCK'S THEORY

Since Rusck developed his theory to calculate induced voltages from natural lightning, many researchers have discussed its validity [6], [13]. Within the approximations originally conceived, Rusck's model predicts essentially the same results as Agrawal's model [14]. Rusck's model will be used here to predict induced voltages, using data from studies on an experimental line with triggered lightning. Previous work has shown that the EMTP-Rusck method gives good results for triggered lightning flashes [3] [4].

With Rusck's theory, it is possible to obtain an analytical expression for the lightning induced voltage at a point along an infinite homogeneous line. Finite lines with simple discontinuities can be considered if the theory is slightly modified [15]. For more details about this method and Rusck's classical expressions, see the appendix.

Methods for using current sources applied to segments of the line have been presented by Rusck in his original work [16], and also by Anderson [17] and Porto [18].

III. EMTP IMPLEMENTATION

The approach used in this paper to implement Rusck's theory inside the EMTP is to take advantage of a facility in the Microtran Version of the EMTP called CONNEC [19]. Similar facilities may be available in other EMTP versions.

Microtran uses the compensation method to handle nonlinearities. This method excludes the nonlinear branches from the network, and replaces them by current sources [20]. The value of the currents will depend on the Thevenin equivalent network (seen from the nonlinear element nodes) and on the nonlinear characteristics themselves. Therefore, the equations of the linear network and of the nonlinear elements must be solved simultaneously.

The Microtran version mentioned before makes this compensation method approach accessible to the user through an interface that does not require any code changes in the EMTP proper. The EMTP calculates, at each time step, the Thevenin equivalent circuit of the linear network seen from the user-specified nodes. It then calls (at the same time step) the subroutine CONNEC to which it passes the values of the Thevenin impedance matrix (Z_{thev}) and open-circuit voltages (V^0) through the argument list. This subroutine must then return the value of the currents through the nonlinear elements to the main program, as shown in Fig. 1.

The subroutine CONNEC enables users to write their own code to describe their own nonlinear elements (for example, the distributed current source from Rusck's theory), and to interface these elements with the EMTP, without having to touch the EMTP code itself. In older versions, CONNEC had to be written in FORTRAN, while in the newest version it can also be written in C^{++} or other languages, to be attached as "DLL" files.

IV. SYSTEM CONFIGURATION

The model previously described was used to study the case of a distribution line with a phase and neutral conductor. The neutral conductor is grounded in three points along the line, and the lightning flash strikes in the vicinity of the line. There is no other equipment installed on the line. The ends of the line were matched with a 455Ω non-inductive resistor connected between the phase and neutral conductor in order to avoid reflections [6].

It is important to note that this configuration represents typical rural distribution lines that can be constructed in regions with elevated keraunic levels, which are very common in Brazil.

The configuration used in this study is presented in Fig.2, with the following parameters:

height of phase conductor1 – 7.5m;
height of neutral conductor2 – 5.68m;
grounding resistance - 50Ω;
distance between the line conductors and the lightning striking point - 145m.

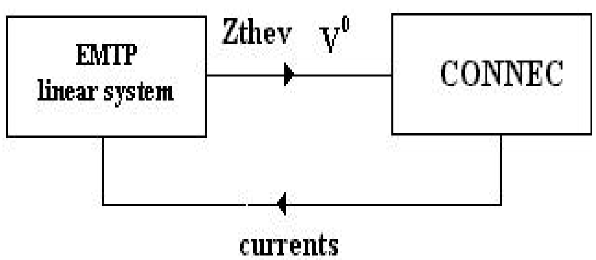

Fig. 1. Subroutine CONNEC and its interface with the main program.

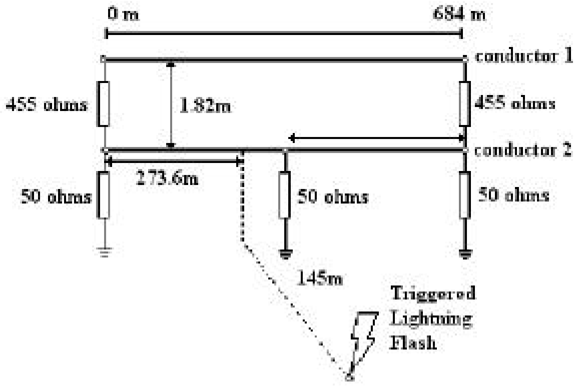

Fig. 2. Phase conductor 1and neutral conductor 2, and discharge configuration.

The return-stroke velocity was not available from the experimental test for each flash, but in simulations included with the test results the value of 120m/ µs was used [6]. Jankov used 100m/ µs [7]. In [21], [22] and [23] an average return stroke propagation speed of 120m/ µs is used. In a companion paper we will use both velocities and discuss the results [24].

Fig. 3 shows a typical measured channel base current waveform of a lightning stroke to ground in the vicinity of the experimental line [6].

Using a data acquisition program, it is possible to obtain the front time and the peak current. The time half-value for the simulations was estimated because the time scale of the measured waveform does not extend far enough to that value (see Fig.3). Simulations were performed to see the influence of the time to half-value for each lightning flash. They showed that this parameter has no great influence on the results for time to half-values between 20 to 60 µs in this configuration. This finding is in accord with [1] that considers peak value, current velocity and front time the major factors.

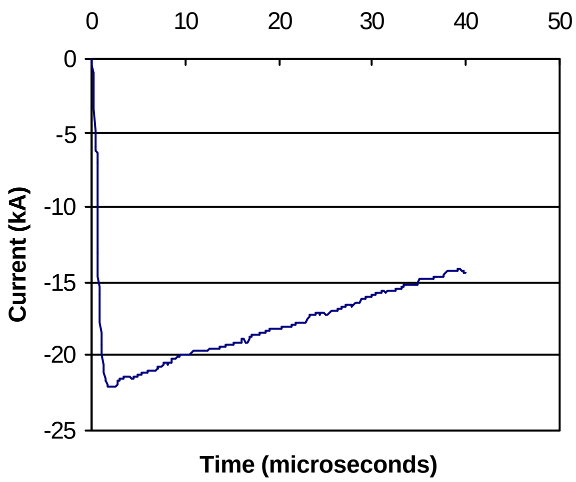

Fig. 3. Typical stroke current waveform.

V. RESULTS AND DISCUSSION

This section shows the comparison between measured and simulated waveshapes, for the system configuration of Fig. 2 and for the data used by Jankov [7].

Fig. 4 gives the results for lightning flash 9305; good agreement for the amplitude and satisfactory agreement for the waveshape can be observed. Fig. 5 shows the results for lightning flash 9306, where a good agreement for the amplitude was obtained. However, the agreement for the waveshape is not as good.

Fig. 6 gives the results for lightning flash 9313-2; a poor agreement for the amplitude can be observed. In this case it is important to consider that the front time value obtained from our digitized measurement data is 1µs, while the value from Jankov used for the simulation is 2.5µs. In the two previous cases the values from Jankov for the simulation and our digitized measurement data were practically the same. For this last case, another simulation, using a front time value of 1µs, was therefore performed. The results are presented in Fig. 7, where good agreement for the amplitude and the waveshape can now be observed.

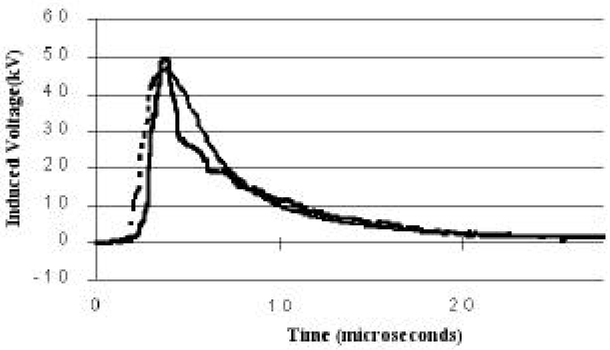

Fig. 4. Induced voltage as a function of time. Induced voltage from EMTP-Rusck (dashed line) and induced voltage from measurements (solid line) for lightning flash 9305 using data from Jankov [7].

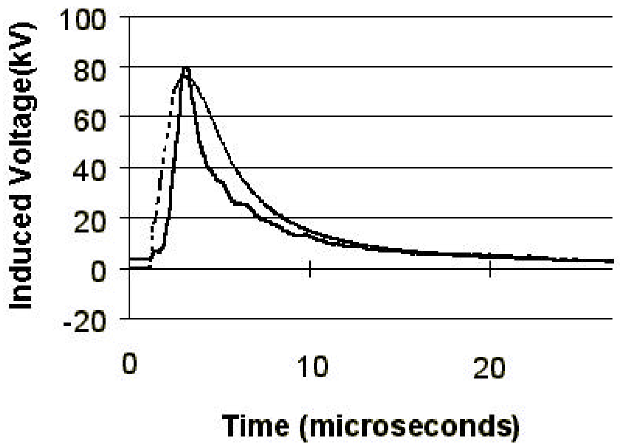

Fig. 5. Induced voltage as a function of time. Induced voltage from EMTP-Rusck (dashed line) and induced voltage from measurements (solid line) for lightning flash 9306 using data from Jankov [7].

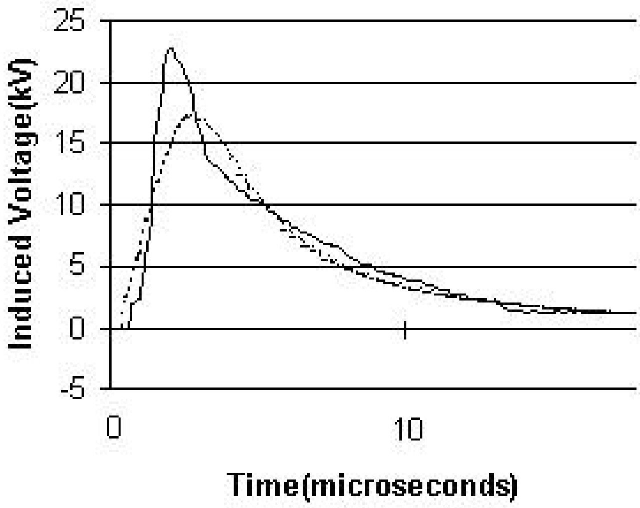

Fig. 6. Induced voltage as a function of time. Induced voltage from EMTP-Rusck (dashed line) and induced voltage from measurements (solid line) for lightning flash 9313-2 using data from Jankov [7].

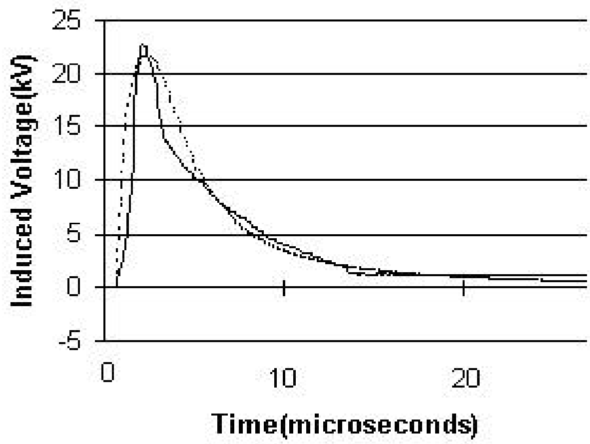

Fig. 7. Induced voltage as a function of time. Induced voltage from EMTP-Rusck (dashed line) and induced voltage from measurements (solid line) for lightning flash 9313-2 using data from Jankov [7], but with front time of 1µs from digitized data.

Table I shows the peak amplitude for the induced voltage obtained from measurements, from the equation for the estimation of the maximal induced voltage based on the Agrawal coupling model, and from the EMTP-Rusck method. For stroke 9305 the relative error between measurements and the EMTP-Rusck method is 3.2%, for stroke 9306 it is 3.9%, and for stroke 9313-2 it is 23.6%. However, for stroke 9313-2 the simulation with front time of 1µs results in a value for U_{max} of 21 kV. In this case the relative error is 6.7%.

In a companion paper, the effects of variations of the lightning parameters (amplitude and waveshape characteristics) on the induced voltages will be presented [24].

TABLE I
VALUES OF INDUCED VOLTAGE

Stroke nº	I_o [kA]	t_f [μs]	t_h [μs]	U_{max} [kV] unknown measured [5]	U_{max} [kV] v=100m/μs Agrawal model [6]	U_{max}[kV] v=100m/μs Rusck model
9305	23	1.5	45	50.0	45.4	48.4
9306	37.5	1.75	45	79.0	74.6	75.9
9313-2	9.75	2.5	40	22.5	18.4	17.2

Where:

I_0 = stroke current magnitude, in kA;
t_f = front time, in μs;
t_h =time to half-value of the stroke current, in μs;
U_{max}= maximum induced voltage, in kV;
v =return stroke velocity, in m/ μs

VI. CONCLUSIONS

This paper shows that Rusck's theory, wich was developed for natural lightning flashes, produces good results for the amplitude and waveshape of the induced voltage from nearby triggered lightning. The results obtained by EMTP simulations are in good agreement with experimental results and with the theoretical equation proposed by Jankov using Agrawal's coupling model.

APPENDIX

EXPRESSIONS USED IN EMTP-RUSCK METHOD

Rusck [16] uses the following classical expression to calculate the electric field created by the lightning discharge:

$$E = -\nabla V_i - \frac{\partial A_i}{\partial t} \qquad (1)$$

where V_i - scalar potential;

A_i - magnetic potential vector;

t - time.

In his theory, Rusck proposed that the induced voltage in a homogeneous infinite transmission line can be calculated from

$$V(x,t) = U(x,t) + h\frac{\partial A_i(x,t)}{\partial t} \qquad (2)$$

$$U(x,t) = \left(\frac{1}{2v_o}\right)\int_{-\infty}^{+\infty} \frac{\partial V_i\left(u, t-\frac{|x-u|}{v_o}\right)}{\partial t} du \qquad (3)$$

Where:

x - point on the line;
t - time;
v_o - velocity of the return stroke;
u - integration variable;
h - height of the line;
$\frac{\partial V_i}{\partial t}$ - as defined in [15].

Rusck showed in his thesis that (3) can be solved by injecting current sources along the transmission line. Rusck's theory readily yields the injected current sources from the scalar potential V_i. The current sources from the magnetic potential vector A_i must be included as well.

A. Current source from the scalar potential

The current source to be injected into the line to represent the scalar potential is:

$$I_{ei}(x,t) = \frac{1}{v_o Z}.\frac{\partial V_i(x,t)}{\partial t}\Delta x \qquad (4)$$

where Z is the surge impedance of the line. To use these sources in the EMTP, it is necessary to discretize the line in segments of length Δx, as shown in Fig. 8. The end sources I_{e1} and I_{en} have their values halved, because the lenght of the end segments is $\Delta x/2$. For the simulations in this paper, Δx = 68.4m was used.

B. Current source from the magnetic potential vector

In a line with no discontinuities, the induced voltage caused by the magnetic potential vector is added to the induced voltage obtained from the transients of the current sources created by the scalar potential. The voltage that must be added is

$$V_i(x,t) = h\frac{\partial A_i(x,t)}{\partial t} \qquad (5)$$

As before, because of the nodal equation approach of the EMTP, this contribution is calculated through a current source. To properly implement these current sources in the EMTP, it is necessary to use the arrangement shown in Fig.9, with the current source

$$I_{vi}(x,t) = -h\frac{\partial A_i(x,t)}{\partial t} \qquad (6)$$

This source is connected to the previously discretized line through a very high resistance R_1. If $R_2 = 1\Omega$ is connected in parallel with I_{vi}, the voltage difference between nodes a_i and b_i is exactly the sum of the voltages induced by the scalar potential and magnetic potential vector.

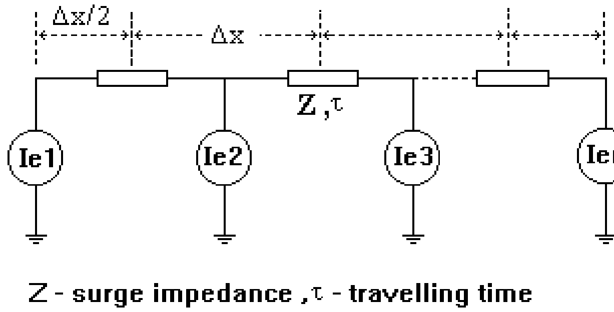

Fig.8. Injected current source

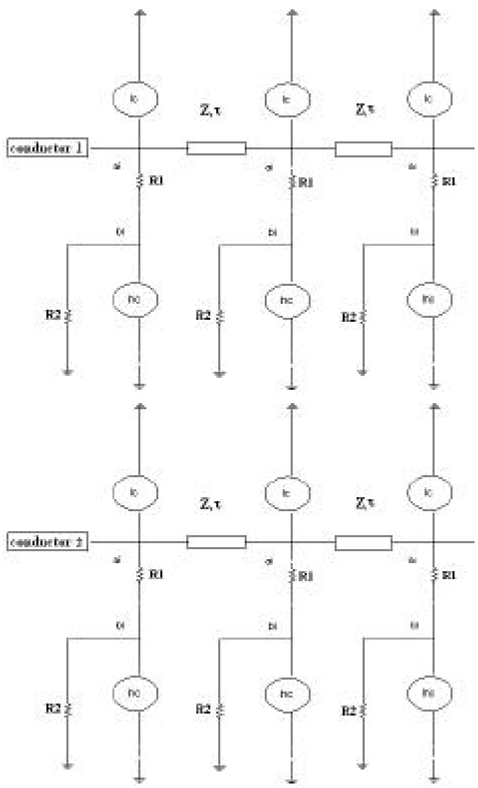

Fig. 9. Current sources in the EMTP implementation.

When there is a line-to-earth discontinuity, the component of the electric field originating in the magnetic potential vector, will produce a circulating current in the line. Therefore, it is necessary to calculate the electromagnetic transients produced by this current. To perform this calculation, it is necessary to use $R_1 = 0$ and make R_2 equal to the resistance that represents the shunt element. For example, if there is a grounding point, the resistance R_2 will be the value of the grounding resistance. If there is an equipment connected, the process is the same, because in the modeling used in the EMTP, all the elements are represented by a current source and an equivalent resistance.

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