# A New Tool for Lightning Induced Voltage Calculations: CiLIV

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## Abstract

We present CiLIV (Circuit for Lightning Induced Voltage), a new tool for lightning induced voltage calculations. The tool can be integrated into power systems simulators, and is based on the theory proposed by Andreotti *et al.* (2001, 2009, 2013). The accuracy, stability and efficiency of the new tool has been demonstrated by comparison with other solutions/codes found in the literature and with experimental data.

## 1. Introduction

Lightning-induced overvoltages have a considerable impact on the power quality of electrical and telecommunication systems, and various tools have been developed for the computation of the electromagnetic transients caused by nearby lightning strikes. The tools which can be integrated into power systems simulators such as EMTP-RV, ATP, PSPICE, MATLAB-SimPowerSystems, PSCAD, etc., are of particular interest, since one can analyze the induced lightning effects on power networks of any complexity. They can be divided into two broad categories: numerical and analytical. LIOV [1, 2], is the most popular numerical tool, LIV [3] is the most popular analytical tool. CiLIV [4, 5] belongs to the analytical category and favorably compares to other tools in terms of accuracy, reliability, and other features. In this paper we briefly present CiLIV, as well as some application examples.

## 2. An overview on CiLIV

CiLIV is based on the theories developed by Andreotti *et al.* [6-9]. It is essentially a circuit which is formulated in the frequency domain and then solved in the time domain. This hybrid approach is essential for lightning induced voltage calculations in electrical systems. In fact, approaches based exclusively on a solution in the frequency domain allow one to treat easily conductor and ground losses, but are limited to linear devices, whereas approaches in the time domain can treat non-linear devices such as surge arresters, but involve complex convolution integrations to account for conductor and ground losses. An important property of CiLIV is that the solution in the time domain is divided into two parts. The *principal part*, which accounts for the signal propagation along the line, and contains irregular terms such as Dirac pulses, is solved entirely analytically [6, 10]; and the *regular remainder*, which accounts for the signal damping and distortion due to losses, is described by regular functions [6, 10] and solved either analytically or numerically depending on to the complexity of the model considered [10]. In particular, lines that can be treated as lossless, such as lines of length less than 2 km [11], have only the principal part, which can be solved entirely analytically. Lossy lines which can be treated as frequency independent have also regular remainders, which can be solved analytically in some cases [10]. Regular remainders of lines with frequency-dependent parameters are generally solved numerically [10].

## 3. The Circuit Model

The model in the time domain, in case of a lossless line, is described by the following equations [4-6]:

$$\begin{cases} \mathbf{i}_0(t) - \mathbf{Y}_0(\mathbf{v}_0(t) - \mathbf{v}_0^i(t)) = \mathbf{j}_0(t) + \mathbf{j}_0^*(t) \\ \mathbf{i}_L(t) - \mathbf{Y}_0(\mathbf{v}_L(t) - \mathbf{v}_L^i(t)) = \mathbf{j}_L(t) + \mathbf{j}_L^*(t) \end{cases} \qquad \begin{cases} \mathbf{j}_0(t) = -2\mathbf{i}_L(t-T) + \mathbf{j}_L(t-T) + \mathbf{j}_L^*(t-T) \\ \mathbf{j}_L(t) = -2\mathbf{i}_0(t-T) + \mathbf{j}_0(t-T) + \mathbf{j}_0^*(t-T) \end{cases} \tag{1}$$

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The corresponding circuit is presented in Fig. 1.

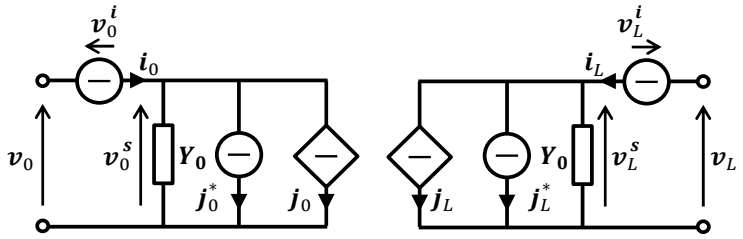


Fig. 1. 2n-ports equivalent representation of an excited lossless multiconductor line (time domain).

In the circuit, at the left (right) port there are the two independent sources $\mathbf{v}_0^i(t)$ and $\mathbf{j}_0^*(t)$ ($\mathbf{v}_L^i(t)$ and $\mathbf{j}_L^*(t)$), which account for the vertical and line-axial components of the horizontal electric field, respectively. $\mathbf{Y}_0$ is the *lossless characteristic admittance matrix* and $\mathbf{j}_0(t)$ and $\mathbf{j}_L(t)$ are controlled sources, which are controlled by the current circulating in the other port.

## 4. Application Examples

We first analyze the network shown in Fig. 2. The network, which is MV, single phase, and with grounded neutral, has a main feeder and two lateral branches. The phase and neutral conductors, both of radius 1 cm, are placed at heights of 10 m and 8 m, respectively. The ground is assumed to be lossy ($\sigma_g$ = 0.001 S/m and $\varepsilon_{rg}$ = 10) both for the lightning electromagnetic field propagation and the surge propagation along the conductors. The main feeder is 600-m-long, and is terminated at one end in its characteristic impedance network (delta scheme) in order to avoid reflections from the line end; at the other end, a medium-voltage/low-voltage (MV/LV) transformer, protected by a surge arrester, is connected. The neutral conductor is grounded at multiple points along the line, with grounding resistance at each point being 50 Ω. The two lateral branches, each one 200-m-long, are both terminated in MV/LV transformers, protected by surge arresters. Lightning channel is located at a distance of 100 m from the main feeder, 150 m from one of the lateral lines (Fig. 2). We will regard each transformer as a capacitor connected between phase and neutral [11]. We assume for the capacitor a value of 0.5 nF [11]. In Fig. 3, we show the induced voltages (phase-to-neutral) evaluated at poles P1, P2, P3 and P4 labeled in Fig. 2. Graphs are obtained assuming a trapezoidal lightning channel-base current (linearly rising current with constant tail) characterized by the following parameters: maximum value of 60 kA, and a rise time of 0.5 μs; it propagates along the vertical lightning channel with a velocity of 130 m/μs.

The second example considered here is concerned with a 2×25-kV 50 Hz High Speed Railway System (HSRS). Specifically, we consider a typical configuration used in Italy. Fig. 4 shows a multi-conductor line (14 conductors) including 2 contact wires, 2 feeders, 2 messenger wires, 4 rail tracks, 2 buried earth conductors, and 2 overhead earth conductors (or protection wires). The line is assumed to be 600 m long, and the protection wires are grounded every 30 m along the line, with grounding resistances of 0.8 Ω. The lightning channel is placed sideways, at a distance of 50 m (measured from the feeder conductor) from the line mid-point. The lightning current is a trapezoidal current with a

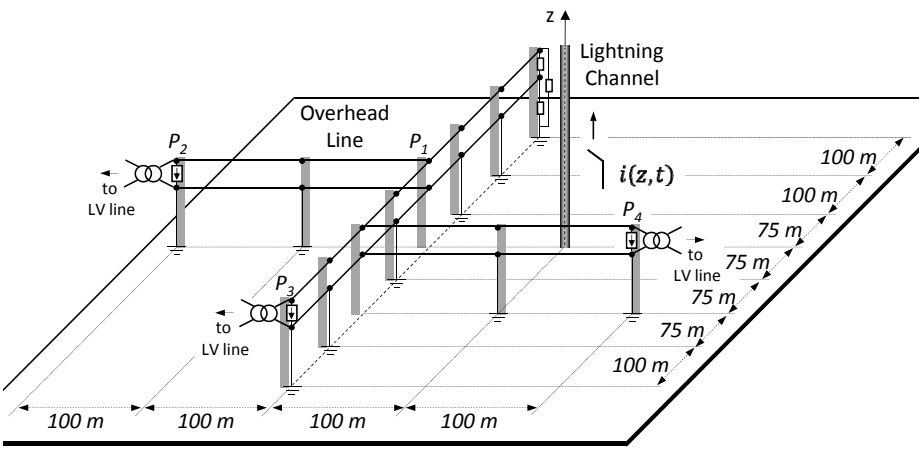


Fig. 2. An example of MV line with distribution transformers and surge arresters (not to scale).

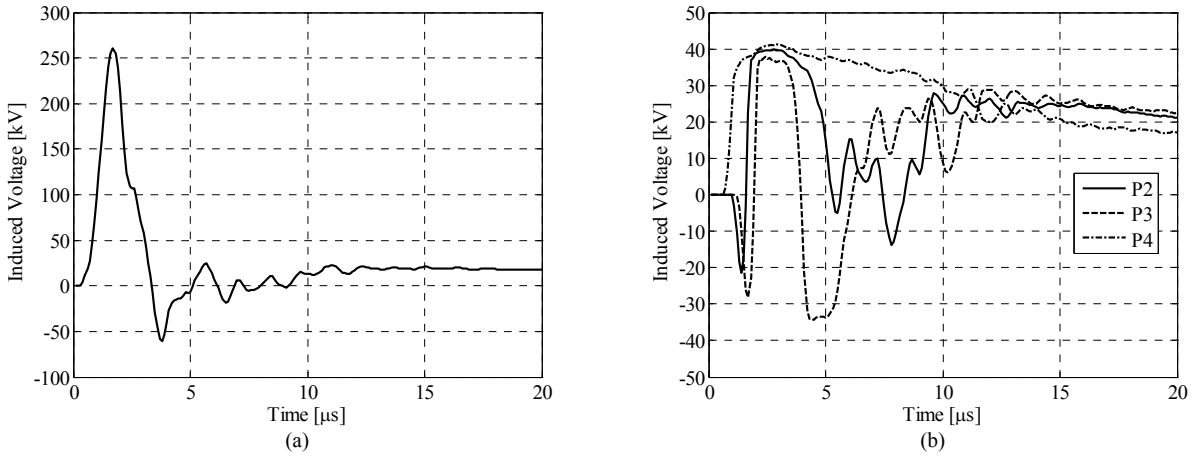


Fig. 3. Induced voltages evaluated at poles P1 (a), P2, P3 and P4 (b) of the network depicted in Fig. 2.

maximum value of 12 kA, and a rise time of 1 µs. It propagates along the vertical lightning channel with a velocity of 130 m/µs. It was assumed that ground is a perfect conductor. In Fig. 5, as an example, we show the voltage (referred to ground) induced on the feeder conductor nearest to the lightning channel, evaluated at the at the mid-point of the line. In Fig. 6, we show the current induced on the grounding connection between the protection wire and the ground, again evaluated at the line mid-point.

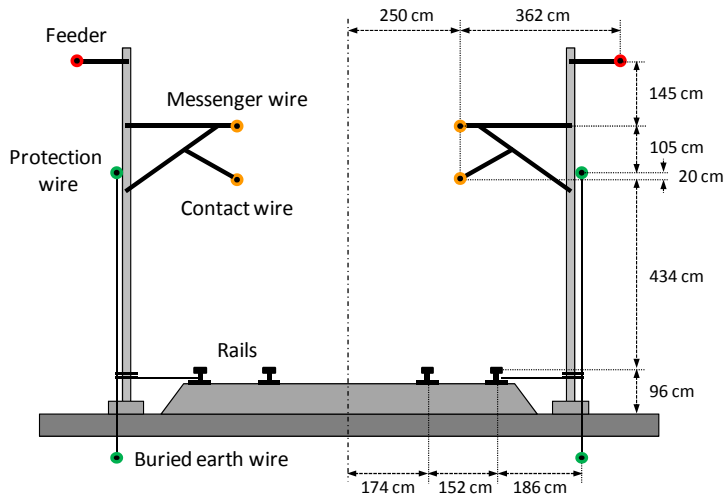


Fig. 4. High-speed railway (cross-sectional view).

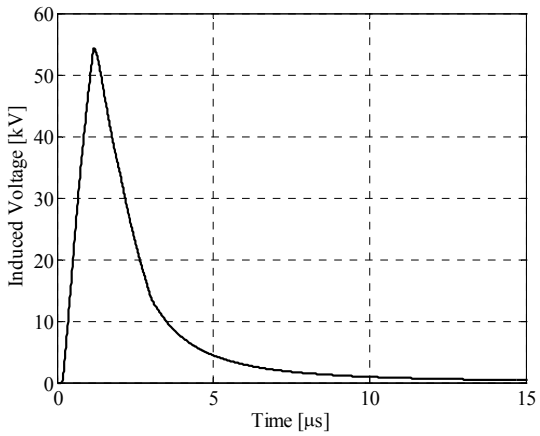


Fig. 5. Voltage induced on the feeder conductor nearest to the lightning channel (at a distance of 50 m). The voltage is evaluated at the mid-point of the line.

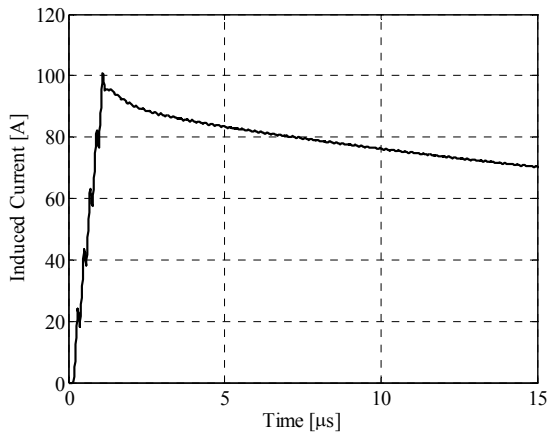


Fig. 6. Current induced on the connection between the protection wire and the ground (for the protection wire nearest to the lightning channel). The current is evaluated at the mid-point of the line.

## 7. Conclusion

In this paper, we have briefly presented a new tool for lightning induced voltage calculations on overhead lines, named CiLIV (Circuit for Lightning Induced Voltage). This tool, integrated into MATLAB-SimPowerSystems, can be used to analyze the induced lightning effects on electrical networks of any complexity, as shown in this work by considering two practical examples: a MV line with distribution transformers and surge arresters, and a 2×25-kV 50 Hz High Speed Railway System.

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