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# Comparative study of 220 kV overhead transmission lines models subjected to lightning strike simulation by using electromagnetic and alternative transients program

***Introduction.*** *In high voltage networks intended for the transport of electrical energy, lightning can strike an electric line striking either a phase conductor, a pylon or a ground wire, causing significant overvoltage on the transmission lines classified as stresse**s the** most dangerous for transformer stations and electro-energy systems in general. Modeling transmission lines becomes more complicated, if the frequency dependence of resistance and serial inductance due to the effect of lightning strike in the conductors and in the earth is considered. The difficulty increases the fact that the parameters of the line can be defined and calculated only in the frequency domain, while the simulation of transients is wanted to be in the time domain.* ***Problem.*** *Several models (J.R. Marti, Bergeron, nominal PI, Semlyen and Noda) exist for the modeling of transmission lines, the Electromagnetic Transients Program/Alternative Transient Program software (EMTP/ATPDraw) gives the possibility to choose between these models which is delicate due to the fact that we do not have experimental results to validate and justify the choice among the models available in the software. In this context,* ***practical value: the*** *overhead transport line OAT-El Hassi (220 kV) of the city of Sétif located in the north east of Algeria* ***is*** *used for the modeling of lightning strike by using the EMTP/ATPDraw software.* ***Originality.*** *A comparative study of the* ***investigation*** *of a lightning* ***strike*** *on an existing high voltage transmission line by different models of existing lines in the EMTP/ATPDraw software library of this software.* ***Results.*** *It was concluded that the choice of the model of the line is very important given the accuracy and quality of the curves of the voltage presented at the different calculation points.* References 29, tables 1, figures 9.
*Key words:* **high voltage, lightning strike, electromagnetic and alternative transients program, line models.**

***Вступ****. У високовольтних мережах, призначених для передачі електроенергії, блискавка може вдарити по лінії електропередач, уразивши або фазний провід, опору, або заземлюючий провід, викликаючи значні перенапруги на лініях електропередач, визначені як загрози, найбільш небезпечні для трансформаторних підстанцій та електроенергетичних систем загалом. Моделювання ліній електропередач ускладнюється, якщо враховувати частотну залежність опору та послідовної індуктивності внаслідок дії удару блискавки у провідниках та землі. Складність підвищується тим, що параметри лінії можуть бути визначені і розраховані тільки в частотній області, в той час як моделювання перехідних процесів бажано проводити в часовій області.* ***Проблема.*** *Існує кілька моделей (J.R. Marti, Bergeron, номінальна П-подібна схема заміщення, Semlyen і Noda) для моделювання ліній електропередач, комп'ютерна програма електромагнітних перехідних процесів/альтернативна програма перехідних процесів EMTP/ATPDraw дає можливість вибирати між цими моделями, що є «тонким питанням» через те, що ми не маємо експериментальних результатів для перевірки та обґрунтування вибору серед моделей, доступних у програмному забезпеченні. У цьому контексті,* ***практична цінність****: для моделювання удару блискавки за допомогою програмного забезпечення EMTP/ATPDraw використана повітряна лінія електропередачі ОАТ-Ель-Хассі (220 кВ) міста Сетіф, розташованого на північному сході Алжиру.* ***Оригінальність.*** *Порівняльне дослідження вивчення удару блискавки на існуючій високовольтній лінії електропередач за різними моделями існуючих ліній у бібліотеці програм EMTP/ATPDraw цього програмного забезпечення.* ***Результати.*** *Зроблено висновок, що вибір моделі лінії дуже важливий з урахуванням точності та якості кривих напруг, представлених у різних розрахункових точках.* Бібл. 29, табл. 1, рис. 9.
*Ключові слова:* **висока напруга, удар блискавки, програма електромагнітних та альтернативних перехідних процесів, моделі ліній.**

**Introduction.** The direct and indirect impact of lightning on one of the conductors is illustrated by the bidirectional propagation of a surge wave of several hundred kV and can reach 200 kA. In the field of insulation coordination as well as electromagnetic compatibility, the stresses produced by lightning always remain of major interest and should be taken into account as a priority in the implementation of any protection system [1]. The influence of a lightning current model that employs simulations of the geometry and maximum values of overvoltages generated in high voltage transmission networks during a direct lightning strike to overhead lines [2-4].

Several models exist for the simulation of transmission lines. The Electromagnetic Transients Program/Alternative Transient Program software (EMTP/ATPDraw) gives the possibility to choose between these models which are delicate due to the fact that we do not have experimental results to validate and justify. In simulations with the EMTP/ATP, the Heidler and CIGRE (Conseil International des Grands Réseaux Électriques) models of lightning current were used [5].

When the frequency dependence of resistance and series inductance owing to skin effect in conductors and in the earth is taken into account, transmission line modeling gets more sophisticated. The challenge is compounded by the fact that line parameters can only be defined and calculated in the frequency domain, but transient simulation should be done in the time domain. The input/output relationships in the frequency domain i.e. multiplications with transfer functions become convolutions in the time domain.

Modeling of transmission lines as a function of frequency can be summarized as follows:

1. Line functions in the frequency domain are calculated (frequency response). The modal decomposition is used in the case of polyphase lines to derive the wave deformation function or the characteristic impedance / admittance, for example.
2. To approximate these functions, direct approximation in the frequency domain or in the time domain following a digital transformation from the frequency domain is used (inverse Fourier transform, or the Laplace transform).
3. Time-domain transients are calculated numerically or analytically by evaluating the convolutional integral.

In the case of an analytical solution the model of the line can be reduced to the equivalent Norton circuit, which is desirable for implementation in EMTP [6, 7].

EMTP/ATP is better for both real and idealized transmission line simulations. The LCC module (LCC module of the ATP-EMTP uses Carson's equations to estimate the transmission line parameters from the data entered by the user) is the most useful because it simply requires the geometry and material characteristics of the line/cable. Skin effect, bundling, and transposition can all be taken into account automatically. Most transmission line models use modal components for simulation in the time domain [8].

The following transmission line models for the calculation of transients are given in order of model complexity:

1. Mutually coupled RLC elements (PI circuits);
2. Constant distributed parameter line model (LPDC).
3. Line model based on the 2nd order recursive convolution (Semlyen);
4. Frequency dependent line model (J. Marti);
5. Frequency dependent ARMA line model (auto-regressive moving average line model that is implemented in the ATP version of EMTP) (Taku Noda).

The PI model only suitable for short cables and known frequency, Bergeron – only suitable for known frequency, but Bergeron, J. Marti and Semlyen – work in the modal domain and assume a constant transformation matrix. The most recent model, NODA, however, works directly in the phase domain [9].

**The aim** of the work is to compare the impact of a direct lightning strike on an existing high voltage power line according to various models in the EMTP/ATP draw software library.

**Transmission line models.**

**1) Linear PI model (short lines).** This is the model which represents the simplest approach to model a transmission line. In Fig. 1 we give the typical scheme of the model multi-conductor PI model circuit. In the case of symmetrical single-phase or three-phase lines, the PI model is represented by matrixes with multi-conductor overhead line parameters. These matrixes are size of 3×3. The elements of the impedance matrix [*Z*] (resistance and inductance) are a function of the arrangement and geometry of the conductors, while the parameters of the admittance matrix [*Y*] (susceptance and conductance) represent overhead line losses. Figure 1 shows a section of a line with a multiconductor arrangement [10]. The total number of PI circuits used for the simulation depends on the particular simulated system.

The PI model is characterized by the absence of dependencies of the calculation time step on the simulation results. The PI model is mainly recommended for short distance modeling overhead lines (<80 km) [11].

In positive sequence as well as for zero sequence, the linear parameters of the overhead line PI model can be obtained from a support program (LINE CONSTANS) implemented in the EMTP/ATP software. The calculations are based on geometric data from the overhead line [12].

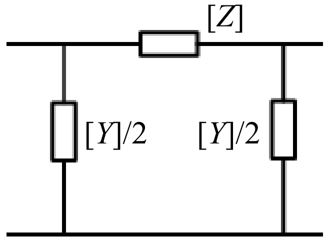


Fig. 1. Typical scheme of multi-conductor nominal PI line model [12]

**2) J. Marti: frequency-dependent model with constant transformation matrix.** For numerical simulation of electromagnetic transients on overhead wires, the Marti transmission line model is the most commonly employed. It's a distributed parameter model in which the simulator automatically translates the line's parameter frequency fluctuation into a frequency range. The transmission line equations are solved in the modal domain, where a system of n linked conductors is represented by n single-phase lines that, owing to a similarity transformation, are independent of each other. A constant and real transformation matrix computed at a frequency set by the user is taken into account when calculating voltages and currents in the time domain [12].

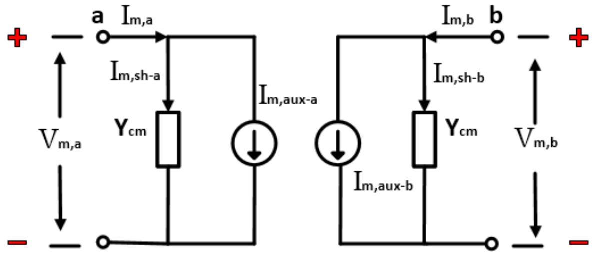


Fig. 2. Principle scheme of J.R. Marti model

**3) Bergeron: constant-parameter K.C. Lee or Clark models.** The Bergeron model is a very simple model. It is based on a distributed LC-parameter traveling wave line model with overall resistance. This Bergeron model in the time domain is commonly used in the analysis of transient faults of the electrical network [13]. It represents in a distributed way, the elements L and C of a section PI.

Bergeron's model, like the PI section model, only depicts the fundamental frequency (50 Hz) with precision; thus, the surge impedance is constant. As long as the losses do not vary, it can also represent impedances at different frequencies. The mathematical equations of this model have been detailed in [14, 15], the equivalent circuit of the Bergeron model impedances is given in the Fig. 3.

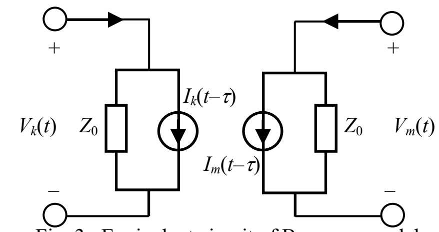


Fig. 3 . Equivalent circuit of Bergeron model

**4) Semlyen: frequency-dependent simple fitted model.** The frequency-dependent model of Semlyen is a method for iteratively performing a real-time convolution in the [15-18]. The proposed line model accounts for the characteristic admittance's frequency dependence. The method produces a simple line equivalent circuit based on a Norton- type circuit, consisting of a constant admittance and a current source. Therefore, this line model is easy to integrate into programs based on the representation of the nodal system.

Semlyen's model reduced computational time and storage requirements to limits close to those of transient calculations with lossless (frequency independent) line representations. The precision of the frequency-dependent modeling is however preserved since the proposed method is based on rigorously valid simplifications, rather than simply empirical ones [18].

**Lightning source**. Lightning is a very strong electrical stress that can reach 200 kA in a few microseconds and has extremely high frequencies [19]. The lightning-strike concept is represented by a current source with parallel resistance in the EMTP/ATP software. Lightning-path impedance is the parallel resistance. The Heidler current model was utilized in this study, and it takes into account four features of lightning current amounts at the striking point.

The EMTP/ATP software gives the possibility to introduce the characteristic values of lightning such as the rise time, the peak of the lightning current, fall time and the pulse duration [20, 21]. It can be represented by a current source of exponential shape in parallel with a resistor representing the lightning channel (about 400 Ω) or even a voltage source always having an exponential shape. In the present investigation, thunderbolt is represented by a voltage source of exponential form based on the second Heidler (Fig. 4) [20, 21].

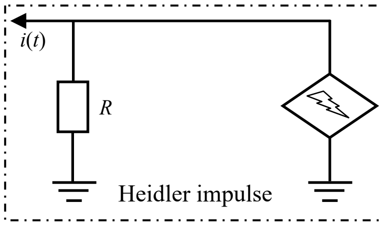


Fig. 4. Heidler type model

**Power system description**. The OAT-El Hassi line (220 kV) located in the north east of Algeria in the wilaya of Setif. The line is divided into a number of identical sections as shown in Fig. 5 for the 220 kV line. Authors chose a length of portion equal to 2.4 km divided into 8 spans (Fig. 5).

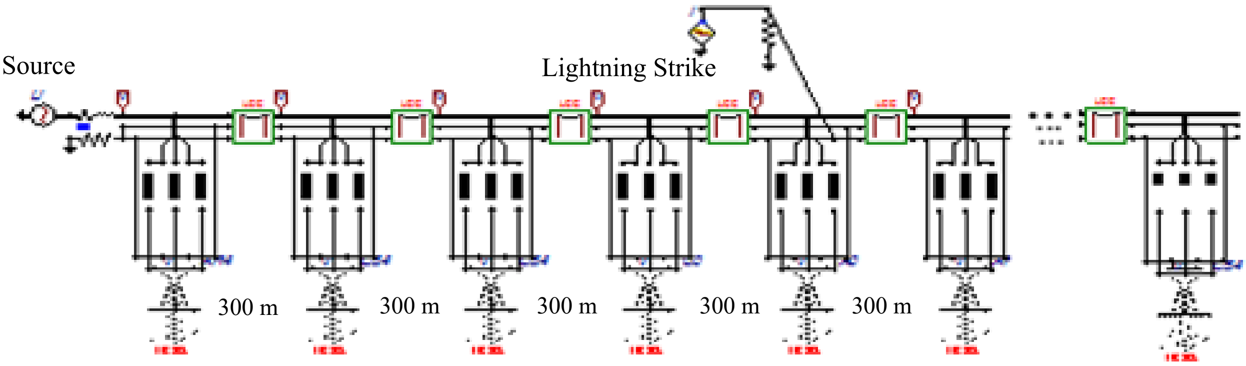


Fig. 5. The OAT-El Hassi line (220 kV) subjected to a 1200 kV overvoltage

Each span has a length of 300 m which is close to the average value of the spans of this line of OAT-El Hassi in Setif, supplied with 220 kV, shown in [22].

This line comprises the following elements: towers, earthing resistance, insulators, sections of the overhead line, ground wire and the lightning current channel [23].

The characteristic tower overvoltage impedance is:

$$Z_T = 60 \cdot \left[ \ln\left( \sqrt{2} \cdot \frac{2 \cdot h}{r_x} \right) - 1 \right], \quad (1)$$

where $r_x$ is the tower base radius, m; $h$ is the tower height, m [24, 25].

The tower earthing system can be modeled as a non-linear resistance, the CIGRE [26] model is used, which is modeled as a non-linear resistance of Type-91 in EMTP/ATP:

$$R_T(I) = \frac{R_0}{\sqrt{1 + I/I_g}}, \quad (2)$$

where $R_0$ is the tower footing resistance at low frequency and low current; $R_T$ is the tower footing resistance, Ω; $I_g$ is the limiting current to initiate sufficient soil ionization, A; $I$ is the lightning current through the footing impedance, A.

The limiting current is a function of soil ionization is given by:

$$I_g = \frac{1}{2\pi} \cdot \frac{E_0 \cdot \rho}{R_0^2}, \quad (3)$$

where $\rho$ is the soil resistivity, Ω·m; $E_0$ is the soil critical electric field intensity (approximately 300 kV/m).

For the insulator the CIGRE [26] model was used and modeled by a capacitance connected in parallel with a model which represents the overflow mechanism of the insulator. The latter is represented by a switch controlled through models, by the implementation of the equations:

$$dl/dt = k_3 \cdot V \cdot [V/(D - L) - E_0], \quad (4)$$

where $dl/dt$ is the speed of the arc, m/s; $k_3$ is the constant, $m^2 \cdot kV^2 \cdot s^{-1}$; $V$ is the instantaneous voltage across the insulator or the gap, kV; $D$ is the length of the insulator or the length of the gap, m; $l$ is the length of the arc, m, $l \geq D$; $E_0$ is the strength of the critical electric field, kV/m.

**Simulation results.** In order to compare influence of various overhead line models on simulation results, simulation of a lightning strike located in the middle of high voltage transmission line have been performed for power system presented in Fig. 5. The modelled 220 kV overhead transmission line with 8 towers was used for lightning-surge simulation. The towers were modelled in simple distributed line model.

In this study, two amplitudes of lightning current (positive polarity) were used to perform shielding failure pattern analysis on the modelled circuit. Simulations are thus conducted with 2 levels of lightning-strike current – 50 kA and 100 kA [27] (Table 1).

Table 1

Lightning amplitudes, front times, and tail times

| Lightning current amplitude, kA | Tail time, μs | Front time, μs |
|---|---|---|
| 50 | 50 | 1.2 |
| 100 | 77.5 | 2 |

For the simulation, lightning-surge current was injected into ground wire of the fourth tower (middle tower). The voltage patterns due to the direct lightning strike on the ground wire are recorded throughout the distance from the network at each section of 300 m.

**Lightning strike on ground wire**: When lightning strikes the overhead ground wire, a voltage builds up in the cable, causing a traveling wave to flow down to the bottom of the concrete pole, through the external ground wire, and in both directions along the overhead ground wire. The result voltage is determined by the striking current and total impedance of the overhead ground wire and the external ground wire.

**Case 1: 100 kA, 2 μs, 77.5 μs.** Figure 6 illustrates the amplitudes of induced voltage across the ground wire when a lightning strike current of 100 kA occurs with a tail time of 77.5 μs and a front time of 2 μs, as simulated by the 4 types of line models – J.R. Marti, PI, Bergeron, and Semlyen.

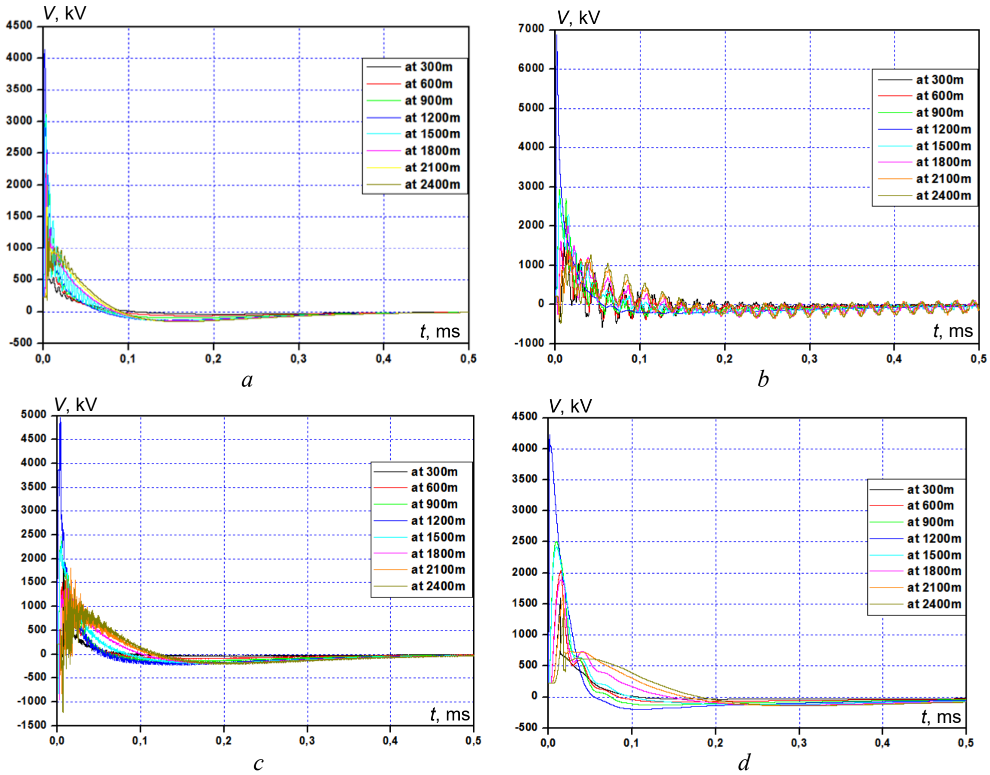
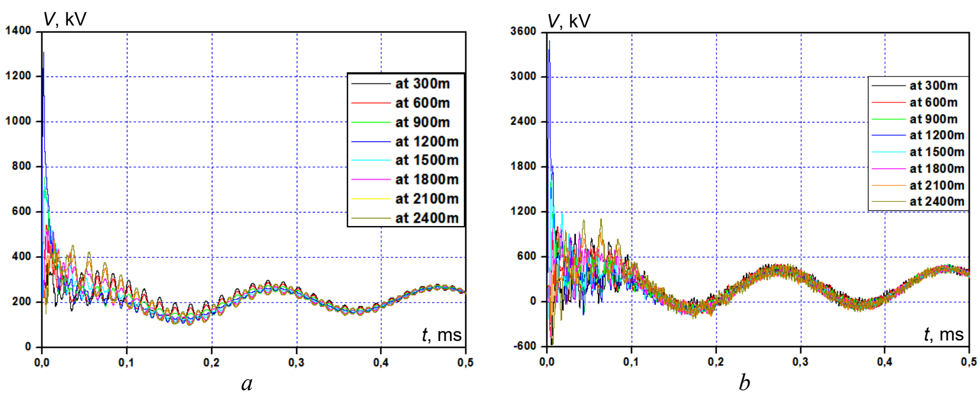
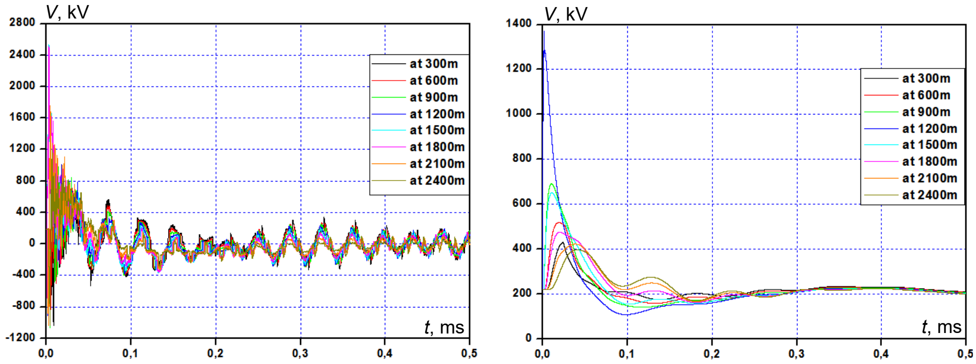



Fig. 6. Induced voltage across the ground wire by different model:
*a* – J.R. Marti model; *b* – PI model; *c* – Bergeron model; *d* – Semlyen model

**Case 2: 50 kA, 1.2 μs, 50 μs.** Figure 7 shows amplitudes of induced voltage across the ground wire when lightning-strike current of 50 kA, with tail time 50 μs and 1.2 μs front time, simulated by the 4 types of the line model J.R. Marti, PI, Bergeron and Semlyen respectively.

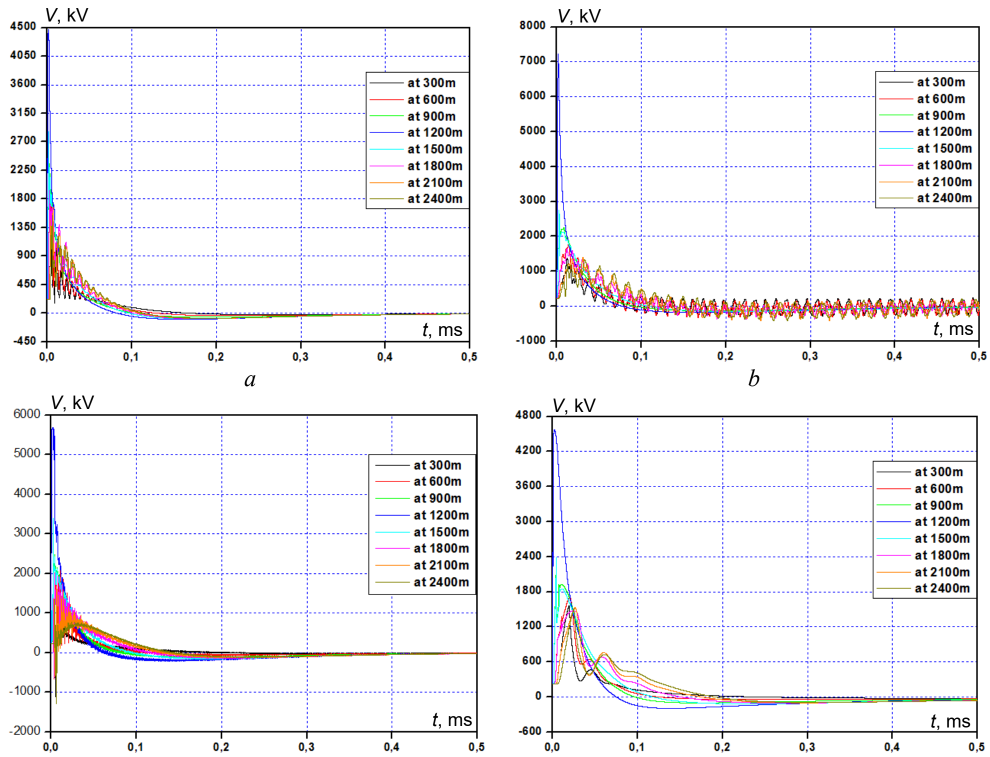





*c* *d*

Fig. 7. Induced voltage across the ground wire by different model:
*a* – J.R. Marti model; *b* – PI model; *c* – Bergeron; *d* – Semlyen model

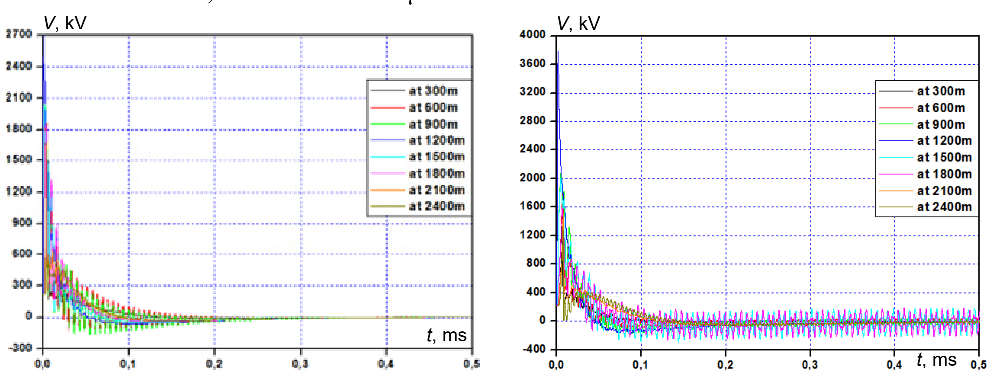
**Lightning strike on phase A. Case 1: 100 kA, 2 µs, 77.5 µs.** Figure 8 shows amplitudes of induced voltage across the phase A when lightning-strike current of 100 kA with tail time 77.5 µs and 2 µs front time, simulated by the 4 types of the line model J.R. Marti, PI, Bergeron and Semlyen respectively.



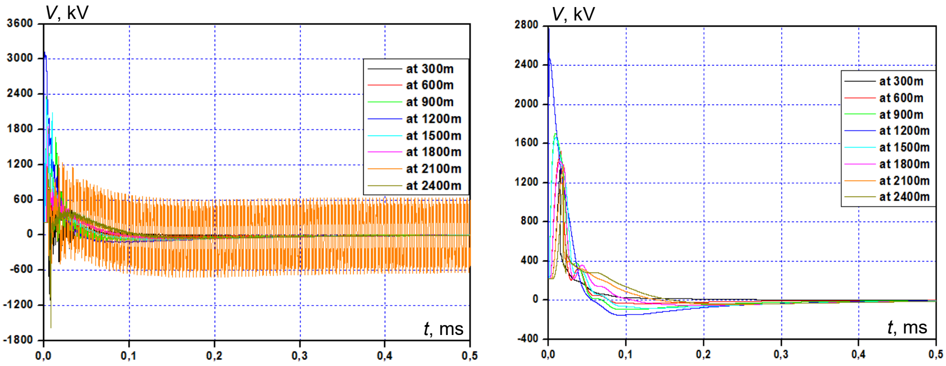

*c* *d*

Fig. 8. Induced voltage across the phase conductor by different model:
*a* – J.R. Marti model; *b* – PI model; *c* – Bergeron model; *d* – Semlyen model

**Case 2: 50 kA, 1.2 µs, 50 µs.** Figure 9 shows amplitudes of induced voltage across the phase A when lightning-strike current of 50 kA, with tail time 50 µs and 1.2 µs front time, simulated by the 4 types of the line model J.R. Marti, PI, Bergeron and Semlyen respectively.




*a* *b*




*c* *d*

Fig. 9. Induced voltage across the phase conductor by different model:
*a* – J.R. Marti model; *b* – PI model; *c* – Bergeron model; *d* – Semlyen model

In the study cases the phase A voltage attenuates completely and becomes zero after less than 0.1 s and that for the 4 models J.R. Marti, PI, Bergeron and Semlyen, which is in good agreement with the results obtained in [28].

According to the simulation results obtained in Fig. 8, 9 the increase in the complexity of the model has an impact on the peak voltages and the waveform. The calculated voltage waveforms are indeed similarly different, but the oscillations of the PI model dominate, same remarks were observed in the search results exposed in reference [29].

The direct lightning strike on one of the phases conductors of the overhead transmission line causes serious faults, exclusively the deactivation of this phase which results in an imbalance and instability in the line which requires the intervention of maintenance personnel emergency. Surge arresters on all phases of the conductors have been suggested as potential solutions; however, while surge arresters are the best solution, they are quite expensive, which is important for transmission lines where corona attenuation is insufficient to reduce the lightning surge to security levels.

**Conclusions.** Lightning has always been a source of disruption for electricity users, however, the demand for electrical systems is relatively increasing and the quality (reliability, availability, continuity of service, etc.) must be taken into account, as well as the permanent need to minimize the cost of production and improve the level of insulation of electrical equipment.

The simulation of lightning strike by existing models in Electromagnetic Transients Program / Alternative Transient Program software was studied in this paper; each model of overhead transmission line has these advantages and disadvantages, from our study results:

- the J. Marti model that traditionally is suitable for overhead line modelling show significant weaknesses both in the fitting process and in the calculation of induced voltages;
- the PI model and Bergeron model resulted in unstable responses and also required fine-tuning of the fitting parameters and large time steps;
- the Semlyen model actually gave the overall best and most reliable results; however, such model is only suitable for cases where the fundamental frequency is known.

**Conflict of interest.** The authors declare that they have no conflicts of interest.

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