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INDUCTIVE COUPLING EFFECT ON INDUCED VOLTAGE ON THREE-PHASE TRANSMISSION LINE IN CONSEQUENCE OF LIGHTNING STROKE

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***Abstract**: The paper deals with surge phenomena on hv and vhv three-phase transmission lines with earth wire. The impact of lightning stroke into the earth wire and its influence on parallel phase conductors is investigated. The model of the transmission line is created by network with distributed parameters and concurs on our previous paper. In this paper are derived basic equations respecting not only inductive and capacitive coupling among phase conductors but they involve the coupling phase conductors to the earth wire, as well. Problem is solved numerically in the time domain. Some examples illustrating the propagation of surge wave caused by lightning stroke are solved here.*

Key words: *Three-phase transmission line, earth wire, lightning, surge waves, time domain, wendroff´s differential formula*

INTRODUCTION

Lightning and switching processes can generate in the power systems fast transient phenomena that result in very high overvoltage. In previous published works only a one-phase transmission line was considered. The aim of this work is to get closer to the real tasks; therefore the algorithm described in [2] and [3] was extended on three-phase transmission line including the earth wire. In this case the propagation of surge waves along the line is very strongly affected by both, the capacitive and the inductive coupling between all conductors and between all conductors and earth as well. The induced voltage into phase conductors caused by the lightning stroke attack into the earth wire is investigated. The problem is solved numerically using the final difference method. Therefore it was necessary to design a new mathematical model, to evaluate the parameters for this model and to compose a new algorithm for calculation. This algorithm was created in mathematical computer program MATLAB.

1 MATHEMATICAL MODEL OF TRANSMISSION LINE

A general transmission system depicted on Fig. 1 consists of three parts: feeding and loading circuits and transmission line of length ℓ. To observe surge phenomena in this system we need a correct model of transmission line. Because surge phenomena are very fast, the model should be created as the network with distributed parameters. In this case voltage and current are time and space varying functions and their distribution along the transmission line can be described by a system of partial differential equations of hyperbolic type.

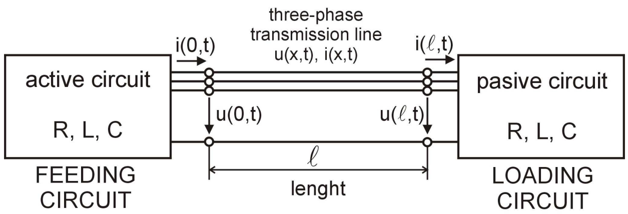

Fig. 1: Schema of the transmission system

Each element of the line according to Fig. 2 can be described by eight equations; for the earth wire we obtain

$$-\frac{\partial u_0}{\partial x} = R_0 i_0 + L_0 \frac{\partial i_0}{\partial t} + \sum_{j=1}^{3} L_{0j} \frac{\partial i_j}{\partial t}, \tag{1}$$

$$-\frac{\partial i_0}{\partial x} = C_0 \frac{\partial u_0}{\partial t} + \sum_{j=1}^{3} C_{0j} \left(\frac{\partial u_0}{\partial t} - \frac{\partial u_j}{\partial t} \right), \tag{2}$$

for each of three phase conductors we write

$$-\frac{\partial u_k}{\partial x} = R_k i_k + L_k \frac{\partial i_k}{\partial t} + \sum_{j=0,\, j \neq k}^{3} L_{kj} \frac{\partial i_j}{\partial t}, \tag{3}$$

$$-\frac{\partial i_k}{\partial x} = C_k \frac{\partial u_k}{\partial t} + \sum_{j=0,\, j \neq k}^{3} C_{kj} \left(\frac{\partial u_k}{\partial t} - \frac{\partial u_j}{\partial t} \right), \tag{4}$$

where $k = 1,2,3$, all parameters of the line are per unit length, the conductance between conductors is neglected.

The injected current wave into earth wire caused by lightning stroke is respected by current source $I(t)$ at the given point of the line. This function is added to the eq. (2), more detailed has been this process described in [2]. To respect the character of the input (feeding circuit) and output (loading circuit) of the line, the system of partial differential equations has to be supplemented by the ordinary differential or algebraic equations which describe the relationship between current and voltage at the input and output ports – Fig. 1.

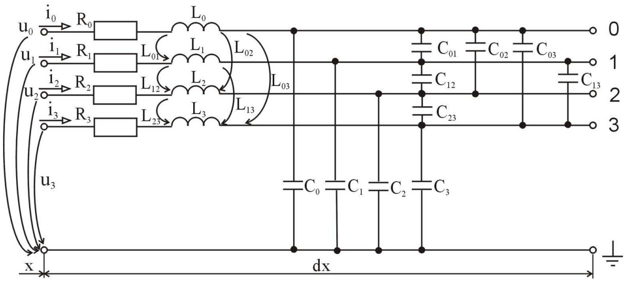

Fig. 2: Schema of one of the elements

2 ALGORITHM FOR NUMERICAL SOLUTION

For numerical solution of wave equations (1) ÷ (4) the method of finite differences based on the implicit Wendroff differential formula [1], [2] was used. The basic formula reads

$$\left.\frac{\partial v(x,t)}{\partial t}\right|_{k,l} = \frac{1}{2}\left(\frac{V_k^l - V_k^{l-1}}{\Delta t} + \frac{V_{k+1}^l - V_{k+1}^{l-1}}{\Delta t}\right) \tag{5}$$

$$\left.\frac{\partial v(x,t)}{\partial x}\right|_{k,l} = \frac{1}{2}\left(\frac{V_{k+1}^l - V_k^l}{\Delta x} + \frac{V_{k+1}^{l-1} - V_k^{l-1}}{\Delta x}\right) \tag{6}$$

After dividing the length of the line into N elements we apply the Wendroff´s formula on the eq. (1) ÷ (4) and receive $8N$ equations. This system of algebraic of equations is than supplemented by 8 difference equations expressing boundary conditions at the input and output of the line. It results into $8N+8$ equations in matrix form

$$\mathbf{A} \cdot \mathbf{v}^{(l)} = \mathbf{B} \cdot \mathbf{v}^{(l-1)} + \mathbf{D}, \tag{7}$$

where $\mathbf{v}^{(l)} = [\{u_k\},\{i_k\}]$ is a matrix of unknown discrete values of voltages and currents in an every space node $k = 1,2,...,N+1$ of the grid at time l-level and can be evaluated from known values u_k, i_k at $l-1$ level, that is at time $t = \Delta t(l-1)$. The coefficients of matrixes **A** and **B** respect parameters of the line and the size of steps Δt and Δx. The schema of matrix **A** is depicted in Fig. 3 and 4. The first figure is for non-transposed transmission line and the second one is for transposed line. This matrix can be divided into 4 submatrices. Submatrices $\mathbf{A_1}$ and $\mathbf{A_4}$ are diagonal and its coefficients depend only on the space step Δx. Submatrix $\mathbf{A_2}$ respects L and R parameters of line. It is different for transposed and non-transposed line according to the matrix of inductances (there are shown in Tab. 1 and 2; coefficients correspond with example solved in part 3). Submatrix $\mathbf{A_3}$ respects C and G parameters of line and it is full for transposed and non-transposed line as well. Matrix **D** respects the values of sources. This equation (7) can be solved in MATLAB.

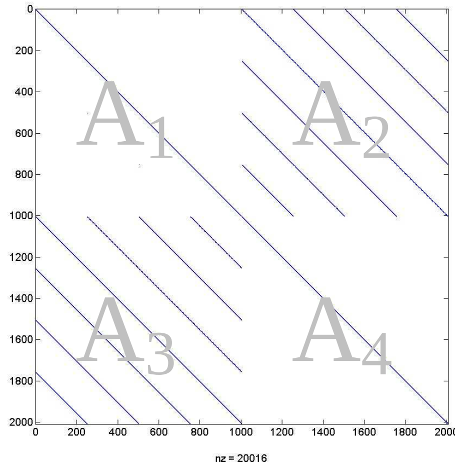

*Fig. 3: Matrix **A** for non-transposed transmission line*

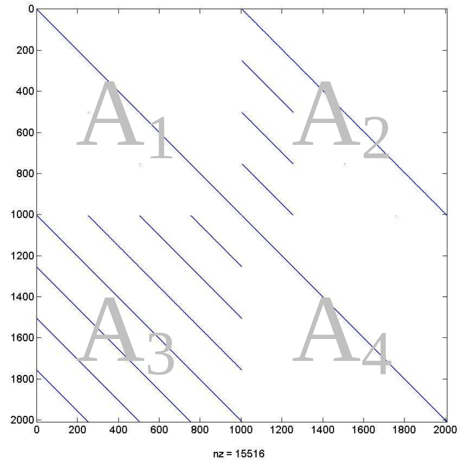

*Fig. 4: Matrix **A** for transposed transmission line*

conductor	***0***	***1***	***2***	***3***
0	0.8324	-0.4666	-0.3219	-0.4666
1	-0.4666	0.9710	-0.3442	-0.3219
2	-0.3219	-0.3442	0.9710	-0.3442
3	-0.4666	-0.3219	-0.3442	0.9710

Tab. 1: Matrix of inductances for non-transposed line. All inductances are in μH. *Conductor 0 is the earth wire; conductors 1÷3 are the phase conductors.*

conductor	***0***	***1***	***2***	***3***
0	0.8324	0	0	0
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Tab. 2: Matrix of inductances for transposed line. All inductances are in μH. *Conductor 0 is the earth wire; conductors 1÷3 are the phase conductors.*

3 PARAMETERS OF TRANSMISSION LINE

The value of line parameters depends on layout of conductors given by a type of used towers. Because of very high rate of rice of injected current wave the influence of skin-effect on resistance value has to be taken into account. Both, self and mutual inductances respecting coupling between phase conductors and earth wire, were evaluated by the algorithm published in [3]. Capacitances were calculated according to algorithm published in paper [4]. All considered coupling are shown in Fig. 2.

4 RESULTS

To illustrate the proposal algorithm the impact of lightning stroke with peak value 31.4kA into the earth wire was investigated. The three-phase transmission line placed on tower Donau was considered (Fig. 3).

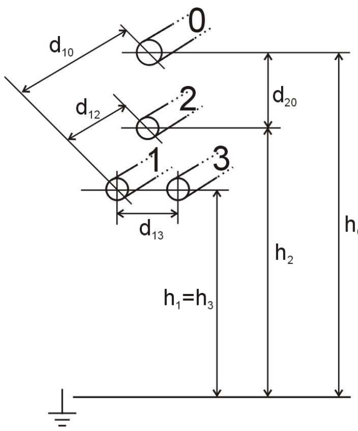

Fig. 3: The transfiguration of the three-phase model

The earth wire was grounded via 2 Ω resistances. We observed a 1000 m long part of line. The direct lightning stroke to the earth wire was applied at distance of 100 m from input. The distribution of induced current is not affected due reflections at the ends because the matched line was supposed.

We investigated impact of various shapes of current wave. Firstly, it was the one-pulse wave (Fig. 4). The distribution of induced current and voltage is depicted on Fig. 5 ÷ 7. It is seen that for transposed transmission line the distribution in the phase conductors is the same (Fig. 6 and 7).

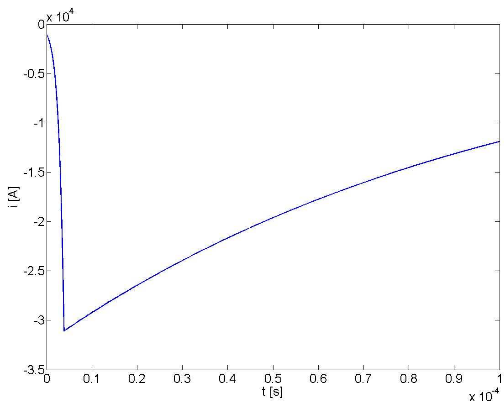

Fig. 4: Model of one-pulse lightning stroke

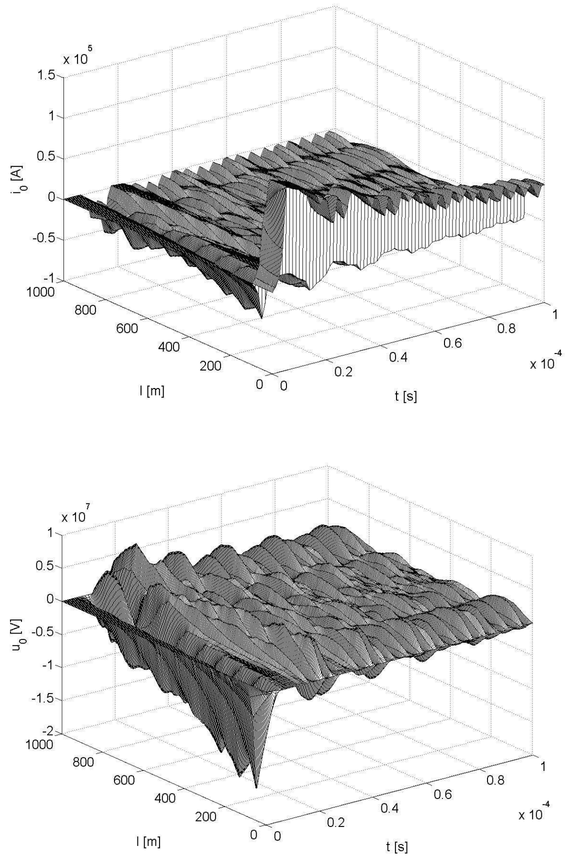

Fig. 5: Distribution of current and voltage along the earth wire

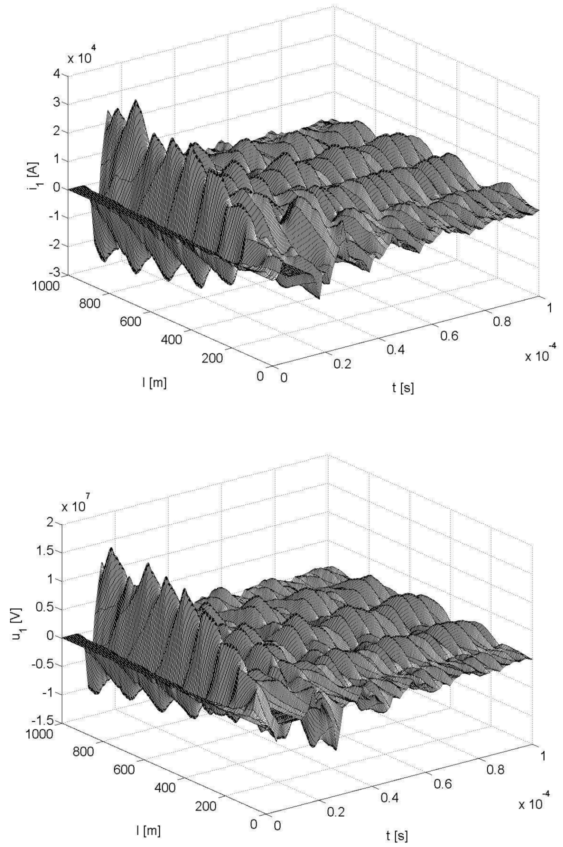

Fig. 6: Distribution of induced current and voltage along the first phase conductor

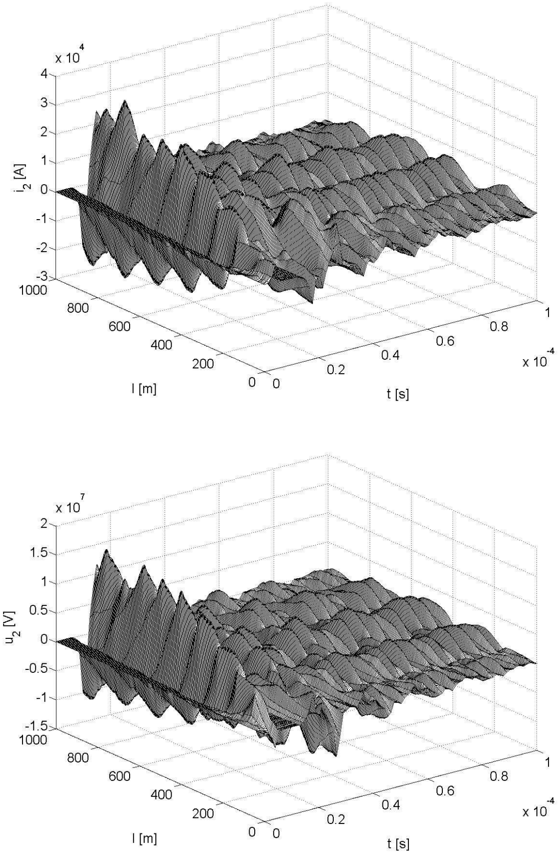

Fig. 7: Distribution of induced current and voltage along the second phase conductor

Secondary, the distribution for two-pulse current wave – Fig. 8 was investigated. In this case are the peak values of current and voltage higher than in the previously case. It is caused by the great rate of rise of the second pulse. The interferences of the response for both pulses can be well watched.

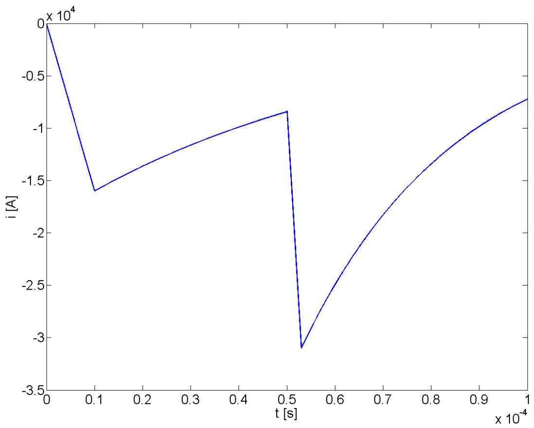

Fig. 8: Model of double-pulse lightning stroke

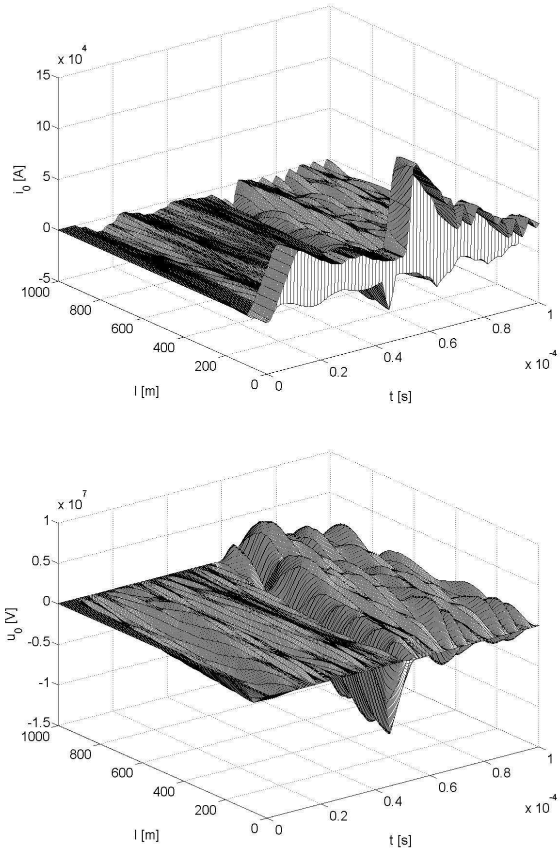

Fig. 9: Distribution of current and voltage along the earth wire

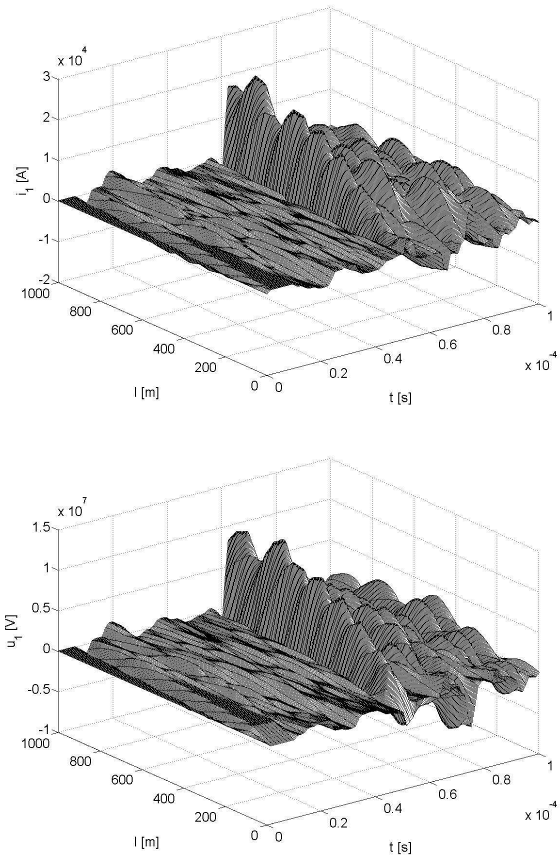

Fig. 10: Distribution of induced current and voltage along the first phase conductor

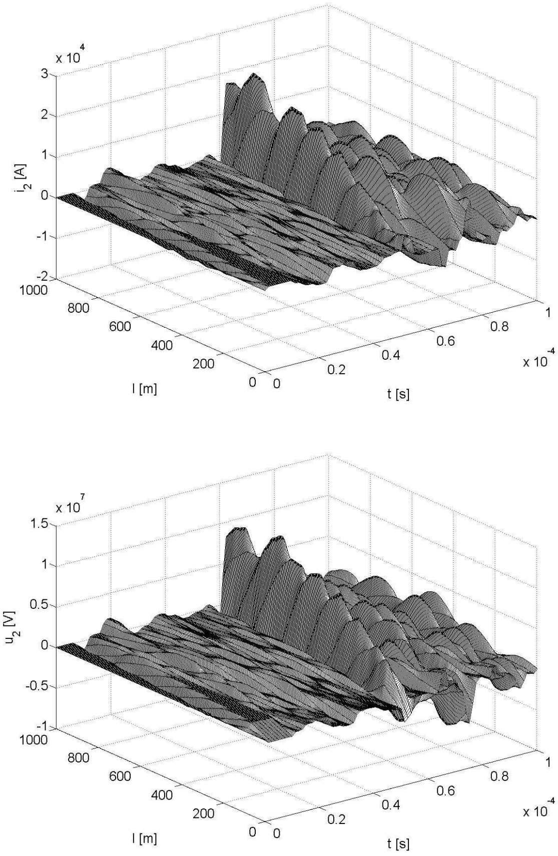

Fig. 11: Distribution of induced current and voltage along the second phase conductor

Obtain results correspond with the supposed fact about transposed line. If the line is transposed there is no difference between voltage and current distributions along the phase conductors although they have another distance between them and to the earth wire.

In solved example has been involved as the influence of coupling between the earth wire and the phase conductors as coupling between each conductor and the earth wire. The peaks of voltage and current induced in phase conductors are very high and can be dangerous not only for insulation system.

5 CONCLUSION

In the paper was suggested an algorithm for numerical solution of the voltage and current distribution along the three-phase transmission line with earth wire. Moreover, the proposal algorithm enables to obtain the time-space distribution of voltage and current along the line including induced voltage caused by lightning stroke into earth wire. The work is supplemented with several interesting illustrative examples. Their evaluation indicates a very good correspondence with known phenomena on transmission lines. The suggested algorithm is suitable for complex analysis of transient phenomena in many practical applications where the model formed by the network with distributed parameters should be used.

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