# Numerical modeling in EMC problems of electric power substations when lightning strikes

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*Abstract*— **For numerical modeling of lightning current spreading in lightning protection, grounding, electric power supply systems the ZYM program is used. Hybrid (field-circuit) thin-wire model is implemented in the program for electromagnetic fields and transients calculations (in ground and in air). Circuit model structure and its parameters are determined automatically, the user should only draw 3D model of a power substation and transmission line. The program is integrated with AutoCAD (using ObjectARX technology) that provides effective geometrical modeling with object and results visualization. Three impulse process calculation methods are researched and implemented: Fourier method, discrete circuits method (similar to ATP-EMTP) and step algorithm based on the Vlach method. The comparison of the methods shows the effectiveness of the latter. The wave process calculation caused by a lightning stroke in the overhead ground wire close to the power substation is carried out as an example. Surge voltage on the transformer and on the electrical equipment is determined before and after surge arrester is installed. The results are animated.**

*Keywords—EMC; LPS; grounding; trapezoid formula; Vlach method; AutoCAD; ZYM; numerical modeling; electric power substation*

## I. INTRODUCTION

Lightning strikes are the main causes of emergency outrages at electric power substations (SS) and power transmission lines (TL). Numeric modeling of lightning strike effects allows to find technical solutions that prevent accidents. There is a set of problems when designing SS.

To protect SS against a direct lightning strike the lightning protection system (LPS) is designed. The object is considered protected if it is inside lightning rods protection zone which is to be built. This is the first, most simple problem, which is solved, for example, by the rolling sphere method.

When lightning strikes into LPS, lightning current creates conductive and electromagnetic noise that can disturb microprocessor-based control system of a SS. This is the second, more complex EMC problem that requires calculation of transient electromagnetic processes and fields caused by impulse excitations.

When lightning strikes into TL (overhead ground wire or tower) insulator back flashover can arise. Then the voltage surge propagating along the line will pose a threat for transformers and other SS electrical equipment. It is required to calculate wave process in SS and TL conductors considering surge arresters that are used for overvoltage surge protection.

The problem list that designer should solve can be extended with electrical safety, EMC by short circuits and electromagnetic ecology problems.

Experts say that most of the described problems can be solved with the help of SES utilities (sestech.com) and wave processes calculation can be executed in ATP-EMTP program.

Certainly, these are powerful programs, world leaders in their fields, however, they are based on the single method for impulse processes calculation. In SES it is Fourier method that is used for linear problems and is the most time-consuming. In ATP-EMTP it is the discrete circuits method (trapezoid formula for inductance and capacitance substitution with discrete resistive models). The drawbacks of the trapezoid formula are associated with the solution oscillations caused by a short front impulse [1, 2].

We develop ZYM program – AutoCAD application for grounding, LPS, EMC and other thin-wire structure problems [3]. In the current version of the program ObjectARX technology is used for AutoCAD control. For transients calculation a set of methods are used: Fourier method, discrete circuits method and Vlach method [4], which in our opinion is the best.

## II. DISCRETE CIRCUITS METHOD WITH TRAPEZOID FORMULA

Using the trapezoid formula inductance voltage is

$$u = L\frac{di}{dt} \Rightarrow u_{k+1} = \frac{2L}{h}i_{k+1} - \left(u_k + \frac{2L}{h}i_k\right) = Ri_{k+1} + E_k. \quad (1)$$

This equation corresponds to the circuit (Fig. 1).
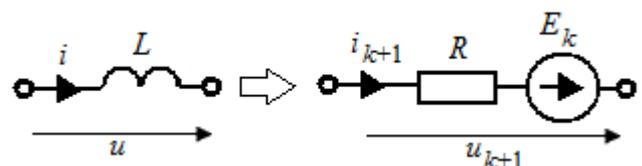


Fig. 1. Inductance discrete model at *k*-step

Using the trapezoid formula capacitance current is

$$i = C\frac{du}{dt} \Rightarrow i_{k+1} = \frac{2C}{h}u_{k+1} - \left(i_k + \frac{2C}{h}u_k\right) = Gu_{k+1} + J_k \,.$$

This equation corresponds to the circuit (Fig. 2).
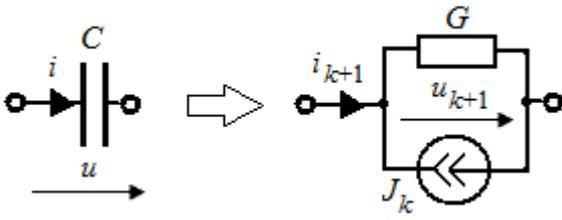


Fig. 2. Capacitance discrete model at $k$-step

After inductance and capacitance substitution is made transients calculation reduces to step-by-step DC-circuit calculation. This is the main advantage of the method. The problem is that the use of the trapezoid formula may lead to oscillations. This is described in [2].

Let the current impulse with the linear front of $T$ duration and unit amplitude is applied to the inductance $L$ (Fig. 3).
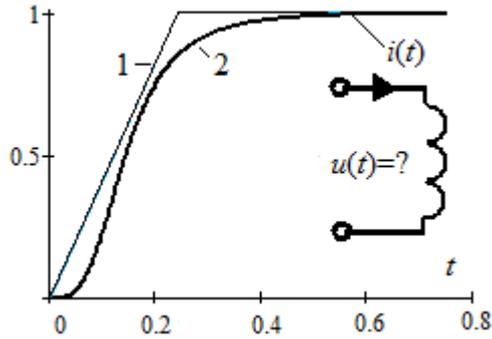


Fig. 3. A problem – to calculate voltage at a given current: 1– linear front, 2– Heidler function

The integration step is chosen as $h=T$. Let's make few steps using the trapezoid formula (1) in case of $L/h=1$.

$$i_0 = 0, \; i_1 = i_2 = ... = i_n = 1,$$
$$u_0 = 0,$$
$$u_1 = 2L/h \cdot i_1 - (u_0 + 2L/h \cdot i_0) = 2,$$
$$u_2 = 2L/h \cdot i_2 - (u_1 + 2L/h \cdot i_1) = -2,$$
$$u_{k+1} = -u_k.$$

So, the solution is oscillating. It is interesting that the implicit Euler formula gives the exact solution in this problem $u_0=0$, $u_1=1$, $u_2=u_3\ldots=u_n=0$.

To resolve this problem the linear combination of trapezoid and implicit Euler formulas is suggested [2]. For inductance it is

$$i_{k+1} = \alpha\left[i_k + \frac{h}{L}u_{k+1}\right] + (1-\alpha)\left[i_k + \frac{h}{2L}(u_{k+1}+u_k)\right] = $$
$$= i_k + \frac{h}{2L}\left[u_{k+1}(1+\alpha) + u_k(1-\alpha)\right], \tag{2}$$

where $\alpha=0.15$ is the weight factor. Based on this formula the EMTP program manual recommends to insert conductance $G=0.15h/2L$ in parallel to inductance when oscillations occur.

Let's analyze the formulas (1), (2) numerically. We will conduct two different shape impulses of 0.25/100 µs duration through the inductance $L=1$ µH.

Case 1: current impulse with linear front (nonsmooth function). Step-by-step calculation of the inductance voltage using the trapezoid formula gives the oscillating solution regardless of the integration step $h$ (Fig. 4). The use of the combined formula (2) does not eliminate oscillations but leads to their damping.
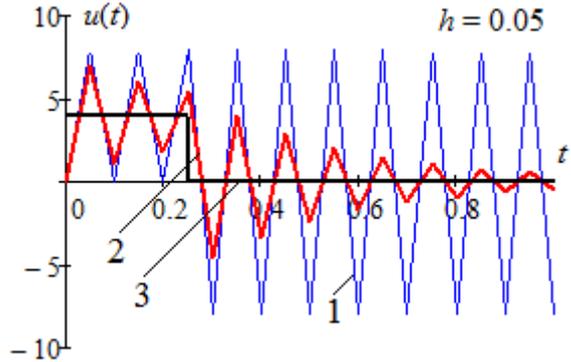


Fig. 4. Problem solution (Fig. 3) using: 1– trapezoid formula (1), 2– combined formula (2); 3– exact solution. Current with linear front, step $h$=0.05.

Case 2: Heidler function current impulse – smooth function with continuous derivative (Fig. 3)

$$i(t) = 1.009 \frac{(6861588t)^{3.351}}{1 + (6861588t)^{3.351}} \cdot e^{-7017 \cdot t}\,.$$

When the step is big the solution is again oscillating (Fig. 5). However, when decreasing the step oscillations disappear and the trapezoid formula gives the exact solution (Fig. 6). Formula (2) is unnecessary.
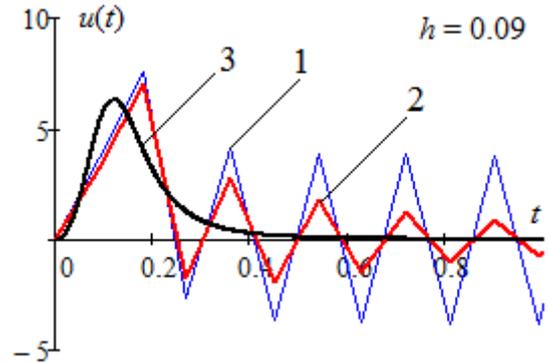


Fig. 5. Problem solution (Fig. 3) using: 1– trapezoid formula (1), 2– combined formula (2); 3– exact solution. Current – Heidler function, step h=0.09.
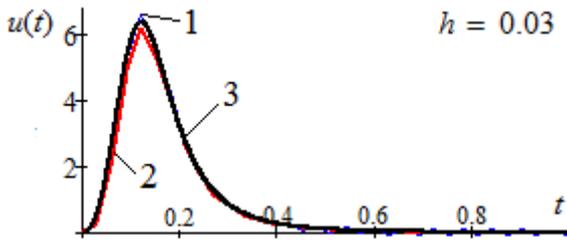
Fig. 6. Problem solution (Fig. 3) using: 1– trapezoid formula (1), 2– combined formula (2); 3– exact solution. Current – Heidler function, step h=0.03.



Fig. 8. Equivalent discrete circuit of capacitance at k– step; $s$ is defined in (3)

So, when current conducts through an inductance the trapezoid formula is applicable only for smooth functions such as the Heidler function and in case of correct step choice. This condition cannot be guaranteed. For example, when lightning strikes and insulator flashover happens voltage increases dramatically in one time step, so, impulse with linear front occurs. Combined formula (2) does not eliminate oscillations.

Analysis of other integration formulas for inductance and capacitance discrete models is the evident direction of discrete circuits method development. One-step formulas of high order (Runge–Kutta methods) don't have absolute stability. Multistep formulas (Gear method, etc.) complicate discrete circuits. The most efficient approach that gives discrete circuits like Fig. 1 and Fig. 2 is the Vlach method.

## III. VLACH METHOD

### A. Numerical method of inverse Laplace transform

Canadian researchers I. Vlach and K. Singhal got a family of formulas of inverse Laplace transform [4].

$$f(t) = \frac{1}{t}\sum_i \text{Re}\left[res_i F(s_i/t)\right], \ t > 0,$$

where $s_i$ – poles, $res_i$ – residues of the operator function. For example, 3rd order formula is

$$f(t) = \text{Re}(\ (5\sqrt{2}j - 2)\cdot F(s)\ )/t, \ s = (2+\sqrt{2}j)/t, \ t > 0. \quad (3)$$

It also makes sense to consider formulas of 7, 11, 15.. 27 order with 2, 3, 4..7 function calculations. Further, there is stability loss due to arithmetic errors. In step algorithms 3rd and 7th order formulas are used.

### B. Step algorithm

Time interval is divided into $n$– equal steps of $h$ length. Inductances and capacitances are simulated as discrete complex circuits (Fig. 7,8). They are completely similar to the resistive circuits (Fig. 1,2) if we replace $Z$ with $R$ and $Y$ with $G$, so, the standard methodology of discrete circuits method implementation can be used for Vlach method also. All the previously considered problems are solved by the step algorithm based on the Vlach method with high precision.
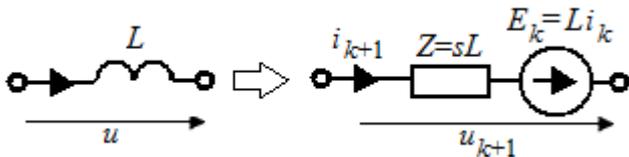


Fig. 7. Equivalent discrete circuit of inductance at k– step; $s$ is defined in (3)
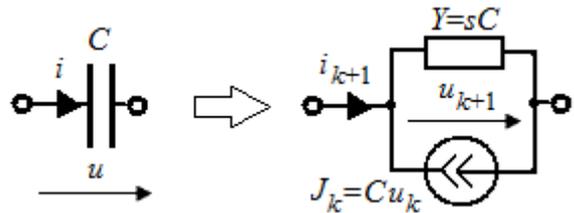
## IV. METHODS TESTING

We will determine voltage at the end of the TL (Fig. 9a) when exposed to a voltage impulse with linear front of 0.1 µs using different methods (Fig. 9). Discrete circuits method with trapezoid formula leads to solution oscillations (Fig. 9b) as described earlier. Vlach method with 3rd order formula (3) simulates the processes with 1% error (Fig. 9c), 7th order formula gives the solution with 1% error using fewer steps. Fourier method error is 3% (Fig. 9d).
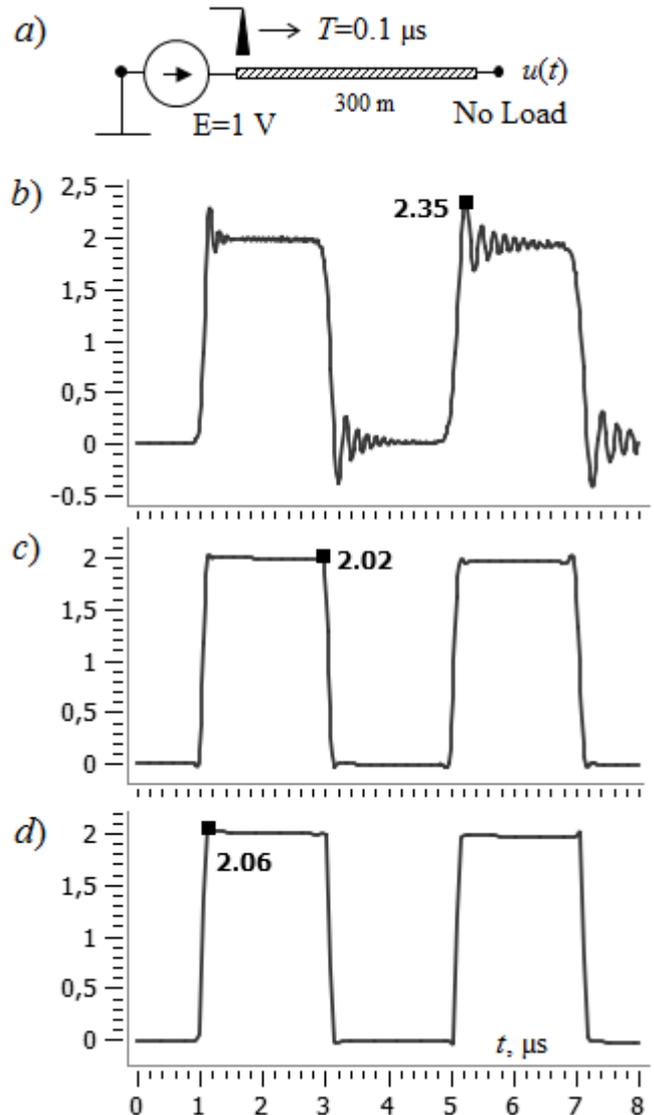


Fig. 9. Calculation model (a) and voltage at the end of the TL: numerical solution using b)– trapezoid formula, c)– Vlach method, d) Fourier method

## V. NUMERICAL MODELING OF A LIGHTNING STRIKE INTO POWER LINES NEAR POWER SUBSTATION

### A. Calculation model

The TL and SS calculation model consists of thin-wire conductors (Fig. 10). TL towers and other standard elements are inserted into AutoCAD drawing from the construction base as AutoCAD blocks. When calculating wave processes SS electrical equipment is simulated with input capacitances, which values are taken from the reference books (Fig. 11). A surge arrester is defined with its voltage-current characteristic. Insulator is simulated with switch that is closed when the voltage exceeds given function $u(t)$. Impulse current input point and its parameters are defined.
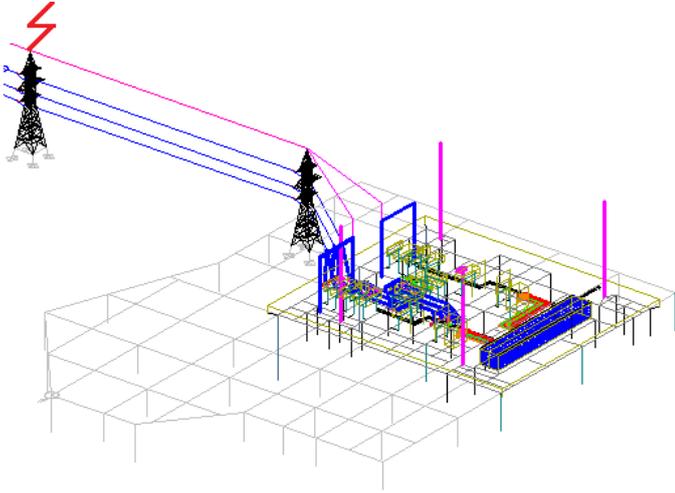


Fig. 10. SS и TL calculation model
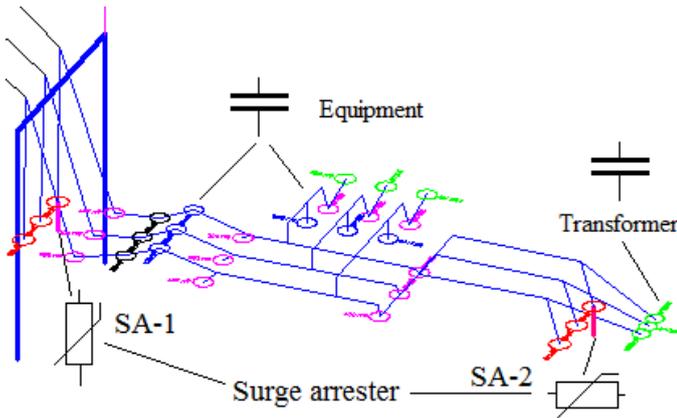


Fig. 11. SS electrical equipment model for lightning surges calculation

### B. Lightning strikes into the transmission line tower

When lightning strikes into the TL tower (Fig. 10) insulator flashover happens and voltage surge propagates along TL and then further over SS conductors. Without protection voltage on the transformer exceeds tolerable level (Fig. 12-1). Surge arrester mounting near the transformer (SA-2) decreases overvoltage significantly (Fig. 12-3). Surge arrester mounting at the end of the TL (SA-1) is necessary to exclude overvoltage on other electrical equipment (Fig. 12-2). Installation of two surge arresters in the phase is the most reliable way of lightning surges protection (Fig. 12-4).

The processes are oscillatory in nature that is related to wave reflections from the transformer, the surge arrester and the impulse current input point. The surge arrester mounting removes the oscillations.

### C. Lightning strikes into the transmisson line

Let the current wave of $I_m$=6.5 kA amplitude with linear front of $T_1$=3.9 µs propagates along the TL as a result of a lightning strike at the TL. Dangerous overvoltage appears at the electric equipment without protection (Fig. 13-1). SA-1 mounting decreases overvoltage to tolerable level (Fig. 13-2). Mounting of SA-2 instead of SA-1 is again more effective (Fig. 13-3). Mounting of both surge arresters decreases overvoltage to the maximum extent and eliminates oscillations (Fig. 13-4).
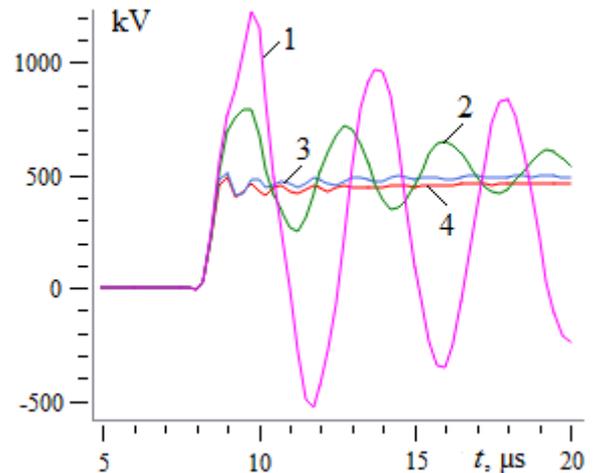


Fig. 12. Voltage at power transformer when lightning (100 kA, 10/350 µs duration) strikes into the TL tower (shown at Fig. 10): 1– without SA, 2– SA-1 installed, 3– SA-2 installed, 4– SA-1 and SA-2 installed (labels – Fig. 11)
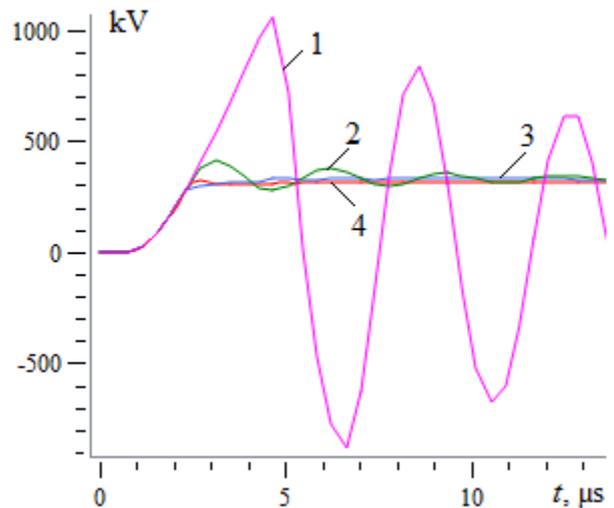


Fig. 13. Voltage at power transformer when lightning (6.5 kA, 3.9 µs front duration) strikes into the TL: 1– without SA, 2– SA-1 installed, 3– SA-2 installed, 4– SA-1 and SA-2 installed (labels – Fig. 11)

By completing the series of calculations at various locations and with different lightning current parameters it is possible to get

integral characteristics as, for example, trouble-free operation period at SS in case of lightning strikes into TL.

conductors. Program integration with AutoCAD simplifies geometrical modeling and results visualization significantly.

## VI. CONCLUSIONS

In ZYM program three main transients calculation methods are implemented that allows us to determine strengths and weaknesses of the methods. Vlach method has a definite advantage over the discrete circuits method with trapezoid formula that is used in the EMTP program when simulating wave processes.

Wave process calculations in air conductors should be made together with current leakage processes in ground.

All lightning protection, grounding, electrical safety and EMC problems should be solved using a single 3D-model of

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