

# Computing methods for building earthing devices in problems related to EMC of substations

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**Abstract—** Calculations for earthing devices (ED) are formulated as chain-field-like problems. The chain-field model of ED, computing techniques and software (AutoCAD application) have been developed, the program makes possible the solution of the problems related to EMC of electric power substations.

**Keywords—** component; formatting; style; styling; insert (key words)

## I. INTRODUCTION

At power facilities switching lightning, short-circuit or transient currents flowing through earthing devices (ED) create electromagnetic interference capable to disturb the operation of electric power substation microprocessor systems and alike process control facilities. To make a substantiated choice of microprocessor systems one should calculate electromagnetic field characteristics in normal and emergency conditions. The program FDTD gives the solution on the basis of ED field model, nevertheless, when linear dimensions of ED exceed by 3-5 orders wire section the design volume time sampling will require a huge number of elements. One should close in artificial way the design area so as to establish boundary conditions. Chain models in EMTP program are considerably simpler but one may obtain accurate results of pulse action only if he adequately accounts for all electromagnetic interactions between components. Moreover, the calculation results will give component voltages and currents but not electromagnetic field strengths (with due account made for shielding) required for the solution of EMC problems.

In terms of formulation, techniques and required results the EMC problems are chain-field-like, when to solve them there will be needed two interrelated models – field- and chain-like. The field model shall allow calculating of electromagnetic parameters of components which will be used further in the chain model to calculate the component currents. To calculate the characteristics of electromagnetic field on the basis of obtained currents (longitudinal and flowing down) the field model will be used again.

## II. CHAIN- AND FIELD-LIKE MODEL OF ED

The ground wire is to be divided into elements of  $l \leq \lambda/10 = \sqrt{10^5 \rho / f}$  length, where  $\lambda$  – is the electromagnetic

wavelength of  $f$  frequency in conducting medium with electrical resistivity  $\rho$ , that enables us to calculate electromagnetic characteristics of components in static approximation. It is assumed that the field sources like electric charges, flowing down and longitudinal currents are concentrated on the axes of round conductors. Internally active resistance and inductance of components shall be determined with due account made for surface field effect and described by means of scalar matrices  $\mathbf{r}$  and  $\mathbf{L}$ . Electric and magnetic couplings between the components are described by squared fully completed matrices of self- and mutual conductances  $\mathbf{G}$ , capacitances  $\mathbf{C}$ , inductances  $\mathbf{M}$ . The current spreading conductance matrix may be obtained by inversion of resistance matrix  $\mathbf{G} = \mathbf{R}^{-1}$ .

Mutual resistance  $R_{ij}$  in uniform medium with electrical resistivity  $\rho$  is to be defined as the relation of potential in mid-point of  $i$ -th element to  $j$ -th element current

$$R_{ij} = R(p, q, l) = \frac{\rho}{4\pi \cdot |l|} \cdot \ln \frac{(q+l-p) \cdot l + |q+l-p| \cdot |l|}{(q-p) \cdot l + |q-p| \cdot |l|} \quad (1)$$

where the positions of design point  $p$  and bar  $q, l$  are arithmetical vectors (Fig. 1). Vector notation permits to use the formula for any rod location in relation to ground level.

Internal resistance of a rod of  $d$  diameter shall be determined in the following way

$$R_{ii} = \frac{\rho}{2\pi |l|} \cdot \ln \frac{|l| + \sqrt{|l|^2 + d^2}}{d}, |l| > d. \quad (2)$$

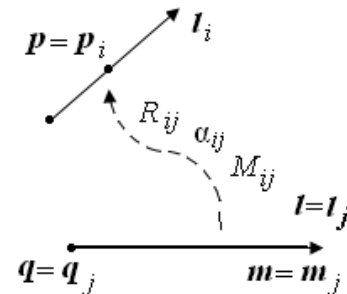


Figure 1. Determination of mutual parameters of  $i, j$ -th elements with point positions:  $q = q_j = (x_q, y_q, z_q)^T$ ,  $m = m_j = (x_m, y_m, z_m)^T$ ,  $l = l_j = m - q$ ,  $p = p_i = (x_p, y_p, z_p)^T$

Vector notation of element resistances in double-layer soil is given in [1]. The matrix of element capacitance is to be received by inversion of the matrix of potential coefficients  $\mathbf{C} = \boldsymbol{\alpha}^{-1}$ , where the matrix elements  $\boldsymbol{\alpha}$  are equivalent (at  $\rho$  being substituted by  $1/\epsilon$ ) to element resistances  $R'_{ij}$  in uniform soil.

According to IEC standard 60050-121 the element mutual inductance is equal to  $M_{ij} = \Psi_{ij}/I_j$ , where  $\Psi_{ij} = \int A_{ij} \cdot dl_i \approx A_{ij} \cdot l_i$  – is the flux linkage of  $i$ -th rod created by  $j$ -th rod current, it is defined by integration of vector potential along  $i$ -th element. By using notations (Fig.1) we shall receive

$$M_{ij} = \frac{\mu_0 \cdot l_i \cdot l_j}{4\pi \cdot |l_j|} \ln \frac{(q+l_j-p) \cdot l_j + |q+l_j-p| \cdot |l_j|}{(q-p) \cdot l_j + |q-p| \cdot |l_j|} \quad (3)$$

To pass to the chain-like diagram of ED (Fig. 2b) one should make the inversion of matrices  $\mathbf{G}$  and  $\mathbf{C}$  defined in mid-points of elements (Fig. 2a) in nodal matrices  $\mathbf{G}_y$  and  $\mathbf{C}_y$  (Fig.2b) on the basis of the invariability of element flowing down current. The topology of longitudinal branches of a diagram (Fig. 2b) is described by the standard matrix of couplings  $\mathbf{A}$  and the matrix  $\mathbf{B}$  shall be introduced ( $b_{ij} = |a_{ij}|/2$ ). Then, [1] the unknown nodal matrices are  $\mathbf{G}_y = \mathbf{B} \cdot \mathbf{G} \cdot \mathbf{B}^T$ ,  $\mathbf{C}_y = \mathbf{B} \cdot \mathbf{C} \cdot \mathbf{B}^T$ .

The calculation of chain-like model of ED shall permit us to define the element potentials and currents (flowing down and longitudinal) by using circuit analysis methods. The nodal-voltage method shall be used at harmonics impacts. Transient processes occurred at pulse impacts are to be calculated by using discrete skeleton or operator methods [1,2]. Upon the found rod flowing down currents in the model (2a) one may evaluate the potential and field distribution, while upon the found longitudinal currents the magnetic field strength may be specified.

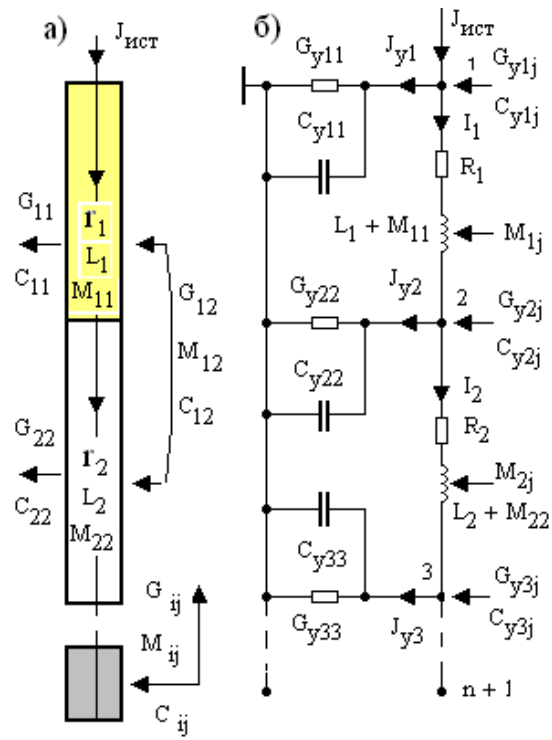


Figure 2. Chain- and field-like model of earthing rod

### III. CHARACTERISTICS OF TECHNIQUES FOR CALCULATION OF PULSE TRANSIENTS IN ED

#### A. Frequency-domain method (FDM) with artificial signal periodization

Let us restrict the length of transient observation by a value  $t_{mn} = (3-10)T_1$ , where  $T_1$  – is the leading edge time

Let us extend the current pulse  $J(t)$  out of the design interval ( $t > t_{mn}$ ) by using the same function but inverting the sign (Fig. 3). Now we have a periodic function  $f(t)$  with the period  $2t_{mn}$ , which has an odd symmetry

$$f(t) = \begin{cases} J(t), & 0 \leq t \leq t_{mn}, \\ J(t_{mn}) - J(t - t_{mn}), & t_{mn} < t \leq 2t_{mn}, \end{cases} \quad (4)$$

that shall permit us to exclude even harmonics from harmonic sequence

$$f(t) = A_0 + \sum_{k=1,3,5,\dots} A_k \cos(k\omega_1 t + \varphi_k), \quad \omega_1 = \pi/t_{mn} \quad (5)$$

The calculation of sequence coefficients shall be carried out with the use of fast Fourier transformation.

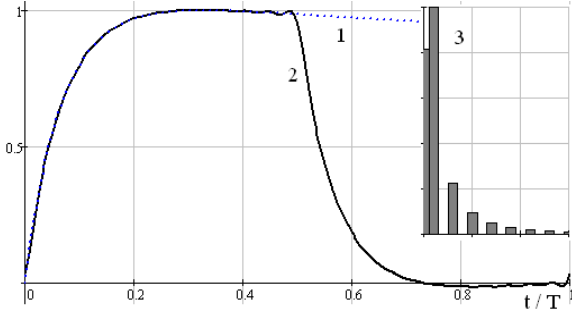


Figure 3. Current pulse (1), periodization (2), amplitude-frequency response (3)

### B. Discrete skeleton method (DSM)

The standard MMF implementation with replacement of inductance and capacitance by resistive models on each time interval (on the basis of implicit Euler formula) is rather effective in EMC problems. Nevertheless to compute wave processes requiring more accuracy for a given interval we suggest to use the discrete skeleton method to develop the paper [2]. The inductance is simulated by resistance  $sL$ , the capacitor – by conductivity  $sC$ , where  $s = (2 + \sqrt{2}j)/h$ ,  $h$  – is the time interval length. Reference conditions of  $n$ - interval are accounted for by the sources  $E_n = Li_n$  for a coil and  $J_n = Cu_n$  for a condenser. Now we shall make calculations of compatible circuit. The transition from the image to an original shall be done by using the formula:

$$f(t) = \text{Re}((5\sqrt{2}j - 2)F(s)) / h \quad (5)$$

A common use of studied techniques shall permit to analyze pulse processes with due account made for frequency and nonlinear properties of elements and soil. In the majority of problems the MMF is more efficient than the frequency shift in terms of solution accuracy and speed. The area of MMF application may be extended with the elaboration of a new discrete impedance-frequency model  $z(j\omega)$ .

## IV. ACCOUNTING FOR FREQUENCY-DEPENDENT IMPEDANCES IN MMF

Let us assume that in MMF it is required to take into account the dependency of rod internal resistance or OHL return conductor internal resistance on the frequency. For these purposes the equivalent circuits having close frequency characteristics are usually applied, but we can propose the most efficient method [1].

Given is the resistance of frequency-dependent element  $z(j\omega)$  or its operator equivalent  $Z(s)$ . We shall take integral of  $Z(s)$  in image space and having passed to the original we shall obtain the transition resistance  $z(t) = \mathbf{L}^{-1}[Z(s)/s]$ , linking the voltage and the current in Duhamel integral

$$u(t) = z(t)i(0) + \int_0^t z(t-x) \cdot i'(x) dx, \quad i(0) = 0. \quad (6)$$

Discrete notation of this integral on the grid with nodes  $t_n = (n-1)h$ ,  $n = 1..N+1$ , at step approximation of current derivative  $i_n' = \text{const}$  shall give us

$$u_{n+1} = \sum_{m=1}^n \frac{i_{m+1} - i_m}{h} \int_{t_m}^{t_{m+1}} z(t_{n+1} - x) dx = \sum_{m=1}^n (i_{m+1} - i_m) R_{n-m+1}, \quad (7)$$

where (taking into account the designation  $k = n-m+1$  and substitution  $y = t_{n+1}-x$ ) the discrete transition resistance of  $k$ -th interval is equal to

$$R_k = \frac{1}{h} \int_{(k-1)h}^{kh} z(y) dy, \quad k = 1..N. \quad (8)$$

Taking the integral in image space instead of  $z(t)$  we shall have  $z_1(t) = \mathbf{L}^{-1}[Z(s)/s^2]$ , then

$$R_k = [z_1(kh) - z_1(kh-h)]/h, \quad k = 1..N, \quad (9)$$

where  $z_1(t)$  – is the response of a circuit to the influence of current  $i(t) = t$ . Extracting the first term  $u_{n+1}$  we shall finally receive the relationship

$$u_{n+1} = R_1 \cdot i_{n+1} - \sum_{m=2}^n (R_{n-m+1} - R_{n-m+2}) i_m = R_1 \cdot i_{n+1} - E_n, \quad (10)$$

to which the diagram below corresponds (Fig. 4).

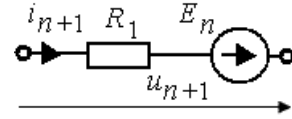


Figure 4. Discrete model of resistance  $z(j\omega)$

In this way the resistance  $z(j\omega)$  is completely described by discrete transition resistances in incremental algorithms.

Let us find as an example the discrete transition resistance of steel rod with operator resistance  $Z(s) = (l/2\pi a) \cdot \sqrt{s\mu/\gamma}$ , where  $l$  – is the length,  $a$  – is the rod diameter. The rod transition resistance is  $z(t) = \mathbf{L}^{-1}[Z(s)/s] = (l/2\pi a) \sqrt{\mu/\gamma\pi t}$ . Then the discrete transition resistances

$$R_n = \frac{1}{h} \int_{(n-1)h}^{nh} z(y) dy = \frac{l}{a} \frac{\sqrt{\mu/\gamma}}{\pi\sqrt{\pi}h} (\sqrt{n} - \sqrt{n-1}), \quad n = 1..N \quad (11)$$

depend only on the number of interval  $n$ .

## V. ACCOUNTING FOR NON-LINEAR ELEMENTS

They are self-conductance of ED element with consideration of spark formation in soil (the model of Riabkova L.R. was used in this paper) and magnetization of steel (universal Neumann curve was used). There are no vital changes in  $n$ -step algorithms occurred due to non-linearity – within transient computation the parameters of non-linear elements are considered as piecewise constant and equal to the value at the beginning of each step during. In the majority of cases the saturation of steel rods of earthing device has a minor effect on the results of calculations, so it is recommended to choose the constant value  $\mu/\gamma$  of rods upon universal Neumann

curve while for error estimation to perform calculations twice: with minimal and maximal values of  $\mu/\gamma$ .

## VI. SYNTHESIS OF SIMPLIFIED ED MODE

In design models of ED there are usually such facilities as earth electrodes, supports, OHL, CL which may be represented as passive single-terminal pairs and reduce the sizing of a model. We shall describe a single-terminal pair through transition resistance  $z(t)$ , which is numerically equal to its input voltage at unit-step current switching. To find  $z(t)$  we shall make a separate calculation and for a given current on a discrete time grid  $t_n = (n-1)h$ ,  $n = 1..N+1$  with  $h$  step and at zero initial conditions we shall define the input voltage. Then [1]

$$z_1 = u_2 / i_2, z_n = \left[ u_{n+1} - \sum_{m=2}^n z_{n-m+1} (i_{m+1} - i_m) \right] / i_2, n = 2..N. \quad (12)$$

The obtained discrete function  $z_n$  is approximated by continuous function  $z(t)$ , for which we shall find the operator resistance  $Z(s)$ . Then at computing transients the discrete model (Fig. 3) shall correspond to a single-terminal pair. Another way is associated with the circuit implementation by using standard methods of electrical network synthesis. For example, for ED of a support it will be sufficient to approximate  $z_n$  by exponential curve  $z(t) = R + (R_0 - R)e^{-t/\tau}$ , that gives us  $Z(s) = (s\tau R_0 + R) / (s\tau + 1)$  and results in  $RL$  equivalent circuit (Fig.5a), which is proper to ED with high conductivity of soil or in  $RC$  circuit (Fig.5b), proper to small sized ED in soils with low conductivity.

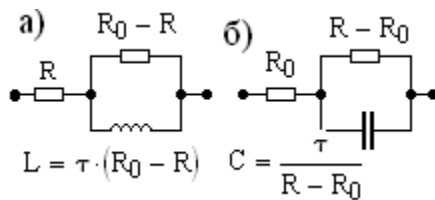


Figure 5. Simplified circuits equivalent to ED

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## VII. ELECTROMAGNETIC SCREENING

All steel structures in buildings, facilities, cable ducts where the loops for eddy currents shorting are possible serve as electromagnetic screens. Wire screens (reinforcing steel in buildings) are simulated by meshes. Bulk shields (steel walls - panels) are recommended to be simulated by meshes according to IEC 62305-4. You will find herein the formula for computation of shielding coefficient  $k = 20 \log(8.5/w)$  of wire screen (non-ferromagnetic) with screen mesh  $w$  of magnetic component of plane electromagnetic wave for lightning frequencies. It is difficult to use this formula as there are no

recommendations as on how to select  $w$  and at  $w = 0$  corresponding to bulk shield  $k \rightarrow \infty$ . Thus, the approximation of plane wave does not correspond to three-dimensional geometry of electromagnetic shields that have a large number of angles and orifices and does not allow computing of the field inside a protected area. In the present paper bulk shields are simulated by meshes where the equivalent rod diameter  $d = 0.36w$  is found under condition of invariability of exterior inductance of a steel plate.

## VIII. SOFTWARE IMPLEMENTATION

The examined models and ED computing methods have been implemented in ZYM program with the use of COM-technologies as AutoCAD application. The program retrieves the geometrical models in AutoCAD, makes calculations (while using the standard Lapack package) and represents the design results in the form of 2D, 3D graphs in AutoCAD format (Fig. 6-8). Transients are animated that ensures the visualization of transient processes in time and space.

## IX. DESIGN EXAMPLES

The procedure of developing areas of external lightning protection of substations by using the method of rolling circle makes possible to substantiate the scheme of lightning protection and to find the area of lightning stroke capturing (Fig. 6). When simulating injection of lightning and short-circuit currents we find the potential (Fig. 7), current and electric field strength distribution in places where microprocessor equipment is installed with due account made for shielding (Fig. 8). Now we shall find galvanic interference of secondary wires due to potential rise in ED at lightning strokes and short-circuits.

## X. CONCLUSIONS

The issues of ED computing in EMC problems are formulated as chain- and field-like problems, they require a common use of both field and chain models. The field-like model is designed to compute electromagnetic parameters of recurrent network and to analyze the electromagnetic environment. The chain model ensures the most efficient method of calculation of element currents (longitudinal and flowing down) at harmonic and pulse impacts. The computation of transients is to be carried out by discrete skeleton method making possible to take into account non-linear and frequency-dependent resistances and having advantages as compared to the frequency method. The proposed mathematical models, methods and design programs for ED permit to solve the EMC problems occurred in electric power industry and in other branches.

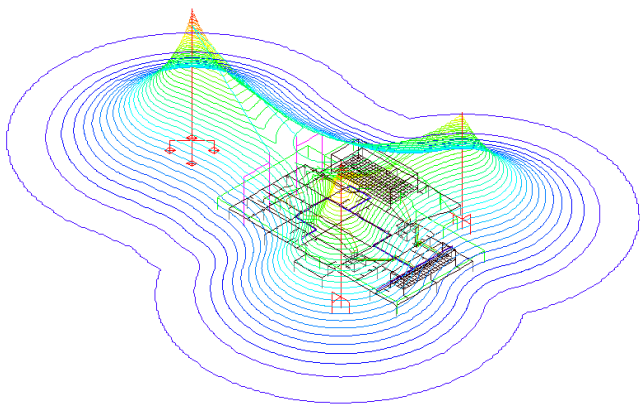


Figure 6. Areas of external lightning protection of substations

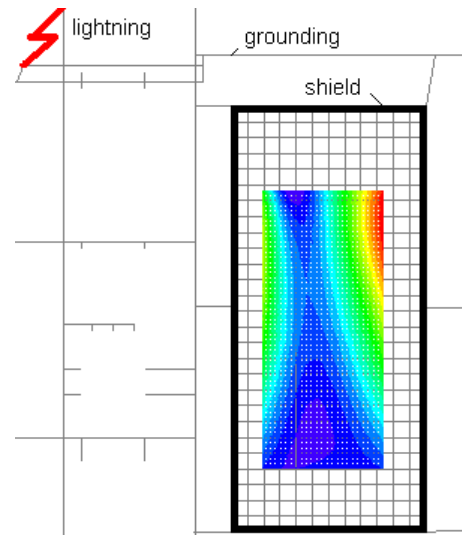


Figure 8. Distribution of electromagnetic field strength at 1m above the floor in a building at 100 kA lightning current, 25 kHz equivalent frequency,  $H_{\max}=76$  A/m (without shielding  $H_{\max}=852$  A/m)

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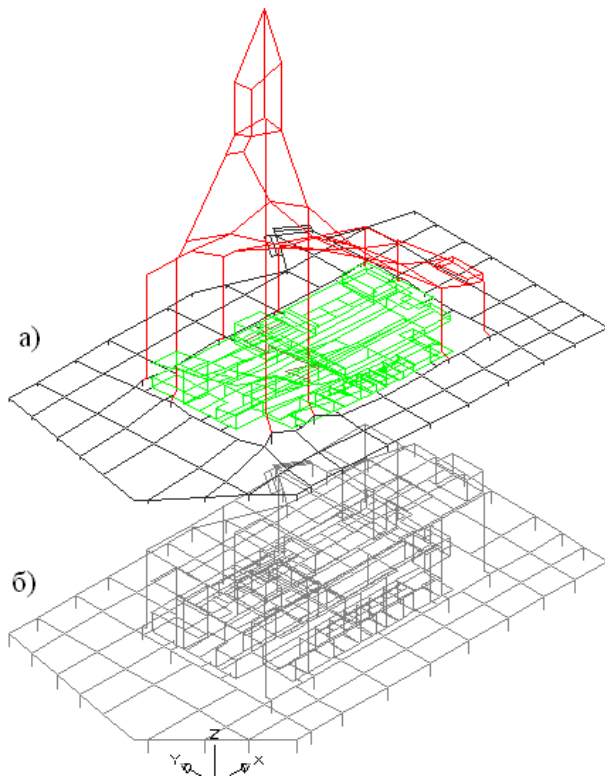


Figure 7. Potential distribution in indoor switchgear at lightning discharge (a); design model in the form of a header (b)