

Imitative Modelling of Electromagnetic Safety Conditions in Smart Power Supply Systems

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Abstract

The implementation of intelligent railway power supply system requires the development of computer technologies for modeling modes and electromagnetic fields determining the conditions for electromagnetic safety. Such technologies are implemented based on the methods developed at the Irkutsk State Transport University.

The formation of intelligent power supply systems will solve the following important tasks: provision of high reliability of power supply for traction of trains, as well as for non-traction and non-transport consumers; increase of electromagnetic safety; minimization of energy losses and operating costs of traction power networks; improvement of electricity quality in traction power networks, as well as in the interface regions with the supply electric power system.

The article presents the technology of electromagnetic environment simulation modeling on alternating current railway. An example of calculations is considered. The amplitude values of the magnetic field strength vary with the average size of train movement from several amperes per meter to 60 A/m, the electric field strength varies comparatively little.

Keywords: Intellectual power supply system, electromagnetic safety, imitating modeling.

1. Introduction

The current stage in the development of the electric power industry is characterized by the transition to a new technological platform based on the concept of intelligent electrical power networks – a smart grid [1]. This concept is fully applicable in railway power supply systems (RPSS) [2–5].

The implementation of intelligent RPSS will solve the following important practical problems:

- provision of high reliability of power supply for traction of trains, non-traction and non-transport consumers;
- increase of electromagnetic safety (EMS);
- minimization of energy losses and operating costs of RPSS;
- improvement of electric power quality in RPSS, as well as in the interface regions with the supply electric power system.

The intelligent RPSS implementation requires the

development of computer technologies for modeling modes and electromagnetic fields determining electromagnetic safety conditions. Such technologies are implemented based on the methods developed at IrGUPS [5–7].

2. Structure of intellectual traction power supply system

The structure of the intellectual RPSS (IRPSS) is shown in Fig. 1.

IRPSS includes the following segments:

- developed complexes providing monitoring of the status of electrical equipment, including devices operating on-line;
- automatic control devices based on digital technologies;
- controlled reactive power sources manufactured using the FACTS concept (flexible alternative current transmission systems);

- distributed generation installations and power storage devices;

- a set of devices for improving the quality of electric power.

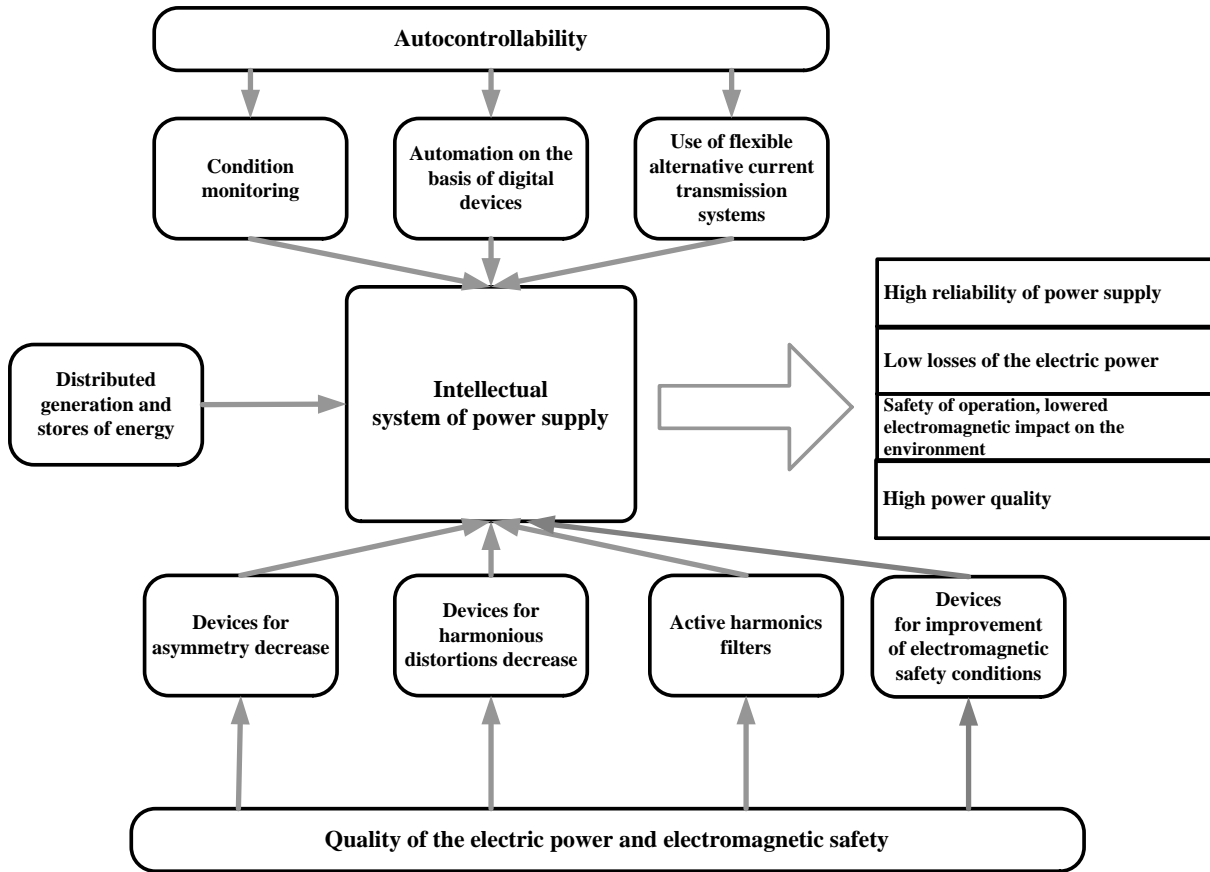


Fig. 1. The structure of intellectual RPSS.

3. Modeling of railway power supply system

Railway power supply system is a combination of three subsystems, each of which can also be considered as a complex technical system:

$$\mathbf{S}_{SPSR} = \mathbf{S}_{EPS} \cup \mathbf{S}_{STPS} \cup \sum_{k=1}^n \mathbf{S}_{APSNIC}^{(k)},$$

where \mathbf{S}_{EPS} is an electric power system or a part adjacent to the traction substations of the considered RPSS; $\mathbf{S}_{STPS} = \mathbf{S}_{STPS}^{(25)} \cup \mathbf{S}_{STPS}^{(2 \times 25)}$ is a traction power supply system (TPSS) with traction network of 25 kV or autotransformer TPSS 2×25 kV; $\mathbf{S}_{APSNIC}^{(k)}$ is k -th region of non-traction and non-transport consumers power supply.

The description of each subsystem can be obtained based on the cortege representation

$$\mathbf{S} : \{ \mathbf{el} \}, \{ \mathbf{Lin} \}, \mathbf{N} \},$$

where $\{ \mathbf{el} \} = \{ \mathbf{el}_E \} \cup \{ \mathbf{el}_I \}$ is a set of elements which can be divided into two subsets: power $\{ \mathbf{el}_E \}$ and information $\{ \mathbf{el}_I \}$ elements; $\{ \mathbf{Lin} \}$ is a set of links between the elements which determines the structure of RPSS; \mathbf{N} is a system function determined by its main emergent property, not inherent in the individual elements.

The \mathbf{N} function for RPSS is defined as a centralized power supply for the train traction and non-traction consumers. In this regard, for \mathbf{N} it is possible to write in such a way

$$\mathbf{N} = \bigcup_{k=1}^3 \mathbf{N}^{(k)},$$

where $\mathbf{N}^{(1)}$ is provision of consumers with electric power with minimal costs for its transmission and distribution; $\mathbf{N}^{(2)}$ optimal power supply reliability, and $\mathbf{N}^{(3)}$ is considered as a logical variable determined by a function of the vector of indicators \mathbf{G} characterizing the quality of electric power, that is, $\mathbf{N}^{(3)} = \varphi(\mathbf{G})$.

At the Irkutsk State Transport University comprehensive research is being carried out to solve the problems which arise in the creation of IRPSS [5–7]. The limited volume of the article does not allow a complete description of the results obtained during the studies. Therefore, this article focuses on improving the electromagnetic security conditions.

Railway electric power supply system of an alternating current is a complex nonlinear dynamic object for the formal description of which the following model can be used:

$$\frac{d\mathbf{X}}{dt} = \Phi(\mathbf{X}, \mathbf{V}, \mathbf{S}, \mathbf{C}, t), \quad (1)$$

where \mathbf{X} – n -dimensional parameter vector characterizing the TPSS mode; Φ – n -dimensional nonlinear vector function; \mathbf{V} – m -dimensional vector of perturbation actions; \mathbf{C} – l -dimensional vector of control actions; \mathbf{S} – q -dimensional vector determining the structural parameters of RPSS.

In view of the large dimension, complexity and insufficient information richness, the use of the model (1) to determine the modes of RPSS at the present stage is difficult. Therefore, simulation methods are used consisting in the reduction of the dynamic model; the investigated time interval T_M is divided into small parts Δt , within which the vectors \mathbf{X} , \mathbf{S} , \mathbf{C} and \mathbf{Y} are considered to be unchanged. Comparison of regime parameters measurements on real objects with results of computer modeling shows that the accepted assumption does not contribute noticeable errors in calculations results.

The considered methods of modeling RPSS are based on phase coordinates use and lattice equivalent circuits having a fully connected topology. For these circuits the following formal determination can be written:

$$TEC : hub \cup con, \forall i, j \in hub \rightarrow con_{i,j} \in con,$$

where TEC – lattice equivalent circuit designation; hub – TEC nodes set; con – TEC branch set.

Creation of a simulation model of railway power supply system requires the TPSS models construction of elements with the determination of algorithm for their interaction and includes the following components:

- modeling of the train schedule;
- formation of instantaneous circuits based on the movement schedule and mode calculation for each of them;
- determination of integral indicators of simulation modeling.

At each modeling interval the following nonlinear equations' system is solved describing the steady state

of the corresponding instantaneous circuits:

$$\mathbf{F}[\mathbf{X}_k, \mathbf{S}_k, \mathbf{C}_k, \mathbf{V}_k] = \mathbf{0}, \quad (2)$$

where $\mathbf{X}_k, \mathbf{S}_k, \mathbf{C}_k, \mathbf{V}_k$ are values of vectors of $\mathbf{X}, \mathbf{S}, \mathbf{C}, \mathbf{V}$ for k -th instantaneous circuits.

After determining of the instantaneous circuit mode, as a result of the equations' system (2) solving, the electromagnetic field strengths (EMF) generated by any of the multi-conductor power transmission lines included in the simulated system can be calculated. When choosing the direction of the Y axis of the Cartesian coordinate system (Fig. 2) vertically upwards, of the X axis perpendicular to the axis of the railway so that the Z axis is directed opposite to the current of the overhead contact system, the components of the electric field strength of the system of N wires at the coordinate (x, y) are determined by the following formulas:

$$\begin{aligned} \dot{E}_y &= -\frac{1}{\pi\epsilon_0} \sum_{i=1}^N \dot{\tau}_i \frac{y_i[(x-x_i)^2 - y^2 + y_i^2]}{[(x-x_i)^2 + (y+y_i)^2][(x-x_i)^2 + (y-y_i)^2]}; \\ \dot{E}_x &= \frac{2}{\pi\epsilon_0} \sum_{i=1}^N \dot{\tau}_i \frac{(x-x_i)yy_i}{[(x-x_i)^2 + (y+y_i)^2][(x-x_i)^2 + (y-y_i)^2]}, \end{aligned}$$

where $\dot{\tau}_i$ – charge of wire i per unit of length determined from the first group of Maxwell's formulas:

$$\dot{\mathbf{T}} = \mathbf{A}^{-1} \cdot \dot{\mathbf{U}}.$$

Here $\dot{\mathbf{U}} = [\dot{U}_1 \dots \dot{U}_N]^T$ is column vector of wire voltages relative to the ground determined in the calculation of the mode; $\dot{\mathbf{T}} = [\dot{\tau}_1 \dots \dot{\tau}_N]^T$ is column vector of wire charges per unit of length, \mathbf{A} – symmetric matrix of potential coefficients, in which

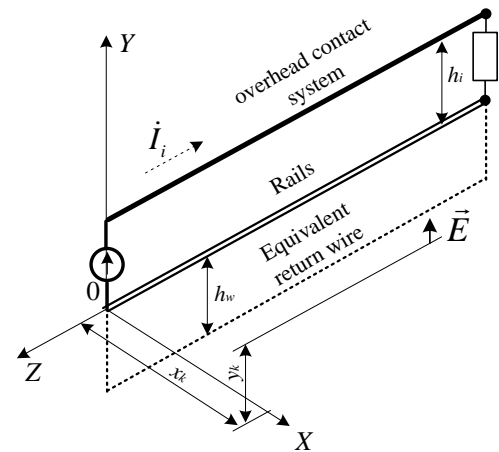


Fig. 2. Coordinate system for calculating EMF.

$$\alpha_{ii} = \frac{1}{2\pi\epsilon_0} \ln \frac{2y_i}{r_i},$$

$$\alpha_{ij} = \frac{1}{2\pi\epsilon_0} \ln \frac{\sqrt{(x_i - x_j)^2 + (y_i + y_j)^2}}{\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}},$$

where x_i , y_i are coordinates of the location of the wire i of radius r_i above the ground ($y = 0$ corresponds to the surface of flat land), ϵ_0 is electric constant.

After the transition from complex effective values of the components \dot{E}_x and \dot{E}_y to time dependences it is possible to obtain the parametric equations of the hodograph of the electric field strength vector

$$E_x(t) = \sqrt{2} E_v \sin(\omega t + \phi_v);$$

$$E_v(t) = \sqrt{2} E_v \sin(\omega t + \phi_v),$$

where multiplier $\sqrt{2}$ is required because voltages are calculated from the RMS values; $\omega=314$ rad/s.

The field strength reaches the maximum value E_{MAX} at the time point determined by the following equation:

$$t_{\max} = \frac{1}{2\omega} \text{Arctg} \left(\frac{E_x^2 \sin 2\varphi_x + E_y^2 \sin 2\varphi_y}{E_x^2 \cos 2\varphi_y + E_y^2 \cos 2\varphi_x} \right).$$

The choice of arctangent value is made by the condition of the second derivative negative value

$$E_y^2 \cos 2(\omega t_{\max} + \phi_y) + E_z^2 \cos 2(\omega t_{\max} + \phi_z) < 0.$$

The field strength effective value along a certain direction Ψ , measured from the positive direction of the X axis, is equal to

$$E_{\psi} = \sqrt{\frac{1}{2\pi} \int_0^{2\pi} 2[E_x(t)\cos\psi + E_y(t)\sin\psi]^2 d(\omega t)};$$

$$E_{\psi}^2 = \frac{1}{\sqrt{2}\pi} \int_0^{2\pi} \{ [E_x(t)]^2 \cos^2 \psi + [E_y(t)]^2 \sin^2 \psi + 2E_x(t)E_y(t)\cos\psi\sin\psi \} d(\omega t);$$

$$E_{\mu} = \sqrt{E_{\text{XC}}^2 + E_{\text{YS}}^2 + 2E_{\text{XC}}E_{\text{YS}}\cos(\varphi_{\text{X}} - \varphi_{\text{Y}})};$$

$$E_{\gamma C} = E_{\gamma} \cos \psi; \quad E_{\gamma S} = E_{\gamma} \sin \psi.$$

Extreme strength values are calculated using the following formula:

$$E_{\varphi E} = \sqrt{\frac{(E_x^2 + E_y^2)^2}{2} \pm \frac{\sqrt{(E_x^2 + E_y^2)^2 - 4E_x^2 E_y^2 \sin^2(\varphi_x - \varphi_y)}}{2}}.$$

In this case, the plus sign corresponds to the maximum, and the minus sign corresponds to the minimum.

Both vertical and horizontal components of the magnetic field strength, created by all wires, are calculated by the following formulas:

$$\dot{H}_x = \frac{1}{2\pi} \sum_{i=1}^N \dot{I}_i \frac{y - y_i}{(x_i - x)^2 + (y_i - y)^2};$$

$$\dot{H}_Y = -\frac{1}{2\pi} \sum_{i=1}^N \dot{I}_i \frac{x - x_i}{(x_i - x)^2 + (y_i - y)^2}.$$

To determine the strengths of both electric and magnetic fields, the RPSS mode is calculated, the charges and currents of separate wires are determined, including those connected in parallel (as in bundled phases or in a contact suspension) and grounded wires, and components \dot{E}_x , \dot{E}_y , \dot{H}_x , \dot{H}_y are determined.

The described method is implemented in the Fazonord software; while the electromagnetic field strengths can be determined both for a single instantaneous circuit and for their totality based on which the dynamics of the EMF strength variations in time is obtained.

4. Modeling results

The electric regime of the traction power network and, accordingly, the electric and magnetic field strengths depend mainly on traction loads, but also to a large extent on the reaction of the external power supply system. At a voltage of 110 kV the response of the system is more significant, and in this case the external network account can play an important role in the modeling. As an example of simulation modeling of EMF during the movement of trains with the determination of time dependencies

$$\dot{E} = \dot{E}(t); \dot{H} = \dot{H}(t)$$

the RPSS circuit presented in Fig. 3 is considered. In this circuit, the external electric power supply system included 110 and 220 kV lines connected through autotransformers with a capacity of 200 MV·A. The marks and sections of the wires as well as the length of the high voltage line are shown in Fig. 3.

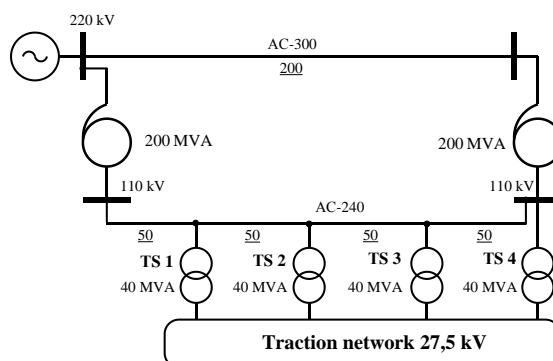


Fig. 3. PRSS circuit: TS - traction substation.

The traction power network of double-track sections is composed of three inter-substation zones with PBSM-95+MF-100 wires with a length of 50 km. The transformers with power of 40 MV·A are installed on traction substations. The movement of odd trains with masses of 3200 tons and even trains with masses of 6000 tons with intervals of 25 minutes was considered. The results of modeling of EMF at a height of 1.8 m are presented in Table 1 and are illustrated in Fig. 4, 5.

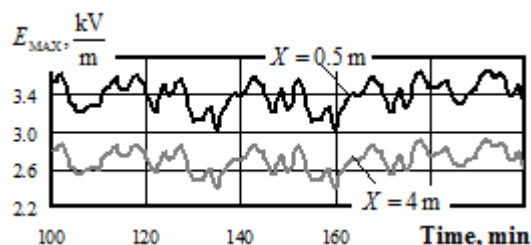


Fig. 4. Dependence of amplitude value of EF strength on time.

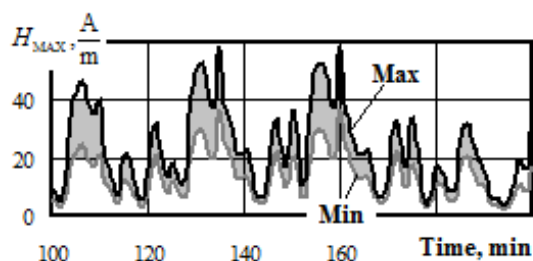


Fig. 5. Intervals of amplitude variation of the MF strength along the X coordinate from -4 to +4 m.

Table 1. Summary indicators of electric and magnetic field amplitude strengths.

Indicators	Parameter	X, m				
		-4	-0.5	0	0.5	4
E_{MAX} , kV/m	Maximum	2,92	3,67	3,67	3,67	2,92
	Average	2,78	3,49	3,49	3,49	2,78
H_{MAX} , A/m	Maximum	43,5	58,4	56,7	56,7	36,7
	Average	11,8	16,1	15,7	15,7	10,2

The zero value of the X coordinate corresponds to the middle of the inter-track space, and the asymmetry of the magnetic field along this coordinate is due to the different currents of the overhead contact system of the two tracks. The overhead contact system currents depend on the level of the overhead contact system voltage; therefore statistical approach to the analysis of the interconnections of currents with the magnetic field

strength is possible. The correlation matrix characterizing the current relationships with the strength of the magnetic field calculated at points with coordinates $Y = 1,8$ m; $X = -4$ m; $-0,5$ m; 0 m; $0,5$ m; 4 m is presented in Table. 2, in which I_5 is the current of the odd-track overhead contact system with trains of relatively low mass, I_6 is the current of the even-track overhead contact system, the values of which are much higher than the current I_5 .

Table 2. Correlation matrix of magnetic field strength.

Parameters	I_5 , A	I_6 , A	H_{MAX} , $X = -4$ m	H_{MAX} , $X = -0,5$ m	H_{MAX} , $X = 0$ m	H_{MAX} , $X = 0,5$ m	H_{MAX} , $X = 4$ m
I_5 , A	1						
I_6 , A	-0,21	1					
H_{MAX} , $X = -4$ m	0,13	0,94	1				
H_{MAX} , $X = -0,5$ m	0,30	0,87	0,98	1			
H_{MAX} , $X = 0$ m	0,34	0,84	0,98	1,00	1		
H_{MAX} , $X = 0,5$ m	0,39	0,82	0,96	1,00	1,00	1	
H_{MAX} , $X = 4$ m	0,62	0,63	0,86	0,94	0,95	0,96	1

Correlation coefficients have a considerable spread, and a significant regression equation cannot be obtained for all observation points. However, for some points, in particular, for a point with coordinates $X = -4$; $Y = 1.8$ m, this equation can be obtained in the following form:

$$H_{MAX} = 3,574 + 0,063I_6.$$

The field of the dependence points and the regression line are shown in Fig. 6.

Based on a similar dependence constructed subsequent to the results of measurements, a technology

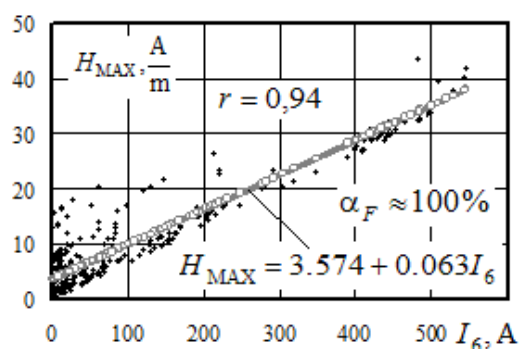


Fig. 6. Results of regression analysis of the interconnection between the magnetic field and currents.

can be implemented to quickly evaluate the electromagnetic security conditions for the magnetic strength for separate objects located in the zone of electromagnetic influence of the traction power network.

5. Conclusions

1. The implementation of intelligent traction power supply system requires the development of computer technologies for modeling modes and electromagnetic fields determining the conditions for electromagnetic safety. Such technologies are implemented based on the methods developed at the Irkutsk State Transport University.

2. The conditions for trains movement considered in the calculation example and corresponding to the average sizes along the Siberian railways showed that the amplitude values of the magnetic field strength vary from several amperes per meter to 50 A/m. The strength of the electric field varies relatively little.

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