

Electromagnetic Environment Management in Smart Railroad Power Systems

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Abstract—The main features of power generating industry contemporary stage are transition to the new technological platform based on smart grid concept. This concept is fully applicable in Railroad Power Systems. Implementation of smart Railroad Power Systems would allow solution of the following practical issues: ensuring high level of power supply reliability; enhancing electromagnetic safety (ES); minimization of power losses and costs for Railroad Power Systems operation; enhancing power quality in Railroad Power Systems and in connected power systems. Implementation of smart Railroad Power Systems requires development of computer-based technologies for modes and electromagnetic fields simulation that determine electromagnetic safety conditions. The methods of defining modes in phase coordinates developed in Irkutsk State Transport University allow carrying out simultaneous calculations of electromagnetic fields (EMF) intensities of multi wire lines when determining the mode of an external power system (EPS) and traction power supply system (TPSS). In this case, the line under consideration is viewed inseparably with complex EPS. Simultaneous calculation of the mode and created EMF allows implementation of the system approach to analysis of electromagnetic environment. Its distinct feature is a possibility of EMF simulation with due regard for all properties and characteristics of the complex TPSS and EPS. Electromagnetic environment management can be reduced to the issue of magnetic field reduction in given points of active network space. Methods for this issue solution are divided into technical and mode ones. The following actions are referred to as technical ones: the use of autotransformer TPSS 2x25 kV; the use of suction transformers with return conductor; installation of adjuvant wire and shielding wire; the use of passive screens installed on passenger platforms. Optimization of train operation schedules and train operation modes are referred to the mode actions in accordance with ES enhancement criterion, as well as the use of automatic train operation with algorithms aimed at peak loads reduction. Magnetic field intensity can be reduced by the use of trains' optimal operation schedule, and by the use of "soft" modes for trains' operation. The last action is capable reducing magnetic field intensity peak values by approximately 25%.

Keywords—railroad, power system, smart grid, electromagnetic safety, modeling

I. INTRODUCTION

The main features of power generating industry contemporary stage are transition to the new technological platform based on smart grid [1] concept. This concept is fully applicable in Railroad Power Systems [2–7].

Implementation of smart Railroad Power Systems would allow solution of the following practical issues:

- ensuring high level of power supply reliability;
- enhancing electromagnetic safety (ES);
- minimization of power losses and costs for Railroad Power Systems operation;
- enhancing power quality in Railroad Power Systems and in connected power systems.

Implementation of smart Railroad Power Systems requires development of computer-based technologies for modes and electromagnetic fields simulation that determine electromagnetic safety conditions (EMS). Such technologies are implemented based on methods developed at Irkutsk State Transport University (ISTU) [8–12].

II. FORMALIZATION OF ELECTROMAGNETIC ENVIRONMENT MANAGEMENT

A combination of electromagnetic processes in a given area of space is characterized by the term of electromagnetic environment (EME). The main features of these processes are electric and magnetic field (EMF) intensities. In a number of cases, especially, when the railroad track goes through a residential area, the levels of electromagnetic fields intensities created by an electrical traction network can exceed the permissible norms [7]. Thus, electromagnetic environment determines the conditions of electromagnetic safety.

The concept of 'electromagnetic environment' is a key one for solving issues of electromagnetic safety and compatibility (fig. 1).

Methods and means of modes simulation in phase coordinates developed in ISTU [9] allow performing

of simultaneous calculations of EMF for multi-wire power lines [7, 9] when determining the electrical power system (EPS) or traction power supply system (TPSS) mode. In this case, the line under consideration is viewed inseparably with complex EPS. Simultaneous calculation of the mode and created EMFs allows implementation of the system approach [10 – 12] to analysis of electromagnetic environment. Its distinct feature is a possibility of EMF simulation with due regard for all properties and characteristics of the complex TPSS and EPS.

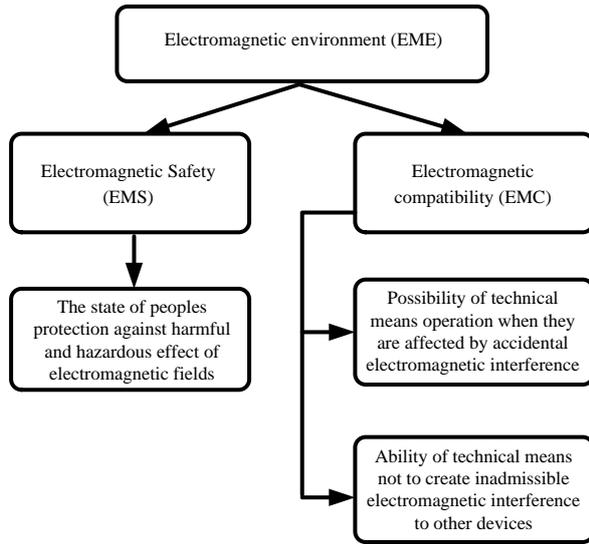


Fig. 1. Relation between EME, EMS and EMC

Advantages of the method proposed are the following: first – a possibility for simulation modeling of trains operation in the TPSS and possibility of determining EMF intensities changing dynamics over time, and secondly – correct accounting of the following factors affecting intensities levels of EMF:

- unevenness of underlying surface caused by the presence of embankments, ditches, slopes and passenger platforms;
- iron cars and cisterns on tracks that significantly affect EMF strengths distribution patterns in space;
- earthed extended iron objects (pipelines, cable lines with earthed coatings, earthed wires) that also change the EMF distribution pattern.

Fazonord software [9] application implemented on the basis of the above methods, allows use up to several hundreds of wires in the models. This brings the possibility of modeling embankments, ditches, cars and cisterns with a set of earthed wires located in such a way, so as the distance between the wires would be significantly shorter than the distance to the observation point. In addition, this technology allows conduct EMF calculations for fixed track structures: tunnels, galleries, bridges.

The technique of electromagnetic safety analysis based on the proposed approach is distinguished by

the following features:

- systemacy, which manifests itself in the possibility of modeling electromagnetic fields taking into account the properties and characteristics of a complex TPSS and a supplying EPS;
- universality ensuring modeling of power transmission lines and traction networks of various design;
- compliance with environment achieved via precise analysis of the underlying surface, underground communications, fixed track structures such as galleries, bridges and tunnels;
- complex approach provided by combination of the mode calculations and determining of EMF intensities.

Due to low voltage in traction network the level of electrical field intensity at a regulated height of 1,8 m lies within admissible limits, that is why the issue of electromagnetic environment management is further analyzed based on the magnetic field intensity criterion.

The issue of EME management can in general be formulated in the following way:

$$\max \mathbf{H} \leq H_{DOP},$$

where $\mathbf{H} = \mathbf{H}_{MAX}[\mathbf{I}(t), \mathbf{K}^{(p)}, \mathbf{K}]$ – strength value vector in traction network space controlled points, $\mathbf{H} = [H_1 \ H_2 \ \dots \ H_n]^T$; n – the number of points where control (observation) of magnetic field is effected; $\mathbf{I}(t)$ – the vector of currents in multi-wire power lines depending of time t , $\mathbf{I}(t) = [I_1(t) \ I_2(t) \ \dots \ I_N(t)]^T$; N – the number of wires, in traction network including rails; $\mathbf{K}^{(p)} = [x_1^{(p)} \ y_1^{(p)} \ \dots \ x_c^{(p)} \ y_c^{(p)}]^T$ – the vector of Cartesian coordinates of traction network wires location, the center of coordinates is located on the railroad axis on the ground surface, X axis of the right-side system is directed along the ground surface, Y axis is vertical to the ground surface, Z axis is directed along the road axis against the accepted positive direction of wires' currents; $\mathbf{K} = [x_1 \ y_1 \ \dots \ x_p \ y_p]^T$ – the vector of Cartesian coordinates corresponding to observation points.

Calculation of the vector components \mathbf{H} for a specific time moment in a specific control point is effected as per the following formulas:

$$\dot{H}_x = \frac{1}{2\pi} \sum_{i=1}^N i_i \frac{y - y_i^{(p)}}{\xi};$$

$$\dot{H}_y = -\frac{1}{2\pi} \sum_{i=1}^N i_i \frac{x - x_i^{(p)}}{\xi};$$

$$\dot{H}_z = 0,$$

where $\xi = (x_i^{(p)} - x)^2 + (y_i^{(p)} - y)^2$.

After transition from complex effective values of components \dot{H}_x and \dot{H}_y to temporal dependences, one can obtain parametric equations for strength vector hodograph of the electrical field:

$$H_x(t) = \sqrt{2} H_x \sin(\omega t + \varphi_x);$$

$$H_y(t) = \sqrt{2} H_y \sin(\omega t + \varphi_y),$$

where the factor $\sqrt{2}$ is required due to the fact that calculations are carried out as per effective values; $\omega = 314$ rad/s.

The field strength reaches H_{MAX} its maximal value in time moments defined by the following equation:

$$t_{max} = -\frac{\text{Arctg} \frac{A}{B}}{2\omega},$$

where $A = H_x^2 \sin 2\varphi_x + H_y^2 \sin 2\varphi_y$;

$$B = H_x^2 \cos 2\varphi_x + H_y^2 \cos 2\varphi_y$$

The choice of one of arc tangent values occurs as per condition of the second derivative negative value:

$$H_x^2 \lambda_1 + H_y^2 \lambda_2 < 0,$$

where $\lambda_1 = \cos 2(\omega t_{max} + \varphi_x)$;
 $\lambda_2 = \cos 2(\omega t_{max} + \varphi_y)$.

The field strength effective value for some direction Ψ , calculated from x axis positive direction is equal to

$$H_\Psi = \sqrt{H_x^2 v_1 + H_y^2 v_2 + 2H_x H_y v_3},$$

where $v_1 = \cos^2 \Psi$; $v_2 = \sin^2 \Psi$;

$$v_3 = \sin \Psi \cos \Psi \cos(\varphi_x - \varphi_y).$$

Strength extreme values are calculated according to the following formula:

$$H_{\Psi E} = [\eta \pm \zeta]^{\frac{1}{2}},$$

where $\eta = \frac{H_x^2 + H_y^2}{2}$; $\zeta = \frac{\vartheta}{2}$; $\vartheta = \sqrt{\theta - \tau}$;

$$\theta = (H_x^2 + H_y^2)^2;$$

$$\tau = 4H_x^2 H_y^2 \sin^2(\varphi_x - \varphi_y).$$

Plus sign corresponds to strength maximum, while minus sign – to minimum.

III. THE SYSTEM ELECTROMAGNETIC ENVIRONMENT MANAGEMENT

Electromagnetic environment management can be reduced to the issue of magnetic field strength lower

ing in given points of tractive network space. These methods can be divided into two groups: technical and mode (fig. 2).

The following solutions can be referred to the first group of actions:

- 1) the use of autotransformer TPSS 2x25 kV;
- 2) the use of sucking transformers with return conductor;
- 3) installation adjuvant wire and shielding wire;
- 4) the use of passive screens installed on passenger platforms.

Efficiency of the said technical solutions is analyzed in the monograph [7] in detail.

The following are referred to the second group of actions analyzed in this article:

- 1) optimization train traffic schedule and train operation according to criterion of electromagnetic environment enhancing;
- 2) the use of automatic train operation with algorithms including units aimed at peak loads lowering.

Algorithm of electromagnetic environment management functioning in TPSS of AC railroads is shown in fig.3.

Implementation of train operation schedules that are optimal as per EME criterion, is possible in prospect only under condition of toughening administrative and economic sanctions for regulations violation of EMF levels. Optimizing the modes of train operation and the use of automatic train operation ensuring lowering of peak loads is possible in a closer prospect, as it would allow, apart from enhancing EME, reduction in power losses in traction network, thus enhancing TPSS efficiency.

EME modeling is effected by distribution of TPSS operating modes in phase coordinates while calculating EMF strengths simultaneously in using the above procedure. Actions aimed at EME enhancing is carried out based on modeling results analysis. Practical efficiency of the actions implemented is checked by control measurements of electrical and magnetic fields' strengths levels.

IV. OPTIMIZATION OF THE TRAFFIC SCHEDULE

Optimization of the traffic schedule with due regard to the criterion $\max \mathbf{H} \leq H_{DOP}$ is directly connected with optimal current loads of the overhead system. One of the ways for reduction in the overhead system currents is formation of train operation optimal schedule and train optimal weights. The easiest solution in this case is generation of train operation schedule with alternation of heavy and light weight trains. In order to study this technology efficiency, simulation modeling of traction power supply system was carried out for a single-track line having the

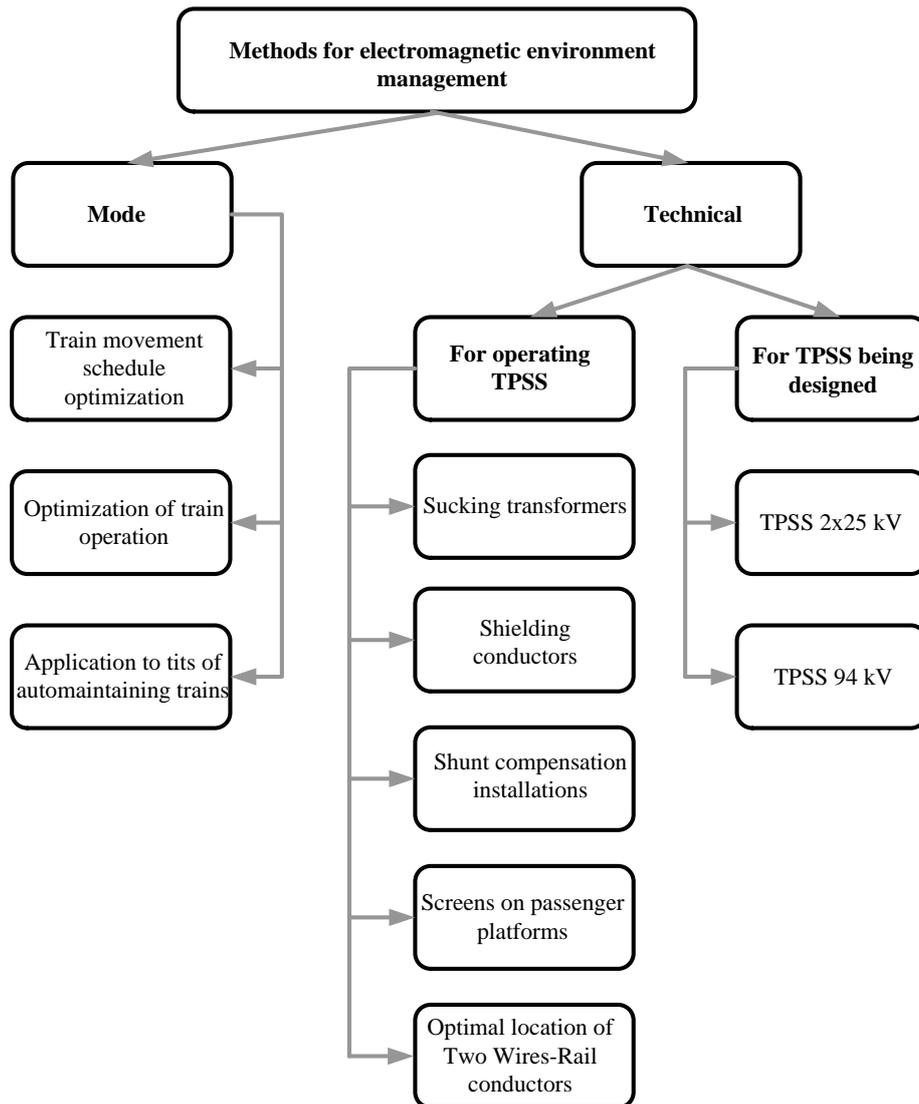


Fig. 2. EME management methods

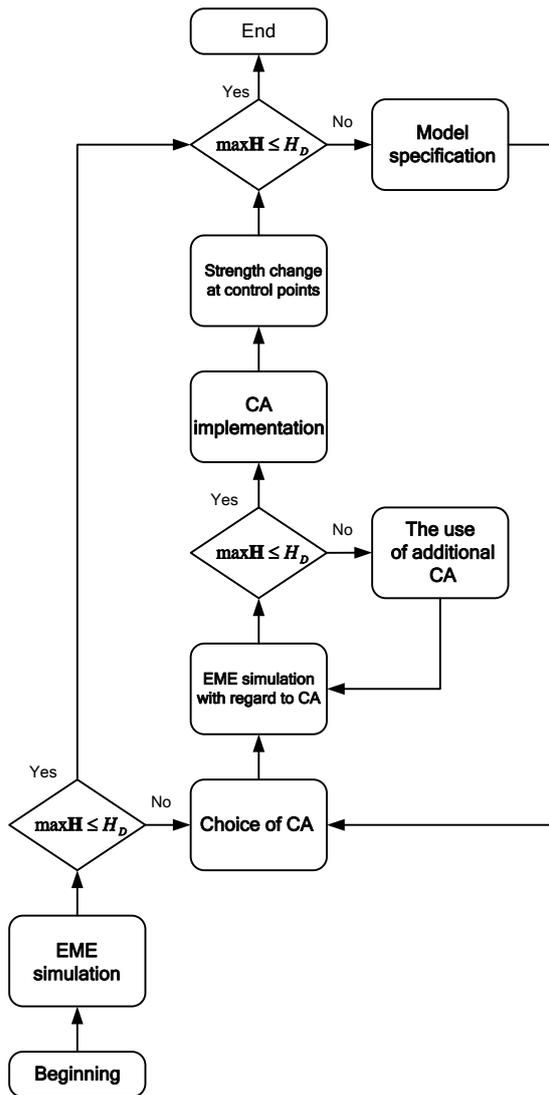


Fig. 3. Algorithm of electromagnetic environment management system functioning: CA – control actions

catenary PBSM-95+MF-100, two inter-substation zones having length of 30 km and three traction transformers 40000 kVA.

To assess the possibilities for current loads and traction network magnetic field reduction, two options were considered which are approximately equal to the volume of odd train operation schedule:

- 1) package schedule with trains having similar weights 3892 t, interval between trains – 9 min, interval between packages – 20 min;
- 2) train operation with weights 3192 t, 4192 t, 5192 t, intervals between trains – 9 min and 12 min, intervals between trains packages – 14 min.

Train operation schedules are given in fig. 4, 5. Modeling results are given in fig. 6, 7 and in table 1.

TABLE I. CONSOLIDATED EMF INDICATORS FOR TRAINS OPERATION SCHEDULES, $x = 3$ M, $y = 1,8$ M

Parameter	E_{MAX} , kV/m		H_{MAX} , A/m		Differences between columns 2 and 3, %	Differences between columns 4 and 5, %
	Option 1	Option 2	Option 1	Option 2		
1	2	3	4	5	6	7
Mean	1,96	1,95	3,45	4,19	0,28	-21,6
Maximum	2,00	2,00	11,0	18,0	0,00	-62,8
Root-mean-square deviation	0,02	0,03	2,96	4,16	-32,7	-40,4

In comparison with double-track road, one-track road is characterized by EMF lower strength levels and a faster decrease with distance from the road axis. In general, the strength values are far from limit ones, though, the results obtained testify to the fact that train operation schedule optimization in accordance with criterion of permissible magnetic field strength can be used as an effective means for EME management.

V. OPTIMIZATION OF TRAINS OPERATION MODE

Different types of locomotives and different types of trains operation can be used for freight train operation subject to train weights, which are also dependent on the engine drivers individual features. When the engine power is limited, the train operation mode would forcedly be 'soft', which is characterized by a limited consumed power, absence of any abrupt jerks and a limited speed. When electric locomotives towing a train have a sufficient power, 'hard' operation mode is quite possible, at which maximal thrust with high level of consumed power alternates with low power consuming coasting. Under this option, catenary voltage is reduced considerably, while current consumption by the train is increased which, in its own turn, leads to the increase in magnetic field strength created by the traction network.

In order to determine train operation modes differences effect on electromagnetic environment, EMF modeling was performed for one of East Siberian mainline railroads. The design section comprises 29 traction substations with 40000 kVA transformers which are power from double circuit line 220 kV. The design scheme included 845 nodes and 4896 branches, which simulate double-track road section with a catenary PBSM-95+MF-100 for each track having length of 1,300 km. An operation schedule was simulated for odd trains having weight of 3,200 t and even trains with weight of 6,000 t and with 35 min interval.

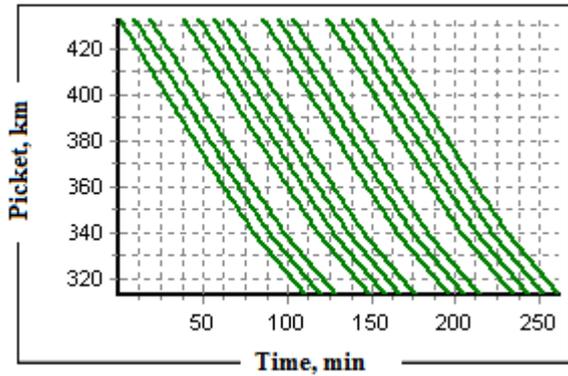


Fig. 4. Train schedule for first option

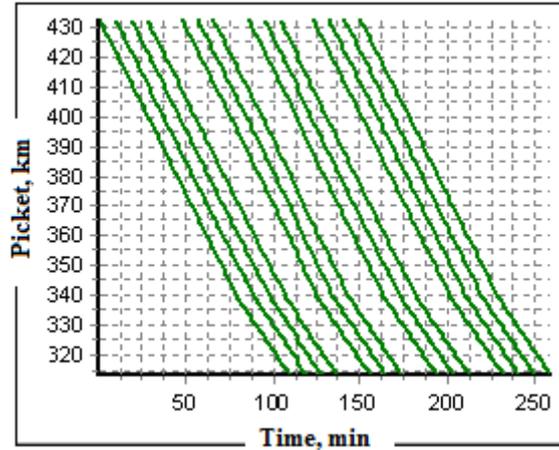


Fig. 5. Train schedule for second option

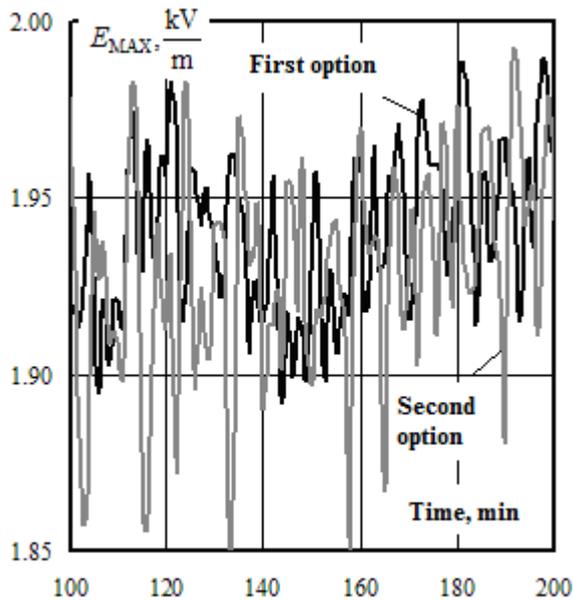


Fig. 6. Electric field strength dynamics in a point with coordinates $x = 3$ m, $y = 1,8$ m

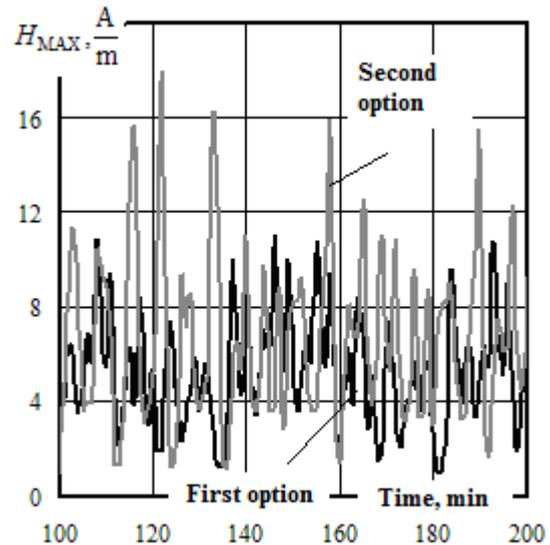


Fig. 7. Magnetic field strength dynamics in a point with coordinates $x = 3$ m, $y = 1,8$ m

Results of magnetic field calculation in a point with coordinates $x = 4$ m, $y = 1,8$ m are represented in table 2.

TABLE II. MAXIMAL AND AVERAGE VALUES OF MAGNETIC FIELD STRENGTH AMPLITUDE, A/M

No.	Parameter	Mode		Difference, %
		Soft	Hard	
1	Average value	12,2	14,0	13,1
2	Maximum	23,1	30,8	25,0

Thus, the use of train operation soft modes can reduce maximal value of magnetic field strength approximately by 25%, and the average strength value for the period under consideration – by 13%.

VI. CONCLUSIONS

1. Electromagnetic environment management can be reduced to the issue of magnetic field strength reduction in given points of tractive network space. Methods for this issue solution are divided into technical and mode ones. The following actions are referred to as technical ones: the use of autotransformer TPSS 2x25 kV; the use of suction transformers with return conductor; installation adjuvant wire and shielding wire; the use of passive screens installed on passenger platforms. Optimization of train operation schedules and train operation modes are referred to the mode actions in accordance with EME enhancement criterion, as well as the use of automatic train operation with algorithms aimed at peak loads reduction.

2. Magnetic field strength can be reduced by the use of train optimal operation schedules, and by the use of soft modes for train operation. The last action is capable of reducing magnetic field strength peak values by approximately 25%.

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