Electromagnetic safety enhancing in railway electric supply systems

Natal'ya Buyakova[1,] *, *Vasiliy* Zakaryukin[2], *Andrey* Kryukov[2, 3], *Tu* Nguyen [3]

[1] Angarsk State Technical University, Angarsk, Russia , 665835;
[2] Irkutsk State Transport University, Irkutsk, Russia, 664074;
[3] Irkutsk National Research Technical University, Irkutsk, Russia, 664074

Abstract. The methods of simulation modeling of traction power supply systems is developed, allowing analyzing the electromagnetic safety conditions in complex traction power networks equipped with sucking transformers. The effectiveness of the application of the sucking transformers (ST) connected in the rail cut with a distance of 3 km between transformers is small due to rails' currents. The sucking transformers with return wires do not have this drawback. The use of ST with a return wire allows significantly improving the electromagnetic safety conditions: the level of magnetic field strength is reduced by tens of percent.

1 Introduction

Railway traction power networks of alternating current are electromagnetically unbalanced and therefore can cause dangerous voltages in disconnected adjacent power lines and communications [1–7]. The sucking transformers (ST) are used to reduce the voltage of magnetic influence in traction power supply systems (TPSS), increasing the interrelation between the overhead contact system and rails. The traction current, instead of returning through the ground, flows along the rails or through a special return wire (Fig. 1).

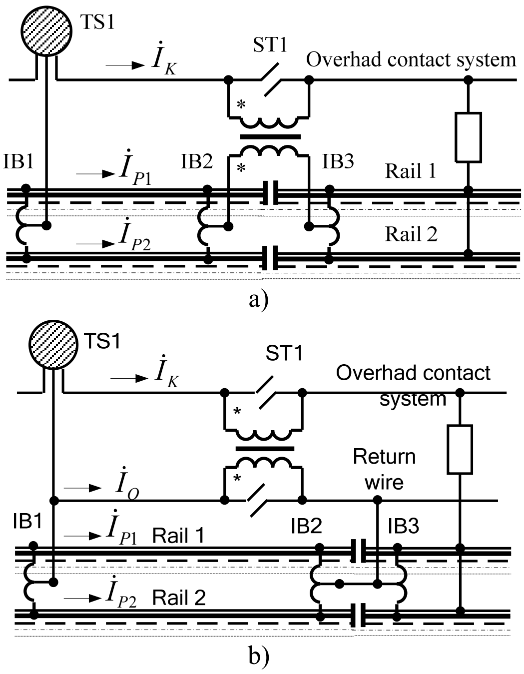

Fig. 1. Circuit of ST switching: a) ST connected in the rail cut; b) ST with return wire; IB1…IB3 – impedance bonds

Reducing the distance between the overhead contact system and return current circuit leads to a decrease in the magnetic field of traction power network and reduction induced voltages to adjacent lines. In practice, two variants of ST switching are used: in the first variant, the transformers are connected to the rail network (Fig. 1, a), in the second variant, the return wire is used (Fig. 1, b).

ST transformation coefficient equals to one. The operating mode of ST is close to short circuit, since the secondary winding is connected either to the return wire with the grounding of the latter or directly to the rails [5, 6]. In both circuits, the currents in the transformer windings are almost antiphase, and the voltages on the windings are relatively small. The return wire for efficient use should be mounted as close as possible to the contact suspension. As indicated in [5], the optimal distance between the sucking transformers connected to the rail cut is 3 km, and for ST with return wire this distance is 4.5 km.

2 Modeling of sucking transformers and impedance bonds

From the point of view of the magnetic field generated by the traction power network, the inter-substation zone with ST can be divided into sections of three types:

- a section of local currents from the traction load to the nearest sucking transformers;
- sections of transit currents on the remaining part of the inter-substation zone, except for the sections from traction substation (TS) to closest ST;

* Corresponding author: bn_900@mail.ru

- sections from substations to ST; they require separate consideration, since in these sections the sucking transformers are located only on one side, and the return of traction currents, which largely depends on the resistance of the substation earth lead and the transient resistance of the rail – ground, occurs through the ground.

The article presents the results of the analysis of the electromagnetic field created by the currents of section near the traction substation. The remaining two variants are characterized by other regularities partially considered in [5], and require additional research.

Modeling of ST is not difficult, since the manufacturing plant gives data in the passport of sucking transformer OMO-800/35 which is similar to the power transformer. The OMO-800/35 single-phase double-winding transformer has the following nominal parameters: power 800 kV·A, winding voltage 1,05 kV, short-circuit voltage 8.5%.

A more complicated situation arises when modeling impedance bonds (IB), since the manuals show the A-parameters of IB as a four-pole for a frequency of 25 Hz, as well as the resistance of the primary winding at 50 Hz and its nominal current.

The algorithm for determining the IB parameters which are suitable for modeling in the program Fazonord includes the following steps [8].

1. According to given four-pole A-parameters $\underline{A}$, $\underline{B}$, $\underline{C}$, $\underline{D}$ input impedances of idling and short circuit are determined $\underline{Z}_K$. The impedance $\underline{Z}_K$ is half divided to obtain active resistances, as well as two coils inductance, both primary and secondary, assuming their equality:

$$\underline{Z}_{1S} = \frac{\underline{Z}_K}{2} = \frac{1}{2}\frac{\underline{B}}{\underline{D}}.$$

2. The magnetization branch impedance is determined from the idling equation of the four-pole:

$$\underline{Z}_\mu = \frac{\underline{A}}{\underline{C}} - \underline{Z}_{1S}.$$

3. Imaginary parts of impedances $\underline{Z}_{1S}$ and $\underline{Z}_\mu$, which are determined for 25 Hz frequency, are positive and substantially higher than real ones, vary in proportion to the frequency and are recalculated at 50 Hz frequency.

4. For modeling, it is more convenient to consider impedance bonds as an autotransformer whose nominal voltage is equal to its 50 Hz impedance multiplied by the nominal current of the primary winding composed of two half-windings. For the purposes of analyzing the modes of the traction power network, the secondary winding cannot be considered, since the loading of this winding at 50 Hz frequency is small. The autotransformer model parameters are calculated through the nominal current I_n according to the following formulas:

– losses and voltage of short circuit

$$P_x = 2\,\mathrm{Re}(Z_{1S})I_n^{\,2};\; U_\kappa = \frac{2\cdot|\underline{Z}_{1S}|\,I_n}{U_n}\cdot 100;$$

– losses and current of idling

$$P_x = \mathrm{Re}\{U_n[\mathrm{Re}(\dot{I}_x) - j\,\mathrm{Im}(\dot{I}_x)]\};\; \dot{I}_x = \frac{U_n}{\underline{Z}_{1S} + \underline{Z}_\mu}.$$

The DT-1-300 impedance bond, most common on the alternating current road network, is characterized by the following parameters:

- rated current of primary winding 300 A;
- impedance at 50 Hz frequency 1.0 Ohm;
- primary winding contains 5 + 5, and the secondary winding contains 30 turns;
- A-parameters at a frequency of 25 Hz are equal to $\underline{A} = 0.33e^{-j4°}$, $\underline{B} = 0.062e^{j14°}$, $\underline{C} = 0.37e^{-j57°}$, $\underline{D} = 3.0e^{j4°}$.

With these initial data, the IB model in the form of an autotransformer has the following parameters:

- nominal power 300 kV·A;
- nominal voltage of the primary winding 150+150 V;
- short-circuit voltage 13.5%;
- short circuit losses 4.65 kW;
- idling current 30%;
- idling losses 17.25 kW.

When checking the model in idle and short circuit conditions, the regime parameters differ from the initial ones by not more than 2%.

3 Methods and results of modeling of TPSS modes

For a detailed study of sucking transformer protective action, a typical inter-substation zone of a double-track section of 25 kV alternating current railway with a length of 45 km with a contact suspension PBSM95+MF100 of two tracks and R-65 rails was considered. The A-185 return wires were supposed to be located above the contact suspensions of each track. The modeling was carried out according to the methods of [9–14] using the Fazonord software [10].

The model of the multi-wire system contained four wires of a contact suspension, two return wires and four rail threads. The return wires were not used in the model without sucking transformers and in the model with connection of ST to the rails.

For option of connecting the sucking transformers to the rail cut, model included 15 elements of traction power network, each of which had 3 km length. For the variant with the return wire, the model included 20 elements of the traction power network with 2.25 km length. The two-way supply of the inter-substation zone was simulated with loads of 5 + *j*5 MV·A applied at the end of the second section of the traction power network between the overhead contact system and the rails of each track.

For analysis of sucking transformers effectiveness, the operation of TPSS has been simulated in three versions:

- absence of sucking transformers;
- ST with return wire located at intervals of 4.5 km;
- ST connected to the rail cut through 3 km; rail – ground transient resistance is taken to be 2 Ohm·km.

Fig. 2 shows dependences of the amplitudes of both the electric and magnetic field strengths, as well as both the horizontal and vertical components effective values, from the *X* coordinate at height of 1,8 m. Strength values were calculated after TPSS modes defining based on technique described in work [14].

Horizontal and vertical components of the electrical field strength created by a system consisting of *N* wires, were defined by the following ratios:

$$\dot{E}_Y = -\frac{1}{\pi\varepsilon_0}\sum_{i=1}^{N}\dot{\tau}_i \frac{y_i[(x-x_i)^2 - y^2 + y_i^2]}{\zeta_i};$$

$$\dot{E}_X = \frac{2}{\pi\varepsilon_0}\sum_{i=1}^{N}\dot{\tau}_i \frac{(x-x_i)yy_i}{\zeta_i},$$

where $\zeta_i = [(x-x_i)^2 + (y+y_i)^2][(x-x_i)^2 + (y-y_i)^2]$; x, y – the coordinates of the point where the strength is defined; $\dot{\tau}_i$ – i wire charge per length unit.

The charges values were calculated from the Maxwell's formulas first group

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

where $\dot{\mathbf{U}} = \begin{bmatrix}\dot{U}_1 & ... & \dot{U}_N\end{bmatrix}^{\mathrm{T}}$ – the wires voltages relative to the zero potential point (the earth); $\dot{\mathbf{T}} = \begin{bmatrix}\dot{\tau}_1 & ... & \dot{\tau}_N\end{bmatrix}^{\mathrm{T}}$ – the wires charges per length unit; $\mathbf{A}$ – matrix whose components are potential coefficients

$$\alpha_{ii} = \frac{1}{2\pi\varepsilon_0}\ln\frac{2y_i}{r_i};$$

$$\alpha_{ij} = \frac{1}{2\pi\varepsilon_0}\ln\frac{\sqrt{(x_i - x_j)^2 + (y_i + y_j)^2}}{\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}},$$

where x_i, y_i – the wires coordinates; r_i – the wires radiuses; ε_0 – electrical constant.

Equations of the strength vector hodograph were represented as

$$E_x(t) = \sqrt{2}\,E_X \sin(\omega t + \varphi_X);$$
$$E_y(t) = \sqrt{2}\,E_Y \sin(\omega t + \varphi_Y).$$

Maximum strength E_{MAX} was reached at moments which were defined using formula

$$t_{\max} = \frac{1}{2\omega}\mathrm{Arctg}(\varsigma),$$

where $\varsigma = \frac{E_X^{\,2}\sin 2\varphi_X + E_Y^{\,2}\sin 2\varphi_Y}{E_X^{\,2}\cos 2\varphi_X + E_Y^{\,2}\cos 2\varphi_Y}$.

The choice of the needed arctangent value was affected by condition

$$E_X^{\,2}\cos 2(\omega\, t_{\max} + \varphi_X) + E_Y^{\,2}\cos 2(\omega\, t_{\max} + \varphi_Y) < 0.$$

The following expressions were used to calculate vertical and horizontal strength components of the magnetic field:

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

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

The presented technique implemented in Fazonord software allows to evaluate of electromagnetic safety in traction networks taking into account Carson Solution for EMF middle and distant zones.

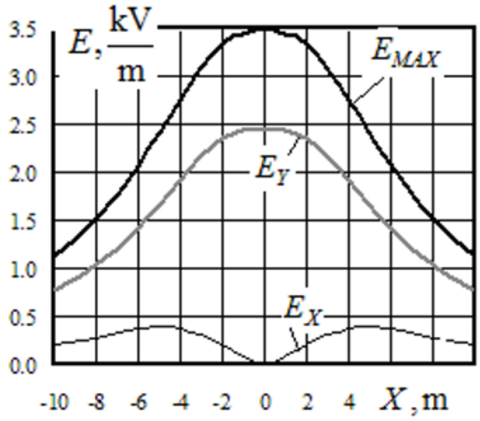

Fig. 2,a. Electric field strengths dependences from *X* coordinate, absence of sucking transformers

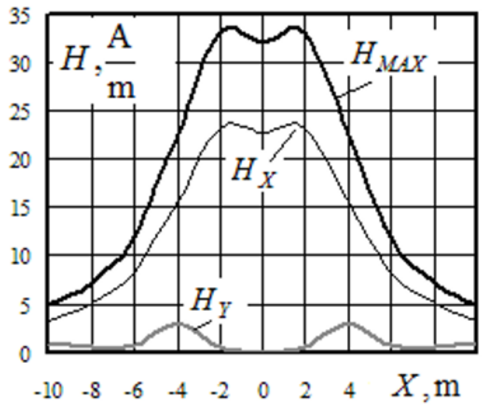

Fig. 2,b. Magnetic field strengths dependences from *X* coordinate, absence of sucking transformers

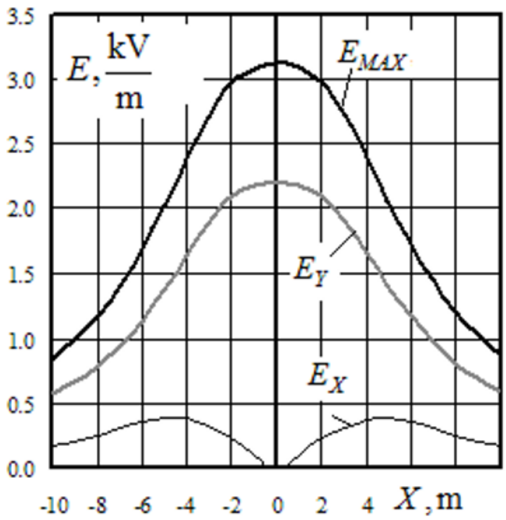

Fig. 2,c. Electric field strengths dependences from X coordinate, sucking transformers with return wire

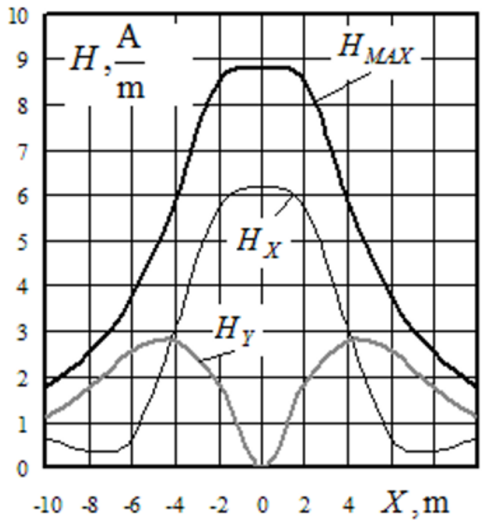

Fig. 2,d. Magnetic field strengths dependences from X coordinate, sucking transformers with return wire

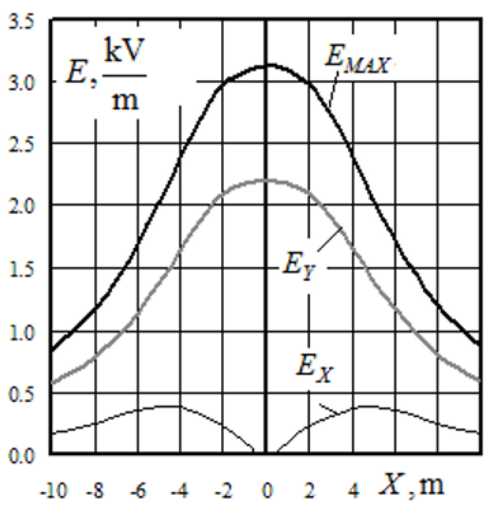

Fig. 2,e. Electric field strengths dependences from X coordinate, sucking transformers in rail cut

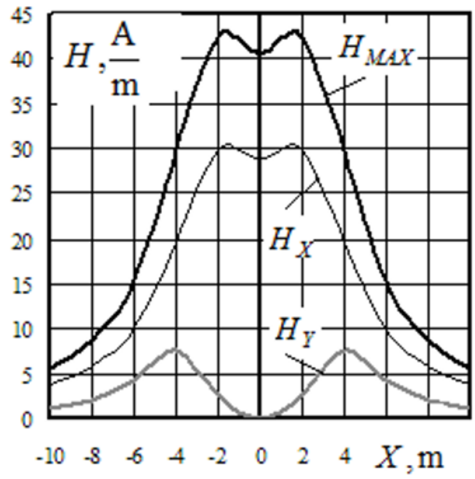

Fig. 2,f. Magnetic field strengths dependences from X coordinate, sucking transformers in rail cut

Comparative strengths are shown in Fig. 3, 4. Summary indicators of electromagnetic field amplitudes are given in Table 1.

Table 1 Summary indicators of strengths amplitudes

Parameter	**Electric field, kV/m**			**Magnetic field, A/m**		
	1	**2**	**3**	**1**	**2**	**3**
Minimum	1,13	0,83	1,13	5,00	1,79	5,70
Average	2,28	1,94	2,28	17,4	4,89	22,2
Maximum	3,46	3,12	3,46	33,0	8,78	42,4

Notes. 1 – absence of sucking transformers; 2 – ST with return wire; 3 – ST connected to rail cut

Fig. 5 shows dependence of electromagnetic field strengths on distance from left TS to observation point along the railway at the above-mentioned load for the inter-track space ($X = 0$) at a height of 1.8 m

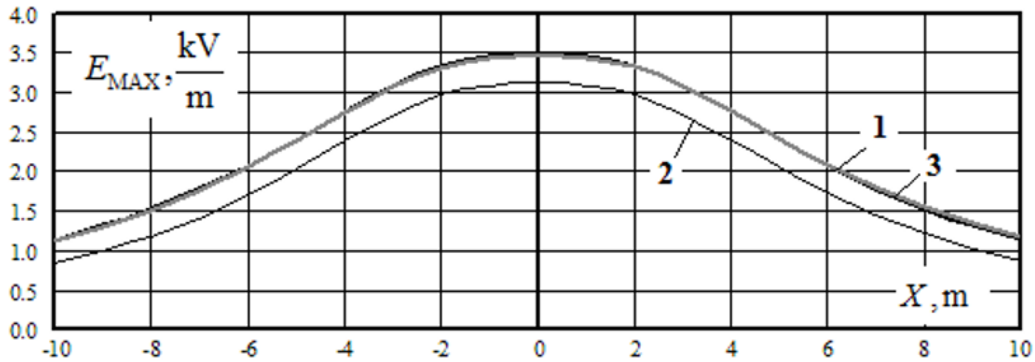

Fig. 3. Comparative dependences of electric field strengths from *X* coordinate**:**
1 – absence of sucking transformers; 2 – sucking transformers with return wire; 3 – sucking transformers in rail cut

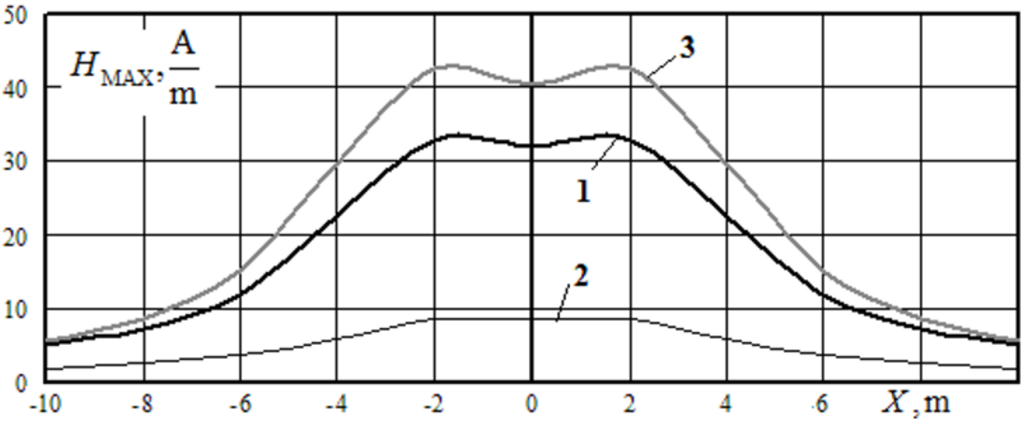

Fig. 4. Comparative dependences of magnetic field strengths from *X* coordinate

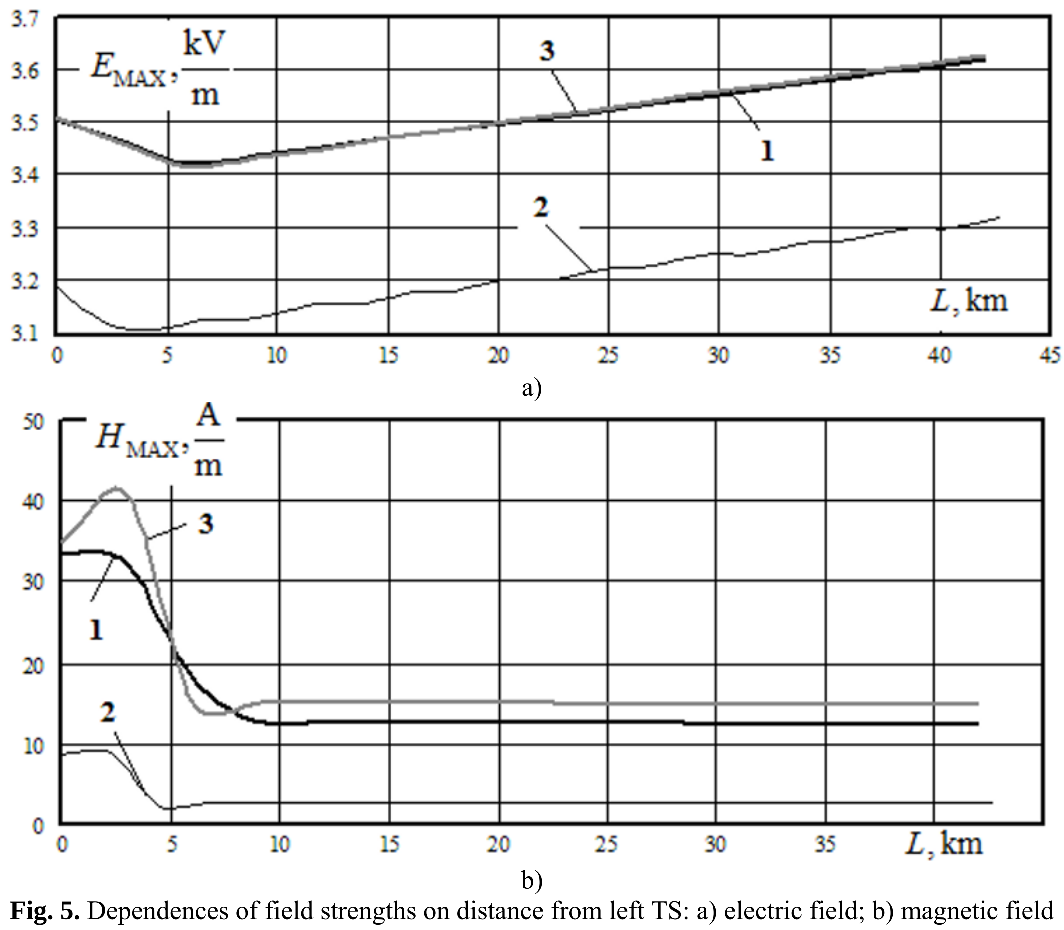

Fig. 5. Dependences of field strengths on distance from left TS: a) electric field; b) magnetic field

4 Conclusions

The final conclusions on the results presented above can be formulated as follows.

1. The developed methods of traction power supply system's simulation allow analyzing the electromagnetic safety conditions in complex traction power networks equipped with sucking transformers.

2. The sucking transformers connected to the rail cut practically do not affect the levels of electric field strengths under the overhead contact system near traction substation. The magnetic field is extended due to the increase in the current of rails: the maximum value of strength is increased by 28%.

3. In the presence of sucking transformers with return wire, the electromagnetic safety conditions are significantly improved: the electric field strength is reduced by 10% and the magnetic field by 73% at the level of the person's head in the inter-track space.

References

1. Apollonskiy S.M. Problems of electromagnetic safety on electrified railway. In 2 volumes. T. II. Electromagnetic safety on railway with alternating current in the traction power network. Moscow, 2017. 414 p.
2. Ogunsola A., Mariscotti A. Electromagnetic Compatibility in Railways. London: Springer, 2013, 529 p.
3. Energieversorgung elektrischer bannen / H. Biesenack, E. Braun, G. George, etc. / Wiesbaden: B.G. Teubner Verlag. 2006. 732 p.
4. Steimel A. Electric traction motive power and energy supply. Basics and practical experience. Munchen: Oldenbourg Industrieverlag, 2008. 334 p.
5. Pavlov I.V. Sucking transformers in the traction power networks of alternating current. M.: Transport, 1965. 204 p.
6. Bader M.P. Electromagnetic compatibility. Moscow, 2002. 638 p.
7. Bardushko V.D., Zakaryukin V.P., Kryukov A.V. Principles for the construction of the power supply systems for railway transport. Moscow, 2014. 166 p.
8. Zakaryukin V.P., Kryukov A.V., Alekseenko V.A. Modeling of track impedance bonds in the calculation of rail track circuit modes // Transport infrastructure of the Siberian region. Irkutsk, 2011. Vol. 1. P. 551-555.
9. Zakaryukin V.P., Kryukov A.V. Complex asymmetric modes of electric systems. Irkutsk: Irkutsk University, 2005. 273 p.
10. Kryukov A.V., Zakaryukin V.P. Methods of joint modeling of both traction and external power supply systems for alternating current railways. Irkutsk, 2011. 170 p.
11. Zakaryukin V., Kryukov A., Cherepanov A. Intelligent Traction Power Supply System // International Scientific Conference Energy Management of Municipal Transportation Facilities and Transport. EMMFT 2017. Advances in Intelligent Systems and Computing, Vol 692. Springer, Cham. P. 91-99.
12. Zakaryukin V.P., Kryukov A.V. Clarified methods for determining mutual electromagnetic influences of adjacent transmission lines // News of higher educational institutions. Problems of power production. No. 3-4. 2015. P. 29-35.
13. Zakaryukin V.P., Kryukov A.V. Determination of the induced voltages when nonparallel power lines are adjacent to one another // Power Technology and Engineering. 2015. Vol. 49. No. 4. P. 304–309.
14. Kryukov A.V., Zakaryukin V.P., Buyakova N.V. Electromagnetic safety in the systems of power supply of the railroads: modeling and management. Angarsk, 2018. 382 p.