Electromagnetic safety in points of overhead power lines and electrified railroads crossing

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Abstract. Traction networks of alternating current electrified railroads generate large electromagnetic fields with 50 Hz frequency. In points of overhead power lines (OPL) and electrified railroads crossing, traction network electromagnetic fields and overhead power lines interfere with each other, which can result in increase in intensities and appearance of the field complex spatial structure. To determine intensities of electrical and magnetic fields which are created in points of crossing, a procedure for intensities summing has been developed, which is based on fields intensities calculation with Fazonord software application, the fields corresponding to traction network and overhead power line mode. Modeling results indicated that intensities of traction network magnetic field are increased up to 13% by interference of 220 kV intensities power lines magnetic field, while at a regulated height of 1.8 m, magnetic field amplitude equals to 82 A/m. At the same time, OPL can increase traction field electrical field strength in the point of crossing by 66% while reaching 5.5 kV/m at 1.8 m height.

1. Formulation of the problem

The share of electrified railroads makes about 25 % of the world's total railroads length [1]. In Russia the share of electrified railroads equals about to 50 %, of which half is electrified under 27.5 kV AC system. Due to electromagnetic imbalance AC traction networks (TN) generate comparatively large electrical and magnetic fields (EMF) which, however, normally do not exceed permissible values [2, 3]. The increase in trains speeds results in increased consumption of current by the rolling stock and increase in EMF intensities [4], which requires an additional analysis of electromagnetic environment while taking into account traction power supply system mode. The latter factor, however, in most cases is not taken into account due to complexity of joint modeling of three-phase railroads power supply system and one-phase traction loads which are move in space and change overtime, as in publication [5].

110-220 kV overhead power lines (OPL) do not generate EMF high strengths [6] in the normal mode. However, in points of overhead power lines and electrified railroads crossing, traction network electromagnetic fields and overhead power lines interfere with each other which can result in increase in intensities and complication of the field spatial structure. To determine field spatial distribution in
the point of crossing, interference method can be used, having traction network and OPL intensities on individual basis. In this case, the field ceases to be plane-parallel which only complicates the task.

The article authors developed procedure for multi-wire system fields determining including traction networks and overhead power lines [3, 7], for preliminary design of electrical system mode which can contain multi-wire lines, one-phase and three-phase transformers of different types, AC traction networks and moving traction loads [8]. Fazonord software application [9] designed by the authors combines possibilities of modes calculation in phase coordinates and simultaneous calculations of EMF strength.

This article is further development of ideas initially represented in work [10], in direction of detailed analysis of electromagnetic field structure in points of overhead power lines and electrified railroads crossing.

2. Modeling methods
Assuming mutual perpendicularity of overhead power lines and railroad overhead system it is possible to calculate components of EMF vectors, followed by calculation of resultant field. The problem solving is hindered by the following factors:

- overhead power can be either single-circuit, or two-circuit;
- mutual voltages phasing of contact network and OPL are to be taken into account, as well as spatial location of OPL different phases wires and the number of railroad electrified tracks.

Crossing of double-track road section and 220 kV line occurs more often. The diagram of such crossing is shown in Figure 1.

![Diagram of contact network and OPL mutual location](image)

Figure 1. The diagram of contact network and OPL mutual location: MW – messenger wire; CW – contact wire.

In this figure, wires of overhead catenary and down track rails are given in black color, while wires and up rails – in gray color. ABC lines shows OPL wires. Different coordinates systems are chosen for railroad and OPL which simplifies fields calculation. Coordinates are determined from following conditions: Z axis is directed along railroad axis, ZT axis – along OPL wires. Currents directions are opposite to Z and ZT axes directions. Coordinates origins are located on the railroad axis. In case of such a choice, it is possible to apply Fazonord [9] software application for individual calculations of traction network and overhead power line EMF to be followed by addition of the relevant field vector components.
In railroad XYZ coordinates system strengths of traction network electromagnetic field are determined using formulas [3]:

\[
\begin{align*}
\dot{E}_x &= \frac{2}{\pi \varepsilon_0} \sum_{i=1}^{N} \frac{(x-x_i) y y_i}{\lambda_{\xi_i}} ;
\end{align*}
\]

\[
\begin{align*}
\dot{E}_y &= -\frac{1}{\pi \varepsilon_0} \sum_{i=1}^{N} \frac{y_i [(x-x_i)^2 - y^2 + y_i^2]}{\lambda_{\xi_i}} ; \\
\dot{E}_z &= 0 ;
\end{align*}
\]

\[
\begin{align*}
H_x &= \frac{1}{2 \pi} \sum_{i=1}^{N} i y \frac{y - y_i}{\xi_i} ;
\end{align*}
\]

\[
\begin{align*}
H_y &= -\frac{1}{2 \pi} \sum_{i=1}^{N} i \frac{x - x_i}{\xi_i} ; \\
H_z &= 0 ;
\end{align*}
\]

where \( \lambda_{\xi_i} = [(x-x_i)^2 + (y+y_i)^2][(x-x_i)^2 + (y-y_i)^2] ; \) \( \xi_i = (x-x_i)^2 + (y_i-y)^2 \).

Similar relations in overhead power line \( X_T Y_T Z_T \) coordinates system are written in the following way:

\[
\begin{align*}
\dot{E}_{T_X} &= \frac{2}{\pi \varepsilon_0} \sum_{i=1}^{N_T} \frac{(x_T-x_{T_i}) y_T y_{T_i}}{\lambda_{T_{\xi_i}}} ;
\end{align*}
\]

\[
\begin{align*}
\dot{E}_{T_Y} &= -\frac{1}{\pi \varepsilon_0} \sum_{i=1}^{N_T} \frac{y_{T_i} [(x_T-x_{T_i})^2 - y_T^2 + y_{T_i}^2]}{\lambda_{T_{\xi_i}}} ; \\
\dot{E}_{T_Z} &= 0 ;
\end{align*}
\]

\[
\begin{align*}
\dot{H}_{T_X} &= \frac{1}{2 \pi} \sum_{i=1}^{N_T} i y_{T_i} - y_{T_i} ;
\end{align*}
\]

\[
\begin{align*}
\dot{H}_{T_Y} &= -\frac{1}{2 \pi} \sum_{i=1}^{N_T} i x_{T_i} - x_{T_i} ; \\
\dot{H}_{T_Z} &= 0 ;
\end{align*}
\]

where \( \lambda_{T_{\xi_i}} = [(x_T-x_{T_i})^2 + (y_T+y_{T_i})^2][(x_T-x_{T_i})^2 + (y_T-y_{T_i})^2] ; \) \( \xi_{T_i} = (x_{T_i}-x_T)^2 + (y_{T_i}-y_T)^2 \).

In the given formulas \( N \) – the number of traction network wires, \( N_T \) – OPL wires number; \( \xi_i \) – charge per wire length unit \( i \); \( \dot{i}_i \) – wire \( i \) current in direction opposite to \( Z \) or \( Z_T \) axis direction; \( (x_i, y_i), (x_{T_i}, y_{T_i}) \) – wire coordinates in relevant cross section.

Observation points coordinates in \( X_T Y_T Z_T \) system are associated with XYZ coordinates with following relations in assumption of coordinates origins concurrence in one point: \( x = z_T ; \ y = y_T ; \ z = -x_T \).

OPL field vectors components are transformed from coordinates system \( X_T Y_T Z_T \) to XYZ system in a similar way:

\[
\begin{align*}
\dot{E}_x &= \dot{E}_{T_Z} ; \\
\dot{E}_y &= \dot{E}_{T_Y} ; \\
\dot{E}_z &= -\dot{E}_{T_X} ; \\
\dot{H}_x &= \dot{H}_{T_Z} ; \\
\dot{H}_y &= \dot{H}_{T_Y} ; \\
\dot{H}_z &= -\dot{H}_{T_X} .
\end{align*}
\]

Thus, to calculate field intensities in a specified point having coordinates \( (x, y, z) \), one has to perform the following operations.

1. Using the given coordinates \( (x, y, z) \) and Fazonord software application in which the function of electromagnetic field intensities determining is implemented after the mode calculation, components of field intensity generated by the railroad traction network should be found.

2. Using the specified coordinates \( z_T = x ; \ y_T = y ; \ x_T = -z \) determine the components of field intensities generated by overhead power line using Fazonord software application.

3. In compliance with expressions (1) calculate the intensities of total components in a specified point:

\[
\begin{align*}
\dot{E}_{xx} &= \dot{E}_x + \dot{E}_{T_Z} = \dot{E}_x^* ; \\
\dot{E}_{xy} &= \dot{E}_y + \dot{E}_{T_Y} = \dot{E}_y^* ; \\
\dot{E}_{xz} &= \dot{E}_z + \dot{E}_{T_X} = \dot{E}_z^* ; \\
\dot{H}_{xx} &= \dot{H}_x + \dot{H}_{T_Z} = \dot{H}_x^* ; \\
\dot{H}_{xy} &= \dot{H}_y + \dot{H}_{T_Y} = \dot{H}_y^* ; \\
\dot{H}_{xz} &= \dot{H}_z + \dot{H}_{T_X} = \dot{H}_z^* .
\end{align*}
\]

Thus, all three components of electrical and magnetic fields’ intensities vectors become determined:

\[
\dot{E}_{x_j} = E_{x_j} e^{i \omega t} ; \quad E_{x_j}(t) = \sqrt{2} E_{x_j} \sin (\omega t + \varphi_j) ;
\]
Vector ends of EMF intensities calculated in some point trace out ellipses lying in the plane determined by these vectors components [11]. The fact of vector affiliation to a specific plane can be shown by vector product of the field two vectors at different time moments; vector of this product is perpendicular to the plane direction in which multipliers are found. In particular, one can analyze two vectors at time moments \( t = 0 \) and for current time \( t \). Vector product \( \vec{E}_0 \times \vec{E}_i \) components are determined in the following way:

\[
\begin{align*}
(\vec{E}_0 \times \vec{E}_i)_x &= 2 E_{2x} E_{3z} \sin (\phi_2 \pi - \phi_3 \pi) \sin (\omega t + \psi_i) ; \\
(\vec{E}_0 \times \vec{E}_i)_y &= 2 E_{2x} E_{3z} \sin (\phi_2 \pi - \phi_3 \pi) \sin (\omega t + \psi_i) ; \\
(\vec{E}_0 \times \vec{E}_i)_z &= 2 E_{2x} E_{3y} \sin (\phi_2 \pi - \phi_3 \pi) \sin (\omega t + \psi_i) .
\end{align*}
\]

Squared absolute value of the vector product is equal

\[
|\vec{E}_0 \times \vec{E}_i|^2 = (\vec{E}_0 \times \vec{E}_i)_x^2 + (\vec{E}_0 \times \vec{E}_i)_y^2 + (\vec{E}_0 \times \vec{E}_i)_z^2 .
\]

These data indicate that ratios of the vector product to its module (vector direction cosines) do not depend on time which indicates intensity vector location at any time moment in the same plane. Extremums are determined by derivative's zero value:

\[
\frac{d E_s}{d t} = 2\omega \sum_{i=1}^{3} E_{2i}^2 \sin (2\omega t + 2\phi_i) = 0,
\]

from which

\[
\tan (2\omega t_{\text{max/min}}) = -\frac{\sum_{i=1}^{3} E_{2i}^2 \sin (2\phi_i)}{\sum_{i=1}^{3} E_{2i}^2 \cos (2\phi_i)} ; t_{\text{max/min}} = -\frac{1}{2\omega} \pm \frac{1}{2\omega} \arctan \frac{\sum_{i=1}^{3} E_{2i}^2 \sin (2\phi_i)}{\sum_{i=1}^{3} E_{2i}^2 \cos (2\phi_i)} ,
\]

where maximum is determined by negative value of the second derivative:

\[
\sin (2\omega t_{\text{max}}) \sum_{i=1}^{3} E_{2i}^2 \sin (2\phi_i) > \cos (2\omega t_{\text{max}}) \sum_{i=1}^{3} E_{2i}^2 \cos (2\phi_i) ,
\]

while minimum – by positive value:

\[
\sin (2\omega t_{\text{min}}) \sum_{i=1}^{3} E_{2i}^2 \sin (2\phi_i) < \cos (2\omega t_{\text{min}}) \sum_{i=1}^{3} E_{2i}^2 \cos (2\phi_i) .
\]

Different field points are characterized by different polarizations and field components ratios. Intensity vector hodograph located in polarization plane can be determined using procedure set forth in work [10].
3. The modelling results
The modeling is performed for overhead power line and traction network location as per Figure 2.

![Figure 2. TN and OPL wires location: 1 – messenger wire; 2 – contact wire.](image)

Measurement of coordinate $z$ was carried out from crossing center of overhead power line with AC-300 wires and traction network $2\times$ (PBSM-95+MF-100+2R-65). Power transit $75 + j40$ MV·A was supposed to be carried by overhead line for each phase with linear voltage 230 kV and currents 648 A, close to maximum-permissible for AC-300 wires. Voltages at OPL starting end were equal to 132.8 kV with angles $0^\circ$, $-120^\circ$, $120^\circ$, currents flowing into these nodes were equal to: $648e^{-j28.6^\circ}$ A, $647e^{-j148.6^\circ}$ A, $647e^{-j91.3^\circ}$ A.

Power transit $8 + j8$ MV·A was carried out by catenary system on each railway track. The calculated voltage on traction substation buses equals to $25.6e^{-j5.6^\circ}$ kV with catenaries currents $450e^{-j51.3^\circ}$ A.

The modeling results are presented in Figure 3 – 6.

![Figure 3. Dependences of electric (a) and magnetic (b) fields amplitudes from $x(x_T)$ coordinate: 1 – traction network; 2 – OPL.](image)
Figure 4. Dependences of electric (a) and magnetic (b) fields amplitudes from x (xT) coordinate: 
1 – traction network; 2 – OPL.

Figure 5. Hodographs of electric (a) and magnetic (b) fields intensities resultant vectors 
in polarization plate for a point with coordinates x = −2 m, y = 1.8 m, z = 2 m.

Figure 6. The chart of the electrical field total strength surface in x, xT coordinates.

The results obtained indicate the following.

1. Magnetic field total intensity of traction network and OPL differ from magnetic field intensity 
generated by only traction network by −2…13 %. In point with coordinates x = 2 m; y = 1.8 m 
magnetic field amplitude in design variant was equal to 82 A/m.

2. Increase in electrical field amplitude maximal value in the point of OPL and TN crossing reaches 
66%; in the point specified in the previous paragraph the value of this parameter equals to 5.4. kV.
4. Conclusions
The procedure developed can be used to resolve practical issues associated with electromagnetic safety improvement for personnel engaged in operation of high voltage power grids and railroads AC power supply systems.

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