MAGNETIC FIELD OF ELECTRIFIED RAILWAY LINES IN SLOVENIA

M.Sc. Bojan Cene
Ministry for Traffic, Slovenia

In the environment in which we live we are exposed to different kinds of radiation. Radiation is divided into ionising radiation as a result of radioactive decay and into non-ionising radiation, which is the consequence of electromagnetic waves. The use of electric power has penetrated every area of human activities. Its accompanying effects are electromagnetic waves, which expand into the space surrounding the installations for the generation, transmission and use of electric power. The research in the last 20 years has concentrated on the possibly harmful effects of low frequency (0 – 300 Hz) electromagnetic waves on man and the environment. However, not much research has been conducted into the magnetic fields under the electric overhead traction systems. Therefore, this paper is presenting the results of the calculation of the magnetic field under the electric overhead traction system on Slovenian railways.

Keywords: electric traction, driving network, final elements, magnetic field

MAGNETNO POLJE ELEKTRIFICIRANIH ŽELEZNIŠKIH PRUGA U SLOVENIJI

U okolini u kojoj živimo svaki dan smo izloženi raznim radijacijama. Radijacije delimo na jonizirajuće, koje su posledica raspada jezgra atoma i nejonizirajuće, koje su posledica elektromagnetnih talasa. Upotreba električne energije proširila se na sve oblasti ljudskih aktivnosti. Njen prateći efekat su elektromagnetna polja koja se šire oko instalacija koje generišu, prenose i koriste električnu energiju. U poslednjih 20 godina istraživanja su se koncentrisala na moguće štetne uticaje niskofrekfenktnih elektromagnetnih polja (0-300 Hz) na čoveka i okolinu. Vrlo retka su istraživanja magnetnih polja pod kontaktnom mrežom elektrificiranih železničkih pruga u Sloveniji. Zbog toga su u ovom radu predstavljeni rezultati proračuna magnetnih polja pod kontaktnom mrežom elektrificiranih železničkih pruga u Sloveniji.

Ključne reči: električna vuča, vozna mreža, konačni elementi, magnetno polje

INTRODUCTION

There is a 3000 V DC system used at electric traction on the Slovenian Railway. If there is an electric traction vehicle running under one of the contact lines pulling the load current, the direction of the current is as follows (Figure 1): DC current comes from the rectifier to the contact line, on the contact line to the current receiver of the electric traction vehicle, from here to traction motors and over wheels to the tracks. Then the current flows partly on the track, partly on the ground back to the point where it is connected to the transformer of the rectifier. Driving network is composed of carrier rope and contact lines. Calculations of magnetic flux density (B) were done with programme "POLJE" at a load current of 500 A. The computer programme "POLJE" was established at Fakulteta za elektrotehniko, računalništvo in informatiko Univerze v Mariboru using final elements method. The considered space around the traction system was a square of 16 m and divided into final elements (Figure 3). Underneath driving network of single way electric railway track system when an electric traction vehicle is on the track, the magnetic flux density is 0,155 mT (Figure 5).

Legal basis for the evaluation of impacts on the environment are the European standard EN 50160: Voltage characteristics of electricity su-

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Kontakt: M. Sc. Bojan Cene
Ministry for Traffic
Tržaška 19a, 1000 Ljubljana, Slovenija
E-mail: bojan.cene@gmail.com

pplied by public distribution systems and EN 61000-2-4: Electromagnetic compatibility (EMC) Part 2: Environment, Section 4: Compatibility levels in industrial plants for low-frequency conducted disturbances for conducted disturbances. The third basis is the Slovenian legislation for non-ionizing radiation because the Slovenian legislation defines stricter measures than corresponding European regulations. The basic act is represented by The Government Decree on electromagnetic radiation in natural and living environment from 1996, published in Ur.l. of RS no.70/96. The legislation defines two levels of environmental protection.

The first level of protection against radiation is valid for Region I, for the region of hospitals, health resorts, sanatoriums and tourist areas meant for residence and recreation, the region of educational guardianship etc.

The second level of protection against radiation is valid for Region II, where environmental intervention, which is due to the radiation more disturbing, is allowed. Region II is mostly an area without lodgings, meant for industrial, trade or similar production activities, for transport, stock or repair activities as well as for all other regions.

This value will not be surpassed underneath driving network of electric traction on Slovenian Railway, not even at current of 2400 A.

ELECTRIC TRACTION AT SLOVENIAN RAILWAYS

At Slovenian railways all electrified lines are supplied by the 3000 V DC system. The direct current to the overhead electric traction network is supplied by rectifier stations (RS), which are located about 30 km apart along the railway lines. This means that in the direct current system of the Slovenian railways exists a duplicate supply of the traction network, except on railway lines running towards neighbouring countries, which operate on AC single phase electric traction systems. The electric traction circuit is shown in figure 1. [1]

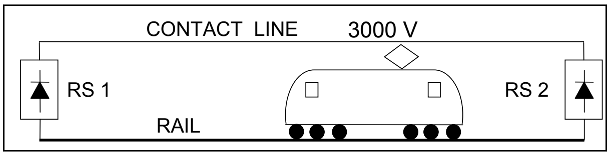

Figure 1. Electric traction circuit

As it can be seen from the figure, the rectifier station is supplying the contact line with direct voltage 3000 V, as required by the traction vehicle, whereby the circuit is closed through the return conductor – the rail back to the rectifier station.

The output of rectifier stations at Slovenian railways varies from 4.5 MW to 6.8 MW. The load currents of the traction network amount to 2400 A, which is equal to the breaking capacity of circuit breakers in rectifier stations. These currents are caused by electric traction vehicles and short circuits in the direct current power supply system of the traction network 3000 V.

Because of the relatively low voltage of the Slovenian traction network in comparison to other power systems we have to deal with high currents. High currents are generating a magnetic field around the network, while high voltages generate an electric field. We have to be aware, that the rated voltage of the Slovenian traction network is 3000 V, which may drop to 2000 V because of great distance between two adjacent rectifier stations. Such voltage drops are caused by electric traction vehicles.

For the calculation of the magnetic field under the electric overhead traction system 3000 V DC the average load current value of 500 A was taken into account.

THE METHOD FOR THE CALCULATION OF THE MAGNETIC FIELD UNDER THE TRACTION NETWORK 3000 V DC

There are various methods available for the calculation of the magnetic field under the electric overhead network. In our case the computer program of the Faculty of Electrical Engineering, Computer Science, and Informatics in Maribor, named “Polje”, was used. This program is capable of analysing 2D cases. Beforehand, all required data of the discussed network should be entered. The arrangement of the electric traction network is shown in figure 2.

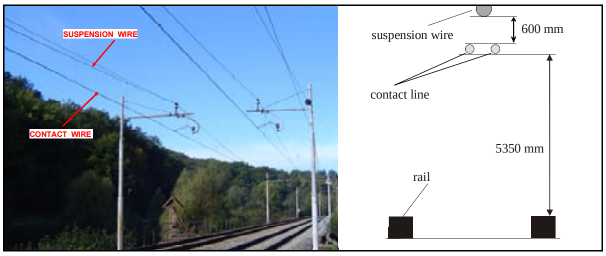

Figure 2. Cross section of the suspension wire, two contact wires, and the rail – a 2D case

As can be seen in figure 2, the traction network of one track is composed of two traction wires i. e. contact wires, and of one suspension wire, which is located 600 mm above the contact wires. The height of the contact wires above the upper edge of the rail is approximately 5350 mm. The distance between the rails is 4536 mm. The cross section of one rail is 6250 mm^2. Data of the contact line and the suspension wire on electrified lines of Slovenian railways are as follows [2].:

- 2 contact wires, designated as Ri 10, made of hard electrolytic copper, S = 100 mm^2, $\rho = 0.0175\ \Omega\text{mm}^2/\text{m}$, m = 0.89 kg/m and
- suspension wire, made of copper, S = 118.5 mm^2, $\rho = 0.015\ \Omega\text{mm}^2/\text{m}$, m = 1.08 kg/m.

In the text processing program “Notepad” the coordinates are entered for each element separately:

- for the suspension wire: coordinates (x,y) and the value of the diameter in m,
- for contact wires: coordinates (x, y) and the value of the diameter in m,
- for the rails: coordinates (x, y) and the value of the diameter in m,
- for the wagon frame: coordinates (x, y) and the value of the diameter in m, if there is a wagon on the track.

In the text processing program “Notepad” the data for current density in the conductors and the rails are also entered. Current density is obtained through dividing the current by the cross section. The selected value of current is 500 A. The value of current density is defined in A/m^2. The value of 500 is selected as the permeability of the wagon, which is the permeability for iron.

The program “Polje” is calling all data from the program for processing of texts “Notepad”. On the basis of these data the program calculates the following parameters, employing the “method of finite elements” [3].:

- distribution of the area surrounding the conductors and rails into finite elements,
- distribution of the potential around the conductors and the rails,
- graphical presentation of the magnetic density at a defined level above the rails, and
- direction of the magnetic field.

STATIC MAGNETIC FIELD

With use of Maxwell's equations, that completely describe electromagnetic field, we can write down next equations for static magnetic field [3]:

$$\text{rot}\, H = J, \tag{1}$$

$$\text{div}\, B = 0, \tag{2}$$

$$B = \mu \cdot H, \tag{3}$$

$$B = \text{rot}\, A. \tag{4}$$

where:

- H…magnetic polish strength,
- B…density of magnetic flux,
- J…current's density,
- A…magnetic vectorial potential,
- μ…permeability.

We define function of magnetic vectorial potential in entire place as solution of vectorial partial equation of second order, Poisson's differential equations appointed. [3]:

- $-\Delta A = \mu\, J.$ (5)

We can write down this in rectangular coordinate system [3]:

- $-\Delta Ax = \mu\, Jx,$ (6)
- $-\Delta Ay = \mu\, Jy,$ (7)
- $-\Delta Az = \mu\, Jz.$ (8)

In our case have of work with two-dimensional (2D) problem [3]:

$\boldsymbol{A}(0,0,A_z)$, $\boldsymbol{J}(0,0,J_z)$,

$$\frac{\partial}{\partial x}\nu_x\frac{\partial A_z}{\partial x}+\frac{\partial}{\partial y}\nu_y\frac{\partial A_z}{\partial y}=-J_z\,. \tag{9}$$

We use method of final elements for rescuing of Poisson's differential equation (PDE). We are using method of final elements for any geometry and any excitation and any edge conditions [2]. We can capture no-linears with this method very well. We write down Poisson's differential equation because of transparency in other form [3]:

$$\nabla\nu\nabla A = J\,. \tag{10}$$

We show rescuing with method of gravities remainders, where is *W* gravity function and get initial equation [3]:

$$k\iint_S\left(\nabla W\nabla A - WJ\right)\cdot dS = 0\,. \tag{11}$$

Surface S, where save, distribute No of final elements, that have for n nodes. At 2D problems are geometric figures and at 3D problems are geometric bodies, that they form us mesh of final elements. Inside element show changing *u* with help of interpolation function (from her order is dependetly also number of nodes) for 2D(x,y) or for 3D(x,y,z) and of nodes values *u*i [3]:

$$A = \sum_{i=1}^{n} N_i A_i \, . \qquad (12)$$

Ackuired equation we put into initial equation, where consider still W(x,Y)=N(x,y) and write equation for node i for one element [3]:

$$\sum_{e=1}^{Ne} \iint_{S_e} \left(\nu_e \sum_{j=1}^{n} \nabla N_i \nabla N_j A_j \right) dS - \iint_{S_e} N_i J_e dS = 0 \, . \qquad (13)$$

We write down upper equation for every element of mesh, considering margins conditions. Contributions of elements, that touch of single nodes add up and we get system of algebraic equations [3]:

$$[S]_{mke} \{A\} = \{D\}_{mke} \, . \qquad (14)$$

Finally solution introduce values of function *u*(*x,y*) in all nodes [3]:

$$\{A\} = [S]^{-1}_{mke} \{D\}_{mke} \, . \qquad (15)$$

We calculate intermediate values by next equation [3]:

$$A = \sum_{i=1}^{n} N_i A_i \, . \qquad (16)$$

RESULTS OF CALCULATIONS OF THE MAGNETIC FIELD UNDER THE TRACTION NETWORK 3000 V DC

The calculations were performed for the following cases of direct current traction network:

- under the traction network of a single track railway line (traction network only without rails
- under the traction network of a double track railway line (traction network only without rails
- under the traction network of a single track railway line with a wagon/vehicle (traction network and vehicle without rails
- under the traction network of a double track railway line with a wagon/vehicle on one track (traction network and vehicle without rails),
- under the traction network of a single track railway line, taking into account the return conductor, i.e. the rails,
- under the traction network of a single track railway line, taking into account the return conductor, i. e, the rails and the wagon on the track.

There are very rare occasions at Slovenian railways, where under the traction network 3000 V DC of a single track or a double track railway line there are no rails. Such cases only arise at great bends of the railway line because of reduction of voltage drops or because of increase of the cross section of the traction network. It is likely that people or vehicles are present under such sections of the traction network, therefore the calculation for these situations is justified.

For the calculation of a concrete case the space surrounding the network and the rails is limited to a distance of 16 m.

The most characteristic case is the traction network of a single track line and the return conductor – the rails. The division of space up to a distance of 16 m by the method of finite elements for this case is shown in figure 3 [3].

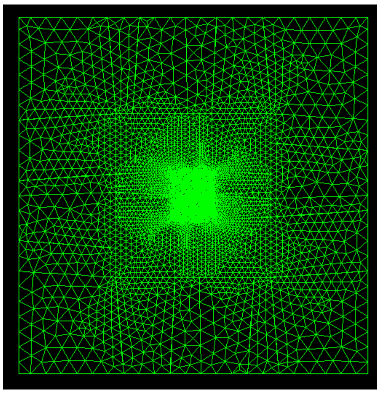

Figure 3. Division of the system into finite elements including two additional frames on a single track line with return conductor – the rails

The value of the magnetic vector potential at 1 m above the ground on a single track line with a wagon is 0, 22 · 10 $^{-3}$ Vs/m (Figure 4) [3].

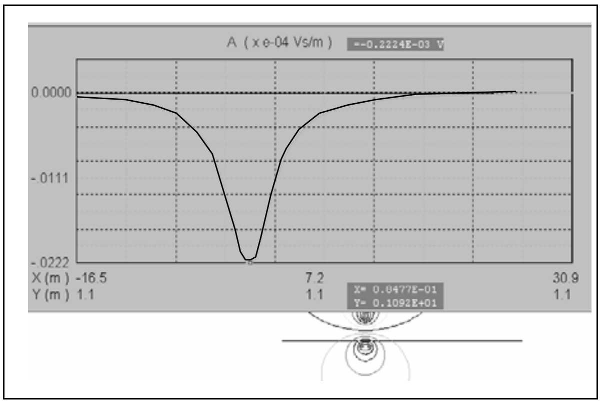

Figure 4. Graphical presentation of the magnetic vector potential of a single track line with return conductor at 1 m above the ground

The value of magnetic density of an electrified single track line with return conductor at 1 m above the ground is 0,155 · 10 $^{-3}$ Vs/m^2 (Figure 5) [3].

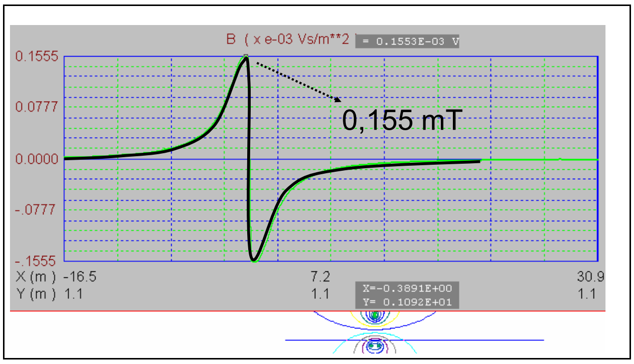

Figure 5. Value of magnetic density at 1 m above ground on a single track line with return conductor

Figure 6 is showing that the direction of the magnetic field around the conductors (contact wire and suspension wire) is different from the direction of the magnetic field around the return conductor – the rails. This is because of the change of direction of the current, which is in the contact line flowing in one direction and in the rails back to the rectifier station in the opposite direction [3].

The table below is showing the values of the magnetic vector potential and of the density of the magnetic field at 1 m above ground for all discussed cases.

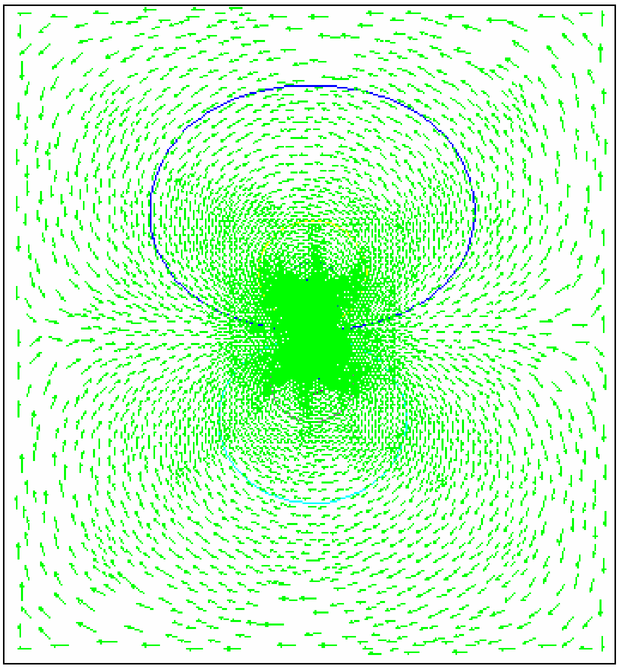

Figure 6. Direction of the magnetic field around two contact wires and around two rails on a single track line

Table 1: Magnetic vector potential and magnetic density for discussed cases of the traction network 3000 V DC

TYPE OF NETWORK	MAGNETNIC VECTOR POTENTIAL A [Vs/m]	MAGNETIC FLUX DENSITY B [mT]
Traction network of a single track railway line (without rails)	0,00026	3,9
Traction network of a double track railway line (without rails)	0,00049	6,6
Traction network of a single track railway line with a vehicle (without rails)	0,00019	0,16
Traction network of a double track railway line with a vehicle (without rails)	0,00068	0,56
Traction network of a single track railway line with rails	0,00022	0,155
Traction network of a double track railway line with return conductor and a vehicle on one track	0,00018	0,43

The results show, that the strongest magnetic field occurs at locations, where the overhead traction network of 3000 V DC runs outside the route of the railway line. On the track itself, where the rails are taken into account, the density of the magnetic field is somewhat lower. If there is a vehicle (locomotive or wagon) under the overhead traction network, the magnetic field is closed through the metal frame of the vehicle.

According to the Official Gazette of the Republic of Slovenia the permissible density of the magnetic field in the frequency range of 0 to 0.1 Hz, to which people may be exposed, is 40 mT. This means, that the traction network 3000 V DC of electrified railway lines does not exceed the permissible value of the magnetic flux density and is therefore not harmful to people. For this analysis the traction network loading current of 500 A was taken into account. This is the average value with regard to the load of the traction network. But even with the highest possible load current of 2400 A the value of 40 mT would not be exceeded.

CONCLUSIONS

There are two steps of protection against radiation of electromagnetic waves, defined with regard to the sensitivity of the individual sphere of the natural or living environment.

Step I of protection against radiation is valid in zone I which includes areas, where a higher degree of protection is required, i. e. in hospitals, health resorts, convalescent hospitals, facilities for residential and recreational tourism, residential areas, nursery schools, medical services facilities, playgrounds, public parks, public recreational areas, mixed commercial, business and residential areas; community, shopping, leisure, sports and similar centres, as well as areas, designated for agricultural activities which also include dwelling houses.

Step II of protection against radiation applies to zone II, i. e. areas, where a higher degree of radiation is allowed. These are particularly non-residential areas, designated for industrial, commercial or similar production activities, storehouses, transport organisations and companies of the service sector as well as all other activities, not included in step I. Step II of protection against radiation also refers to areas designated for public roads or railways in zone I.

Maximal permissible values of magnetic field density as a consequence of operation or use of sources of low frequency radiation in zones I and II are defined in table 2 [4].

Table 2: Maximal permissible effective magnetic flux density as a consequence of operation or use of low frequency radiation sources in zones I and II

Frequency range (Hz)	Maximum permissible effective magnetic flux density B (mT)	
	Zone I – for new and reconstructed sources of radiation	Zone II – for new and reconstructed sources of radiation and for existing sources of radiation in zone I and II.
> 0 =< 0,1	4 (1)	40 (1)
> 0,1 =< 1,15	2,8	28
> 1,15 =< 1.500	0,5/f (2)	5/f (2)
> 1.500 =< 10.000	0,002	0,021

(1) – for frequency range from 0 to 0,1 Hz, maximum values valid for peak values of magnetic flux density,

(2) - f is frequency, expressed in Hz.

The results in Table 1 show that the magnetic field produced by contact lines of the electrified railway lines in Slovenia, using 3000 V DC, is not threatening railway personnel, performing their work under the overhead contact installations of the traction system (railway station personnel, railway line workmen ...). The same applies to passengers on station platforms when waiting for the train as well as for persons, crossing the railway line at level-crossings.

The density of the magnetic flux in the driver's cabin on the locomotive and in carriages is equal to zero, as the magnetic field produced by overhead contact lines is closed through the metal structure of the locomotive or the carriage. The same applies to the passengers in cars, crossing the electrified railway lines at level crossings, as the magnetic field is closed through the metal structure of the car.

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