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Electromagnetic Fields and Induced Voltages on Underground Pipeline in the Vicinity of AC Traction System

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Abstract: Various regulations, aimed at the protection of human beings and electrical equipment against possible adverse effects resulting from exposure to electromagnetic fields, have been issued in many countries. Most of them are based on safety guidelines published by international expert groups. In this paper, electric and magnetic fields are calculated in the vicinity of 25 kV traction line supplying railway traction systems. Calculation results are compared to exposure limits specified by safety guidelines and regulations. Possible countermeasures for reduction of electromagnetic fields are proposed. Also, this paper presents a method for calculation of the induced voltages to an underground gas pipeline from a neighbouring 25 kV electric traction overhead line in case of short circuit. Calculations are performed with EMTP-ATP software. Possible countermeasures for reduction of induced voltages are proposed.

Key words: Electric and magnetic fields, electric traction system, induced voltages, underground gas pipeline.

1. Introduction

Great quantities of energy, especially electric energy, are needed for the development of human society. Any transportation system needs a source of power to drive its vehicles carrying their passengers or goods from one place to another. From the early invention of steam engines to modern electric locomotives, railway transport systems have had a long history and huge developments to become one of the most popular modes of public transport over the last century. Electric traction is an environmental friendly, pollution-free and energy efficient mode of transport [1]. In this paper, special attention is given to the electric traction system which has its uniqueness, so its operation is different from the operation of power transmission systems [2]. Electric traction power supply system consists of traction power transformers which are connected to traction supply network by cables. Traction supply network consists of overhead line placed above the railway [3, 4]. In this paper, electric and magnetic fields are calculated in the vicinity of 25 kV (50 Hz) overhead line which is a part of railway traction system in Croatia [5].

Electric fields are created by differences in voltage: the higher the voltage, the stronger will be the resultant field. Magnetic fields are created when electric current flows: the greater the current, the stronger the magnetic field. An electric field will exist even when there is no current flowing. If current does flow, the strength of the magnetic field will vary with power consumption but the electric field strength will be constant. Magnetic fields are not blocked by common materials such as metal bulkheads. Like electric fields, magnetic fields are strongest close to their origin and rapidly decrease with distance from the source [6]. In most of the countries the values of electric and magnetic fields are

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limited to prevent eventual adverse effects on humans [6, 7].

Inducted voltages have many negative effects on underground gas pipeline, such as the possibility of creating electric spark or increase in corrosion of material [8]. The corrosion is caused either by leakage currents or by induced voltages in case of short circuit on electric traction system. Spark can be dangerous if it penetrates the inside of the pipeline which is used for the transport of flammable materials [9], while the corrosion destroys the pipeline itself. Buried gas pipelines and railway traction overhead lines are often placed at the same corridor, so it is necessary to see the influence of overhead lines on pipelines [10]. Calculation of inducted voltages on underground pipeline in case of short circuit in the vicinity of railway traction system is presented in this paper.

2. Electric Traction System 25 kV 50 Hz

The operation of single phase 25 kV (50 Hz) electric traction system is significantly different from the electric power system which supplies it [3].

Electric traction system is supplied from electric power system through power transformers located at traction substation. These transformers are connected to two phases of the power transmission system. Traction power supply network is separated by neutral section in two parts which are supplied from different traction substations. Fig. 1 shows the 25 kV 50 Hz electric traction system.

2.1 Power Supply Network

Locomotives are supplied with electrical energy through power transformers 110/25 kV. Traction supply network consists of a conductors placed above the railway (Fig. 2). Conductors are mounted on the masts next to the railway. Locomotives are supplied with electrical energy over the pantograph and the current flows through the rails.

The overhead line consists of catenary and contact conductors which are connected. The locomotive

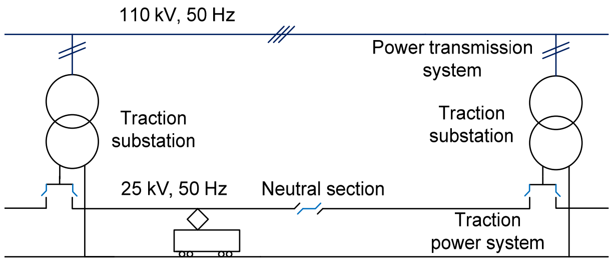

Fig. 1 Electric traction system.

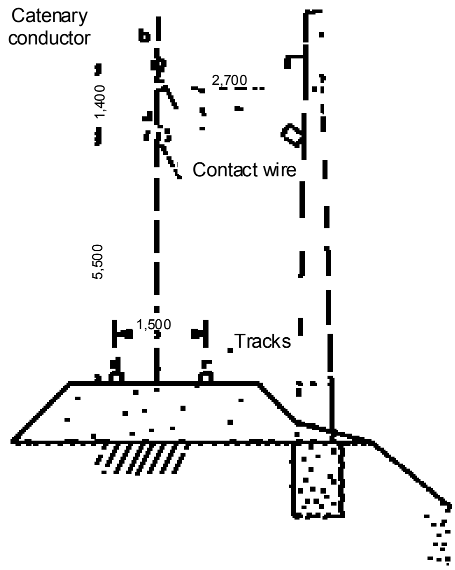

Fig. 2 Cross section of single-railed open railroad 25 kV, 50 Hz (type BzII).

pantograph slides over the contact conductor. Catenary conductors are kept at a mechanical tension because the pantograph causes oscillations in the conductor and the wave must travel faster than the train to avoid producing standing waves that would cause the conductors to break. Tensioning the line makes waves travel faster. Design of power traction network varies depending on the number of tracks which are electrified, and the position (open or railroad station). Fig. 2 shows the cross-section of single-track. The nominal cross section of contact conductor is 100 mm^2, and catenary conductor is 65.8 mm^2. At the temperature of 80 °C, the maximum operation current for the copper wires is limited to 4 A/mm^2. Therefore, the maximum operation current for contact wire is 400 A and for catenary wire 260 A. About half of the total current returns through the rails while the remaining current flows to ground.

Traction power network in the traction system is performed in isolated sections in order to avoid the equalizing currents that would occur between adjacent traction substations. Equalizing currents occur in the supply network when the contact sections are simultaneously connected to two substations of the electric power system. The sectioning is executed in the section switchgear by disconnectors. Also, the sectioning is performed near the traction substations at the end of radial power supply sections.

3. Calculation and Analysis of Electric and Magnetic Field

In this chapter, the electric and magnetic fields are calculated at the different positions of the traction power system. Parts of the railway power supply network are modelled using EFC-400 software [11].

In order to perform the calculation of electric and magnetic fields, it is necessary to determine the voltage and maximum operating current on overhead line.

The voltage on the contact conductor is relatively stable. For the movement of locomotives, it is necessary to ensure that voltage does not significantly differ from the nominal value. In the system of 25 kV (50 Hz) minimum and maximum allowed value of the continuous operating voltage is 19 kV and 27.5 kV, respectively [12]. In order to ensure better voltage conditions and to reduce the impact of voltage drop at the contact conductor, the voltage on the 25 kV bus in the traction substation is slightly higher than the nominal. In calculations it is assumed that the voltage in the railway power supply network is U = 26.5 kV. This ensures stricter calculation conditions.

Electric current, on the contrary, has no constant value. Moreover, its value depends on the number of trains in operation and their current positions on the observed part of railway. In the previous chapter nominal operating current through the overhead line BzII I_n = 660 A was obtained. The cross section of the contact conductor reduces during the time due to the mechanical contact with pantograph, so the lines should not be loaded with nominal current. For the purpose of this paper, the highest value of current 600 A was assumed. It should be noted that such great current value almost never occurs in the railway power system. Calculations were carried out for single-railed open railroad shown in Fig. 2.

3.1 Limited Values of Electric and Magnetic Fields

Restrictions on the values of electric and magnetic fields were made in order to avoid potential negative effects of exposure of human beings. Therefore, it is necessary to calculate electric and magnetic fields in the vicinity of electric traction system.

At the level of the European Union the recommendation 1999/519/EC [13] on limited values of electromagnetic fields (0-300 GHz) was adopted. Limiting values are recommended by the frequency bands [6, 13]. For the frequency of 50 Hz, the following recommended limited values are allowed: E = 5 kV/m, H = 80 A/m and B = 100 μT. In the calculation, the operation frequency f = 50 Hz was analyzed.

A regulation on the protection form electromagnetic fields was adopted in the Republic of Croatia on 2003. It defines two areas (area of professional exposure and area of increased sensitivity) in which limited values of the electric and magnetic field are defined. In the area of professional exposure to the fields of operating frequency 50 Hz the limited values are same as in Ref. [13]. In the area of increased sensitivity the following limited values are allowed: E = 2 kV/m, H = 32 A/m and B = 40 μT. The new reference levels are proposed in 2010 by International Commission on Non-ionizing Radiation Protection and for the frequency of 50 Hz the following limiting values are allowed: E = 10 kV/m, H = 800 A/m and B = 1 mT. In the area of increased sensitivity the following limiting values are allowed: E = 5 kV/m, H = 160 A/m and B = 0.2 mT [13, 14].

3.2 Calculation of Electric Field

The electric field is calculated as a negative gradient of a scalar potential $\varphi(x, y, z)$ [4]:

$$\vec{E}(\vec{r}) = -\vec{\nabla}\varphi(\vec{r}) \tag{1}$$

where,

$$\vec{\nabla} = \begin{pmatrix} \partial / \partial x \\ \partial / \partial y \\ \partial / \partial z \end{pmatrix} \tag{2}$$

For a line-type charge segment which lies in the origin parallel to the X-axis, potential at the point $P(x_p, y_p, z_p)$ can be determined as:

$$\phi(x_p,\ y_p,\ z_p,\ t) = \frac{Q_i}{4\pi\varepsilon_0} \ln \frac{x_p + \sqrt{x_p^{\ 2} + y_p^{\ 2} + z_p^{\ 2}}}{(x_p - L_i) + \sqrt{(x_p - L_i)^2 + y_p^{\ 2} + z_p^{\ 2}}} \tag{3}$$

where,

Q_i—total charge;

L_i—length;

ε_0—vacuum permittivity.

From the obtained potential in all points of space electric field can easily be determined as the ratio of potential difference between two points and their distances. Fig. 3 shows a 3D (three-dimensional) model of electric traction system with four spans in the area where the fields are calculated. Fig. 4 shows the distribution of electric field around the traction contact network at the open railway and Fig. 5 shows this distribution at statio..

At the open railway, the value of the electric field surrounding the overhead line is lower than 1.5 kV/m at the height of 1.5 m [6] above ground level (Fig. 4). It is interesting to calculate the electric field at the railway station. Railway station with five electrified tracks was analyzed in calculations. In this model, the grounded objects were not taken into account, but by adding them the calculated values of the electric field would be smaller. The highest value of the field at the open railway and at the station is near the conductors. At the height of 1.5 m above the ground level electric field is lower than 2 kV/m.

The obtained results show that the electric field of

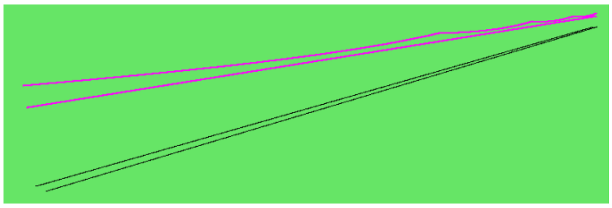

Fig. 3 3D model of electric traction system.

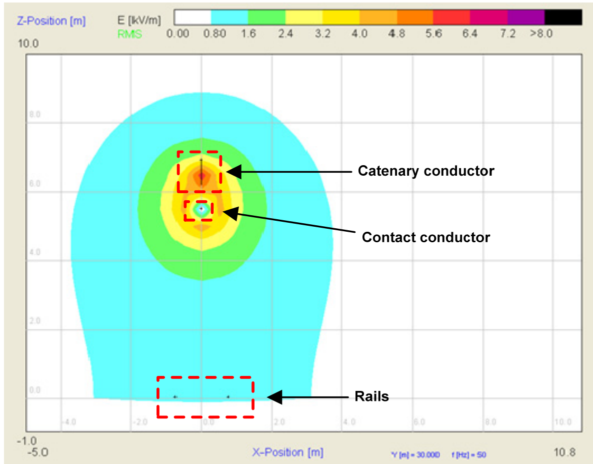

Fig. 4 Distribution of electric field at the open railway.

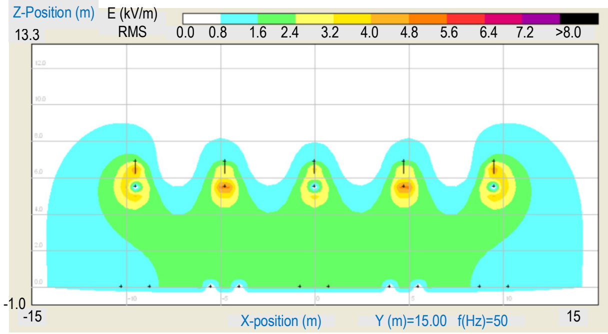

Fig. 5 Distribution of electric field at the station.

the railway network is within the limits of Ref. [13]. Critical value of 2 kV/m is reached at the height of 3.52 m.

3.3 Calculation of Magnetic Field

The magnetic induction is calculated with the Biot-Savart equation as a superposition of the subfields of individual conductor segments. Every infinitesimal segment contributes to the total field [4]:

$$\overrightarrow{dB}(t) = \frac{\mu_0}{4\pi} \frac{\overrightarrow{dl} \times \vec{r_0}}{r^2} I(t) \tag{4}$$

where,

$I(t)$—electric current through the conductor;

$\vec{dl}$ —infinitesimal length of conductor carrying electric current;

r—distance from conductor to the point where the field is calculated;

$\vec{r_0}$—unit vector to specify the direction of the vector distance r from the current to the point where the field is calculated.

If the segment i of the length L_i is in the origin of the coordinate system parallel to the X-axis, its contribution to the field at the point $P(x_p, y_p, z_p)$ is then:

$$\left|\vec{B_i}(t)\right| = \frac{\mu_0}{4\pi} I_i(t)\left[\frac{L_i - x_p}{\sqrt{(L_i - x_p)^2 + r^2}} + \frac{x_p}{\sqrt{x_p^{\ 2} + r^2}}\right] \quad (5)$$

with the vector components:

$$B_{xi}(t) = 0$$
$$B_{yi}(t) = -\frac{z_p}{\sqrt{y_p^2 + z_p^2}}\left|\vec{B_i}(t)\right| \quad (6)$$
$$B_{zi}(t) = \frac{y_p}{\sqrt{y_p^2 + z_p^2}}\left|\vec{B_i}(t)\right|$$

The magnetic field H can be determined from magnetic induction B. These two values are connected by equation:

$$\vec{B} = \mu_0 \mu_r \vec{H} \quad (7)$$

where,

$\mu_r = 1$—relative permeability of air;

μ_0—vacuum permittivity.

Magnetic induction occurs in the vicinity of the conductor which is flowed by electric current. Calculation of magnetic induction is more complex than the calculation of electric field due to variations of current value. In the calculations, maximum value of current 600 A through the conductors was assumed.

The distribution of magnetic induction in the vicinity of the contact and catenary conductor at the open railway is shown in Fig. 6. The value of magnetic induction at the height of 1.5 m above the ground in the middle of the track is 59.96 μT.

To determinate the value of magnetic induction in the vicinity of buried pipeline the boundaries of calculation have to be expanded according to Fig. 7.

Magnetic induction was also calculated on railway

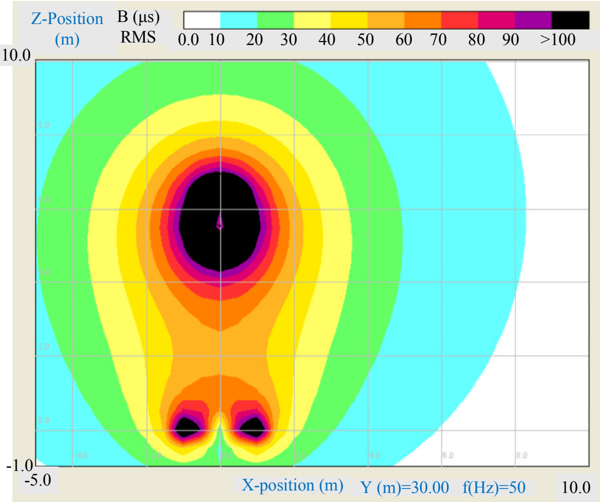

Fig. 6 Magnetic induction distribution at the open railway.

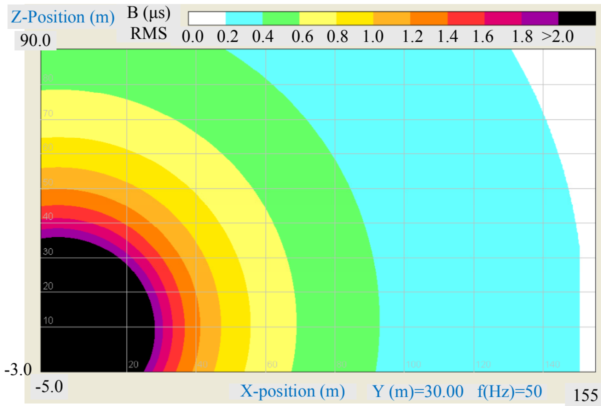

Fig. 7 Magnetic induction distribution at the open railway in case of expanded boundaries.

station. If the station has more than one track then the current is evenly distributed to the all tracks. This is not true only in moments in which locomotive enters or leaves the railway station. The distribution of magnetic induction on the station with five tracks is show in Fig. 8. This is the case when the current is evenly distributed by the tracks. The total current through conductors of 100 A was used in calculations.

Magnetic induction at a height of 1.5 m above the ground is lower than 2.6 μT. For the total current of 600 A value of magnetic induction does not exceed 15.6 μT which is only 40% of the lower limit value.

3.4 Measures for Reduction of Electric and Magnetic Field

The electric field in the electric traction system is

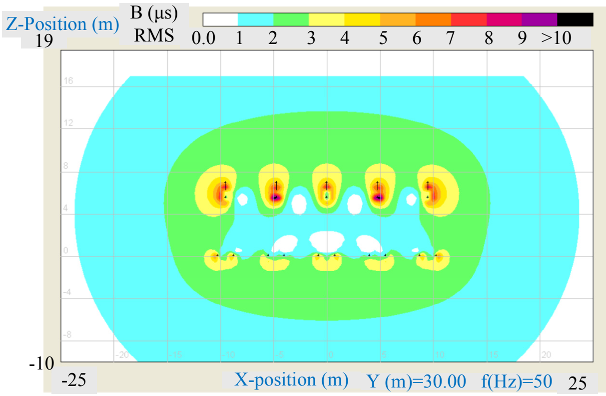

Fig. 8 Distribution of the magnetic induction at the railway station.

relatively stable because the voltage on overhead line does not change significantly. However, the electric field can be easily eliminated by installing metal bulkhead between the overhead line and space in which people reside.

The level of magnetic field depends on current in the overhead line. By correction of timetable and operation mode of the trains it is possible to reduce the energy consumption which results in less current in electric traction system [14]. Installation of parallel return conductor above overhead line has significant positive effect on the reduction of magnetic induction in the vicinity of electrified railway [15].

Further research in this field will analyze the factors which have influence on electric and magnetic field in electric traction system.

4. Induced Voltage on Undergrounded Pipeline in the Vicinity of Traction Overhead Line

Voltage can be induced on all ungrounded metal structures which are located in the vicinity of electric or magnetic field source. The value of induced voltage on pipeline can reach significant value, because pipelines and railway corridors often have a same parallel route. Induced voltages were analyzed on buried pipeline in case of short circuit on overhead line in electric traction system. Ungrounded pipelines are grounded every 1 km or more. Voltage cannot be induced on buried pipeline due to electric field because of ground conductivity.

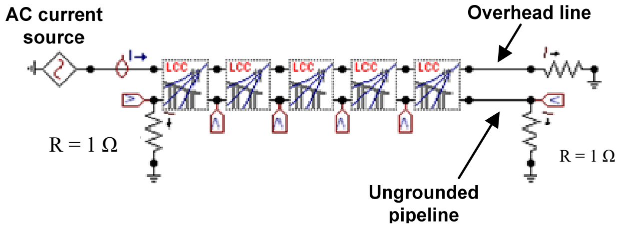

Fig. 9 EMTP model for calculation of induced voltages on ungrounded buried pipeline.

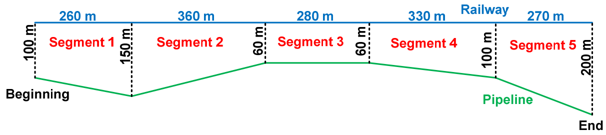

Fig. 10 Distances from buried pipeline to electric traction system.

The calculation was carried out by EMTP (electro magnetic transient program)/ATP (alternative transient program) software. Overhead line and pipeline were modelled using π model in LCC (line-cable constant) module as presented in Fig. 9.

Fig. 10 shows the part of the corridor with total length of 1,500 m and all distances required for induced voltage calculation.

Pipeline corridor was divided in five segments. Each segment was modelled with single LCC module. Since the distance between the pipeline and overhead line is not constant, geometric mean distance was used in calculations. The height of contact conductor is 5.5 m and radius 10 mm. Ground resistivity is 500 Ωm on the operation frequency of 50 Hz. Inner radius of pipeline is 19.13 mm and outer 20.32 mm [16]. Short circuit current of 5 kA was used in calculations. In the next paragraphs the results for different grounding conditions of pipeline is presented.

4.1 Pipeline earthed at the Beginning

Pipeline is earthed over the 1 Ω resistance only at the beginning so the induced voltage increases with distance (Fig. 11). The induced voltage (U_i) is highest at the end of the pipeline.

4.2 Pipeline Earthed at the End

Pipeline is earthed only at the end over the 1 Ω resistance so the induced voltage decreases with

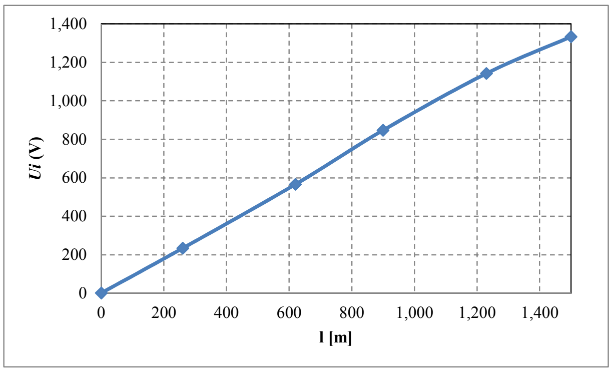

Fig. 11 Induced voltage–pipeline earthed at the beginning.

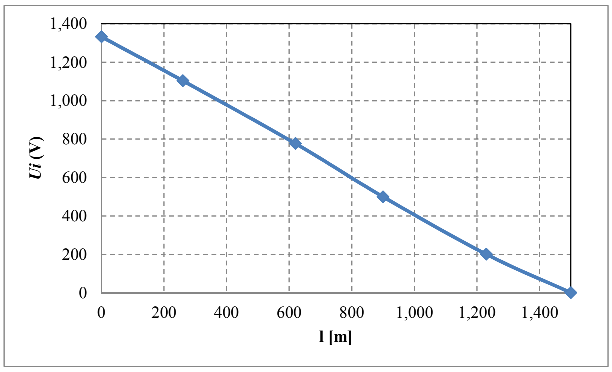

Fig. 12 Induced voltage–pipeline earthed at the end.

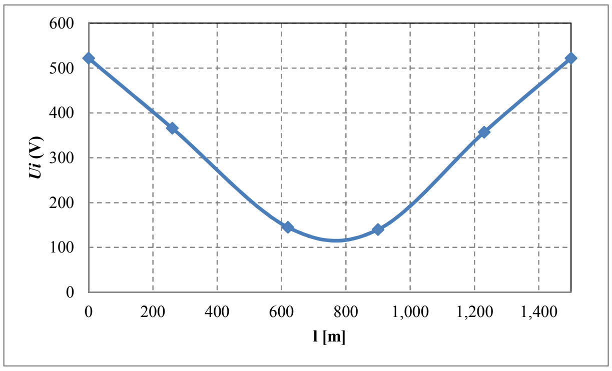

Fig. 13 Induced voltage – pipeline grounded at both ends.

distance (Fig. 12). The induced voltage is highest at the beginning of the pipeline.

4.3 Pipeline Earthed at Both Ends

Pipeline is earthed over the 1 Ω resistance at the both ends.

Induced voltages are highest at the beginning and at the end of the pipeline (Fig. 13). In case when pipeline is grounded at both ends induced voltages are lower compared to two previous cases.

The allowable voltage during the flow of power system frequency fault current is typically between 300 and 1,500 V [17]. In all three cases, the calculated values are within prescribed levels.

5. Conclusions

The values of electric and magnetic fields are limited by various regulations in order to prevent eventual adverse effects on humans. In this paper, electric and magnetic fields were calculated in the vicinity of 25 kV (50 Hz) overhead lines which is a part of electric traction system. Calculation results were compared with the limits specified by safety guidelines and regulations. Calculated electric and magnetic fields are within the limits. Some of the possible countermeasures for reduction of electric and magnetic fields were proposed.

In the second part of the paper induced voltages on the buried pipeline were calculated in case of short circuit on overhead line in electric traction system. Various cases of pipeline grounding were analyzed. Calculation results showed that the optimum position of grounding is at both ends of the pipeline.

Further research will be focused on analysis of various factors which have influence on calculation of electric and magnetic field in electric traction system. Accuracy of the model for calculation of induced voltages can be improved by increasing the number of segments used for modelling of buried pipeline and overhead line.

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