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Inductive influence of 25 kV, 50 Hz electrified single rail traction system

Bosko Milesevic[1,*], and *Ivo* Uglesic[2]

[1]Energy Institute Hrvoje Pozar, Transmission and Distribution Department, Savska 163, 10000, Zagreb, Croatia
[2]University of Zagreb, Faculty of Electrical Engineering and Computing, Unska 3, 10000, Zagreb, Croatia

Abstract. The paper presents the methodology for calculation and measurement of induced voltage caused by railway system operation on the sensitive metallic structures. The arrangement and characteristics of railway system 25 kV, 50 Hz are provided. The procedures of short-circuit current calculation and supply current measurement in the railway system are described. The basic theoretic background of inductive interference is explained. The reduction factors of the communication cable, railway system and environment are mentioned and clarified. On a case study, the results of the induced voltage calculation and measurement is compared. It is proved that induced voltage directly depends of supply current or short-circuit value.

1 Introduction

Electrified traction system enables the transport of people and goods using clean electric energy. The electric energy is transmitted from traction substation to the vehicles through contact network. The current on the contact wire and catenary conductor varies in dependence of the vehicle number and types. Those current is limited by wire's characteristics.

The paper presents the arrangement of 25 kV, 50 Hz single rail traction system supplied from traction substation. The basic characteristics of the system are presented including the electric parameters of traction substation, contact network and the rails [1]. In order to determine the current and voltage conditions on the contact network in the nominal operation conditions, it is necessary to know the types of traction vehicles operating on observed system. The short-circuit current value is calculated from the values of line-to-ground short-circuit current and three-phases short-circuit current at the busses of the power substation which supplies the railway system.

The railway network may also have a return conductor installed on the masts of the contact network and connected to the rails. Its function is important for the current which flow from traction vehicle to the traction substation. The railway system 25 kV, 50 Hz is a single-phase system and it is asymmetric comparing with the power grid. This can affect to the power quality parameters in the high voltage transmission network, but also to the values of power frequency electric and magnetic fields in the vicinity of railway system. The current which returns from traction vehicle to the traction substation has an opposite direction than supply current, so the increase of return current value can affect to the reduction of the magnetic field [2], [3].

Electric railway, as an asymmetric system, has a considerable influence on the sensitive metallic structures located in the same corridor [4]. While the capacitive influence due to 25 kV voltage on the contact network can be neglected, the inductive influence is very important and it should be considered during the normal operation conditions and in the case of line-to-ground short-circuit in contact network for a new lines and reconstructed lines [5], [6].

This paper presents a procedure for the calculation of short-circuit current in the contact network with the known short-circuit currents of the power grid. The curve of the short-circuit current value is determined depending on the distance from the traction substation.

The methods of induced voltage calculation on the sensitive metallic structures in the electrified railway corridor is shown in the case of short-circuit in contact network. The calculation is performed for the communication line in the accordance with international standards. The obtained induced voltage is compared with the limits [5], [6].

2 Railway system 25 kV, 50 Hz arrangement and characteristics

The operation of a single-phase 25 kV (50 Hz) electric traction system is significantly different from the three-phase electric power system which supplies it [1].

Electric traction system is supplied from power transformers located at traction power substation (TPS). These transformers are connected to two phases of the

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[*] Corresponding author: bosko.milesevic@fer.hr

three-phase 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 [7].

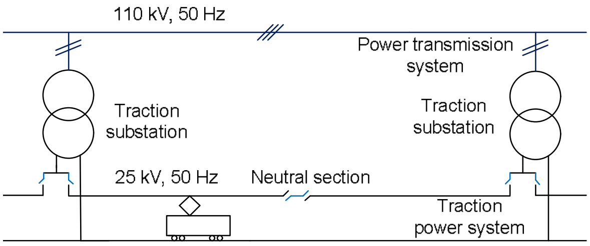

Fig. 1. Electric traction system.

2.1 Current flow in the railway system

Locomotives are supplied with electrical energy through power transformers 110/25 kV. Traction supply network consists of conductors placed above the railway [8]. 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 and ground back in the traction substation [9]. Currents directions are depicted in Fig. 2.

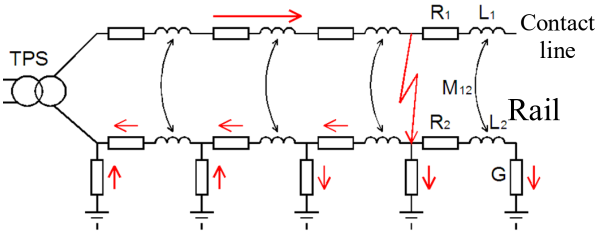

Fig. 2. Current directions in AC railway system.

The values of each current component are crucial for magnetic field distribution around the railway system and indirectly for magnetic coupling. The reduction of magnetic coupling between the railway system and sensitive structures is used into account by reduction factors what is explained in next paragraph.

2.2 Current calculation and distribution in railway system

The calculations of the maximal short-circuit current in the contact network should be performed to determine induce voltage. The impact of the electric power grid is modelled based on the results of three-phase and single-phase short-circuit current calculation on the 110 kV busbars of the traction power substation. Since the short-circuit in traction system is represented as double-phase short-circuit in 110 kV power network (Fig. 1) it is necessary to find the value of positive and negative sequence of equivalent impedance of power grid. Assuming that the negative sequence impedance and positive sequence impedance have the same values, it can be shown that the values of equivalent impedances calculated from double-phase short-circuit current and from three-phase short-circuit current have the same value. The equivalent impedance of power grid can be calculated from equations (1) and (2) using the values of three-phase short-circuit current value and the values of double-phase short-circuit current value respectively [10]:

$$Z_{m3} = \frac{1.1 \cdot U_n}{\sqrt{3} \cdot I_{K3}} \tag{1}$$

$$Z_{m2} = \frac{1.1 \cdot U_n}{2 \cdot I_{K2}} \tag{2}$$

where the U_n is the nominal voltage 110 kV, I_{K3} is the three-phase short-circuit current and I_{K2} is the double-phase short-circuit current.

According to well-known ratio of three-phase and double-phase short-circuit values [11]:

$$\frac{I_{K3}}{I_{K2}} = \frac{2}{\sqrt{3}} \tag{3}$$

and incorporating this ratio to equations (1) and (2), it can be shown that the values of equivalent impedances Z_{m3} and Z_{m2} are equal so the value of equivalent impedance of power grid impedance can be calculated directly from the value of three-phase short-circuit current. The impedances Z_T and Z_{KM} represents traction transformer and contact network. The impedance of contact network is a complex number given in [Ω/m]. The impedance Z_{KM} depends on network geometry, conductor materials and soil resistivity.

Equivalent electrical scheme for short-circuit current value calculation in contact network is presented in Fig. 3. Contact network is connected to power grid through two traction transformers 110/27.5 ± 10 x 1,5 % kV, u_k=10%.

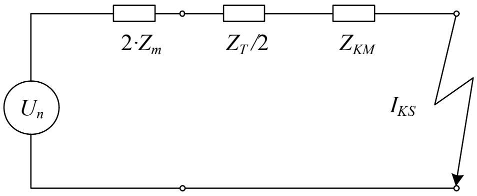

Fig. 3. Equivalent electrical scheme for short-circuit current value calculation.

The impedance of the traction transformers has been determined by its nominal parameters i.e. total power (S_n), voltage level (U_n) and short-circuit voltage (u_k). The impedance of usual traction transformer S_n = 7.5 MVA, u_k=10% is j9.363 Ω.

Now, it is possible to calculate short-circuit current for each point of contact network:

$$I_{KS} = \frac{U_n}{2 \cdot Z_m + 0.5 \cdot Z_T + Z_{KM} \cdot l} \tag{4}$$

where the l is length from traction substation and observed point on contact network.

To determine the maximum short-circuit current, it is assumed that two traction transformers are in operation.

The part of return current that flows through rails depends on parameters such as train distance from substation, rail-to-earth conductance, number of rails which conduct the return current, single or double track line, soil resistivity, etc. In the middle part between the traction vehicle and substation, the return current is 45%-50% of supply current (Fig. 4). The calculations are based on model shown in Fig. 2 and performed in electromagnetic transient program [12], [13].

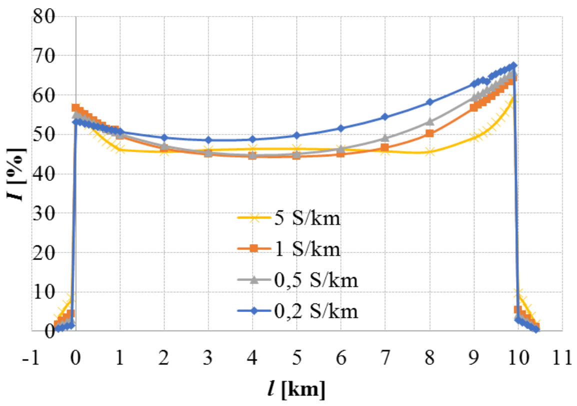

Fig. 4. Return current in rails depending on rails conductance.

3 Inductive interference

The calculations of induced voltages caused by inductive coupling between traction system and sensitive metallic structures should be performed in railway corridor 1 km wide.

For those calculations, the magnetic field distribution in case of short-circuit is a crucial parameter. The inductive coupling between metallic structures appears always when the magnetic field exist in the space. Only the AC magnetic field can induce voltage on the sensitive structure [14].

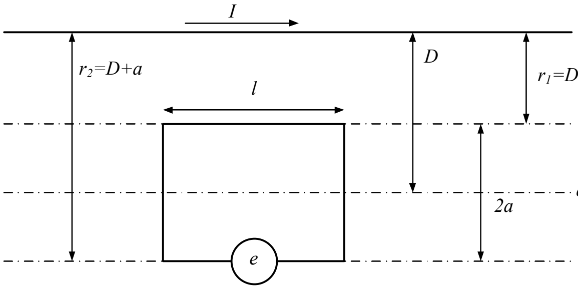

Fig. 5. Calculation of induced voltage caused by magnetic coupling.

The magnetic field that appears in the vicinity of the infinite long conductor is:

$$H = \frac{I}{2\pi r} \tag{5}$$

where the $I = I\,sin(\omega t)$ is the current through the conductor and r is a distance from conductor.

Magnetic flux through the surface S (Fig. 5), caused by magnetic field H, is:

$$\Phi = \iint_S \mu_0 \mu_r H \cdot \vec{n} \cdot \overrightarrow{dS} \tag{6}$$

where the μ_0 is permeability constant of vacuum, μ_r is the relative permeability of the space, $\vec{n}$ and $d\vec{S}$ are the unit length vectors on the surface.

It can be written:

$$\Phi = \iint_S \mu_0 \mu_r H \cdot \vec{n} \cdot \overrightarrow{dS} =$$

$$= \mu_0 \mu_r l \int_{D-a}^{D+a} \frac{I}{2\pi r} dr = \frac{\mu_0 \mu_r l \cdot I_0 \sin(\omega t)}{2\pi} \ln \frac{D+a}{D-a} \tag{7}$$

So, the induced voltage is:

$$e = -\frac{d\Phi}{dt} = \frac{\mu_0 \mu_r l \cdot I_0 \omega \cos(\omega t)}{2\pi} \ln \frac{D+a}{D-a} =$$

$$= -\omega \cdot M \cdot I \cos(\omega t) \tag{8}$$

where $M = \frac{\mu_0 \mu_r l}{2\pi} \cdot \ln \frac{D+a}{D-a}$ is a mutual inductance between metallic structures.

So, the calculation of induced voltage can be performed using the equation:

$$U_i = 2\pi f \cdot M \cdot I_{KS} \cdot l \cdot r_x \tag{9}$$

where the f is nominal frequency, M mutual impedance, I_{KS} short-circuit current and r_x reduction factor.

3.1. Mutual impedance and reduction factor

The contact network and communication line can spread in parallel or can be approaching (Fig. 6). The parallel spread implies that distance change in 5% of the mean arithmetic value of the minimum and the maximum distance on each section (Fig. 7).

Aslant approaching is depicted in Fig. 6 [6]. The mean arithmetic distance is used in calculation with the condition that maximum distance do not excide three times of the minimum i.e. $1/3 \leq a_1/a_2 \leq 3$. If the ratio excides 3, more section should be used.

The mutual inductance of two electrical circuits with the ground as return conductor is very complex to be exactly mathematically expressed. Therefore, approximate equations based on measurements are used. The soil specific resistance has a significant impact on the mutual inductance value because the return current flows through the ground.

The mutual inductance for the frequency 50 Hz depending on the distance between the two circuits and soil specific resistance is given in [5], [7].

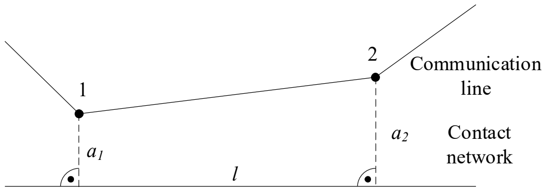

Fig. 6. Determination of the equivalent distance of the communication line from the contact network.

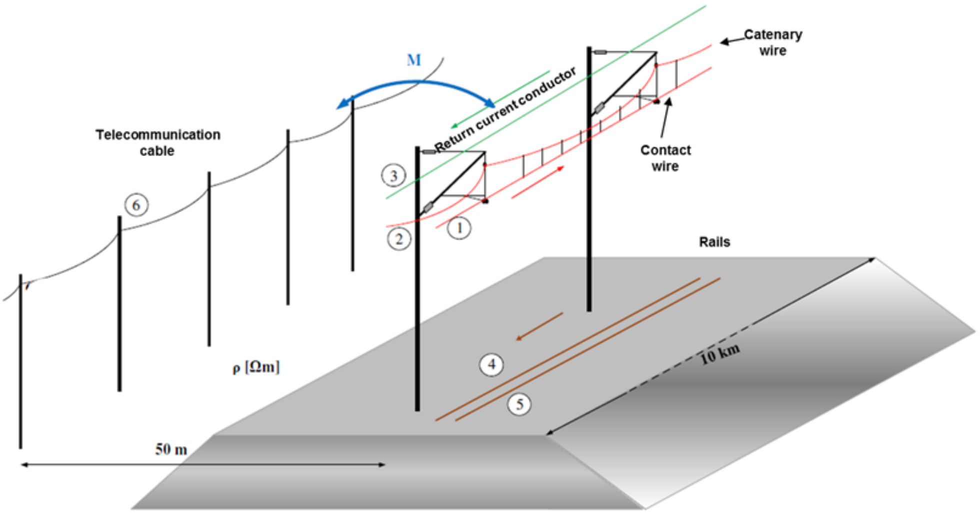

Fig. 7. Inductive coupling in railway system.

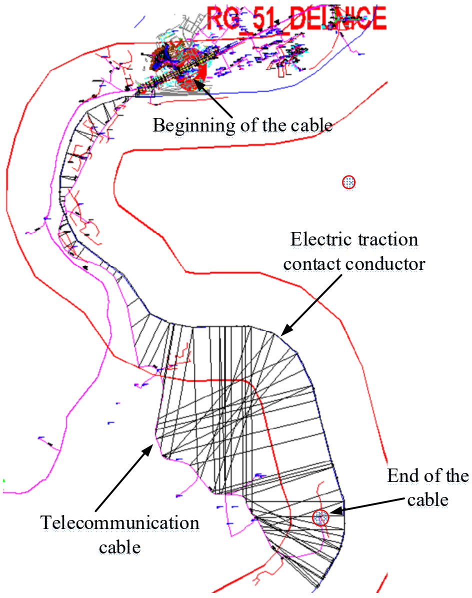

Fig. 8. Position of railway system and communication line.

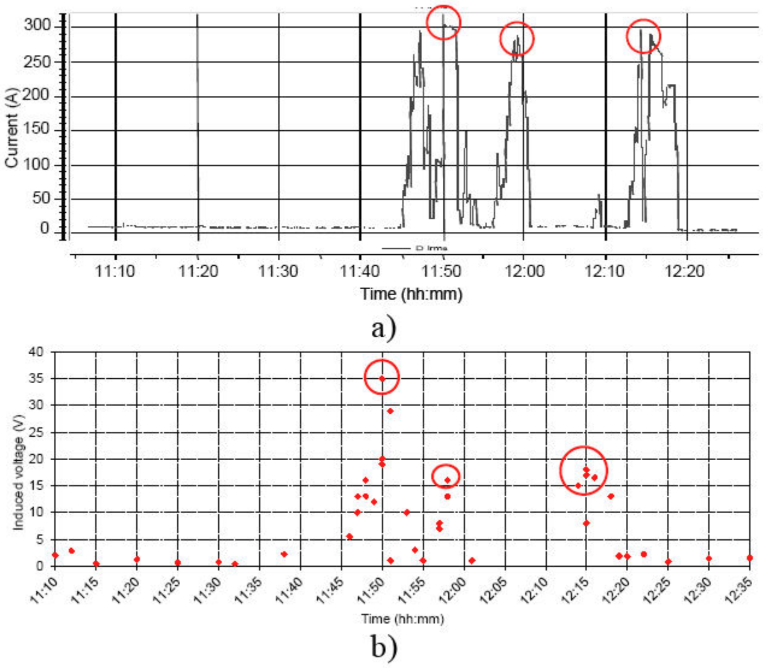

Fig. 9. The current in traction contact conductor and corresponding induced voltage

The resulting induced voltage reduction factor consists of the reduction factor of rails r_T, the reduction factor of return conductor r_p, the reduction factor of communication cable r_K and shielding factor r_Q:

$$r_x = r_T \cdot r_p \cdot r_K \cdot r_Q \qquad (10)$$

If it is possible, the reduction of the environment including threes, grass, other metallic structures etc. can be used.

The reduction factor of the rails r_T is dependent on the ratio of distance from contact wire to rails, the number of the rails, the return current value in the rails, the construction of the rails, the distance from traction substation, the soil specific resistance and other parameters. In the calculations, for the single rail system the r_T factor is used as 0.5 which means that about 50% of the return current flow through the rails.

According to the [5], the reduction factor of return conductor can be estimated with value 0.65.

The reduction factor of the communication cable is given in cable specifications. Diagrams and tables with this reduction is usually provided by the cable manufacturer.

4 Calculation and measurement of the induced voltage

The calculations are made according to the methodology and equations presented in previous paragraph. The measurements include determination of supply current and corresponding induce voltage. In Fig. 9 a) the effective value of current in contact network and in b) the induced voltage on sensitive structure is depicted. The measurements are performed by oscilloscope using the electrical scheme depicted in Fig. 10.

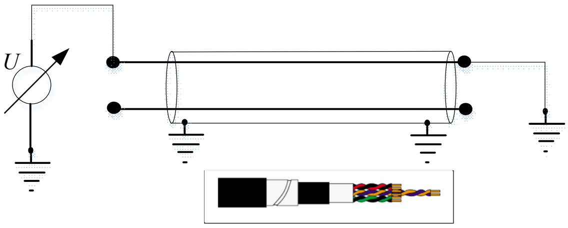

Fig. 10. The electrical setup for induced voltage measurement.

One of the cable wires is connected to the oscilloscope, while the others are idle. The cable sheath, if it exists, should be grounded. It can be easily concluded that the value of induced voltage directly depends on current as a source of perturbation.

The communication cable without armour (r_K=1) is laid in the north-south direction (Fig. 8). It is divided to the 75 sections and orthogonal projection to the rail is founded. The current in contact network was 300 A during the measurements so the same current value is used for calculations.

The induced voltage obtained by calculations was 47,3 V and by the measurements was 35 V. The graph of the induced voltage increase is shown in Fig. 11. The measured value is smaller than the equivalent calculated voltage. This fact is expected because the reduction factor of cable and environment is not considered.

It is recommended to measure the induced voltage on all cables where the calculated voltage exceeds the limit values.

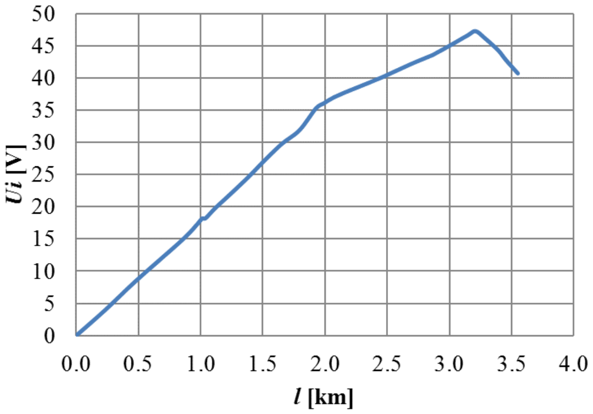

Fig. 11. Induced voltage rises on observed cable.

5 Conclusions

Electrical railway system 25 kV, 50 Hz is a single-phase asymmetric consumer of electrical energy that can significantly affect to sensitive metal structures by inducing voltage. In case of reconstruction of existing railway system or construction a new one it is necessary to check the impact of this system to communication lines.

The short-circuit current in railway system is changeable depending on the location of short-circuit point on the contact network. To determinate value of this current which affect to specific sensitive structures the value of short-circuit current in transmission system and the equivalent electrical scheme of railway system should be provided.

The coupling between the systems is dominantly inductive both in case of short-circuit and normal operation. International standards recommend the procedure for induced voltage calculation. Special attention should be devoted to reducing factors that are usually unknown and changeable. For all communication lines where the value of induced voltage exceeds limit values the measurement tests are recommended.

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