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Estimation of current distribution in the electric railway system in the EMTP-RV

Bosko Milesevic*, Bozidar Filipovic-Grcic, Ivo Uglesic, Bruno Jurisic

University of Zagreb, Faculty of electrical engineering and computing, Croatia

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ABSTRACT

Current distribution in the electric traction system is an important factor regarding the electromagnetic influences on the surrounding metallic structures. The current value directly determines the magnetic field and consequently coupling of the systems. A single rail traction system can be equipped with return conductor. The return current flowing through return conductor has an opposite direction of supply current and decreases coupling and interferences.

This paper presents the AC current distribution for both designs, with and without return conductor. Also, the soil resistivity is varied. The higher the soil resistivity, the higher is the amount of return current in rails and return conductor. The different construction of return conductor results in different impedance of return path. The relations of return conductor construction and return current value are analysed.

Lightning can directly impact different traction system elements such as contact network, tower or return wire. The current distributions in several cases of lightning impacting different traction system elements are presented.

1. Introduction

Electric railway systems have very heterogeneous constructions and power supply configurations. Generally, those systems can be divided with regard to their supply voltage to DC (1.5 kV and 3 kV) and AC (15 kV, 16.6 Hz; 25 kV, 50 Hz) [1,2]. The tracks can be realized as single-track, double-track and multi-track depending on the traffic demand and intensity. The electric traction vehicles are supplied from the contact network and the return current flows through the rails, return conductors and ground. The current in the electric railway system induces voltages in the surrounding metallic structures such as telecommunication lines and pipelines, [3–7].

The paper presents a model of 25 kV, 50 Hz railway supply system. The influence of railway system construction elements on return current distribution was analysed. The developed model enables the calculation of the rail impedance [8] and current distribution with respect to the rail cross-section. The conductivity of the rails is often unknown and its value varies along the rail route. Therefore, in the simulations, the rail conductivity should be varied in the wide range [9]. The distance between the traction vehicle and traction substation also determines the value of the return current in each return path. Different return conductors were considered including different cross-sections and materials such as copper and aluminium conductor steel reinforced. Also, the case without return conductor has been analysed.

The increase of the return current in the metallic structures in the vicinity of the tracks reduces the total magnetic field of the railway line. This reduces induced voltages in the surrounding metallic structures such as telecommunication lines and pipelines [10]. Induced voltages have many negative effects on underground gas pipelines, such as the possibility of creating electric spark or increase the corrosion of material [11]. The corrosion is caused either by leakage currents or by induced voltages in case of short circuit on the electric traction system. A spark can be dangerous if it penetrates the inside of the pipeline which is used for the transportation of flammable materials, while the corrosion destroys the pipeline itself [3].

A new approach for current distribution calculation is developed including both AC and lightning current. The models have been developed in the EMTP-RV for the estimation of the current distribution in the railway system in normal operation and in case of lightning impact. The system impedances were determined for different constructions of the railway line. The electrical and geometric parameters with the most significant impact on the current distribution were determined. The parametric analysis was performed to study the impact of conductor's cross-section, conductivity and soil resistivity on the current distribution.

* Corresponding author.
E-mail address: bosko.milesevic@fer.hr (B. Milesevic).

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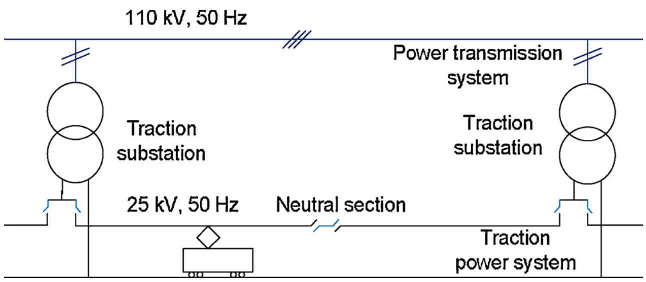

Fig. 1. Electric traction system.

2. Single rail system construction and operation

The 25 kV, 50 Hz railway supply system consists of railway traction substation, overhead contact line, bypass line, rails and return wire [1]. The grounding system of the rails is performed by connecting one or both rails to the grounded towers of contact network. Supply current flows through the contact network (contact wire and catenary conductor) and returns to traction substation. Current in each of those parts depends on numerous parameters.

Fig. 1 shows a typical 25 kV, 50 Hz electric traction system.

The electric traction system is supplied from the electric power transmission system through power transformers located at the traction substation. These transformers are connected to two phases of the power transmission system. The traction power supply network is separated by a neutral section in two parts which that are supplied from different traction substations.

The electric traction system is supplied with electrical energy through power transformers 110/25 kV. The traction supply network consists of the conductors placed above the rails (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 back through the rails.

The overhead line consists of a catenary conductor and contact wire which are connected. The locomotive pantograph slides over the contact conductor.

Catenary conductors are kept at a mechanical tension because the pantograph causes oscillations in the conductors 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. The 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 line. The nominal cross section of contact conductor is 100 mm^2, and catenary conductor is 65.8 mm^2. Since the distance between those two conductors is not constant, in EMTP (transmission line model in EMTP-RV) the height of the tower is 6.5 m and vertical height midspan is 6 m. At the temperature of 80 °C, the maximum operation current for the copper wires is limited to 4 A/mm^2. Therefore, the maximum operating 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 the ground [3].

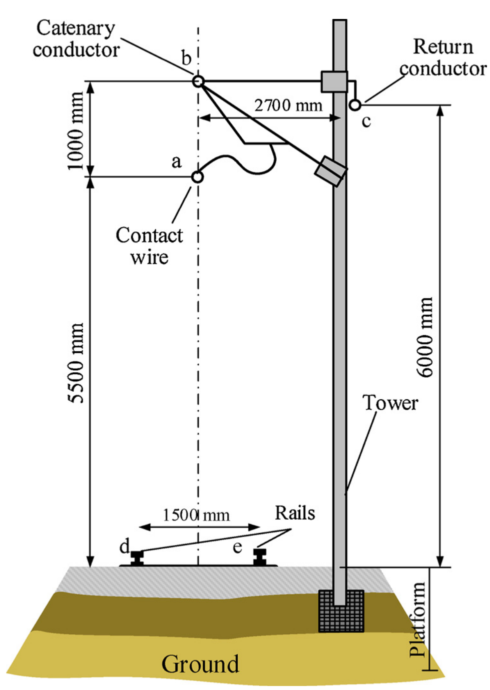

Fig. 2. Cross section of single-railed open railroad 25 kV, 50 Hz.

The electrical parameters of standard track UIC60 are used. The cross-section of each rail is 76.7 cm^2 so the diameter of equivalent cylinder is 9.88 cm.

Traction power network in the traction system consists of isolated sections in order to avoid the circulating currents that would occur between adjacent traction substations. Circulating currents could 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. EMTP model of railway system

The model of single rail 25 kV, 50 Hz traction system is developed. The traction section is represented by frequency dependent (FD) line model in EMTP considering the geometry of the system and soil resistivity. Rail conductivity is taken into account based on field measurements of tower footing resistance in the contact network.

13 km long section of the electric traction system is modelled, from electric traction substation to electric traction vehicle (locomotive). FD line model in EMTP-RV includes different values of soil resistivity, with and without return conductor. The geometry of the system is presented in Fig. 2. The distance of return conductor from rail axes is 2.7 m.

The model was developed for two values of soil resistivity, 100 Ωm and 1000 Ωm. Soil resistivity and rail to ground conductivity values are parameters that are variable and have a different value in each traction part. The model is divided into segments of different lengths. Next to the traction substation and traction vehicle each segment has a length of 100 m, and in the other parts of the model the length of the segments are 1000 m.

In this paper the average ground conductivity of 1 S/km was assumed. The current source is connected directly to catenary conductor and contact wire. The nominal current is 100 A corresponding to expected current on the single track sections. Moreover, the Cigre concave lightning current source is added in the model. In the first case, it was connected to contact line and in the second case to return the conductor.

The part of model next to current source representing electric traction substation is shown in Fig. 3.

Traction substation is presented by AC current source and traction vehicle by RL element. Since in this paper only the magnetic coupling and current distribution is studied, the type of the traction vehicle is not crucial for simulations. More sophisticated models of rotating machine such as detailed winding model should be used in case when it is necessary to compute voltage distribution along the machine winding, which is not considered in this paper.

Sensitive line is incorporated in FD line model in the first kilometre next to the substation. The distance between source and load is 12 km but additional 1 km of the line is connected at both sides. The current I_{railRO2} flows through the rails out of the supply segment and penetrates

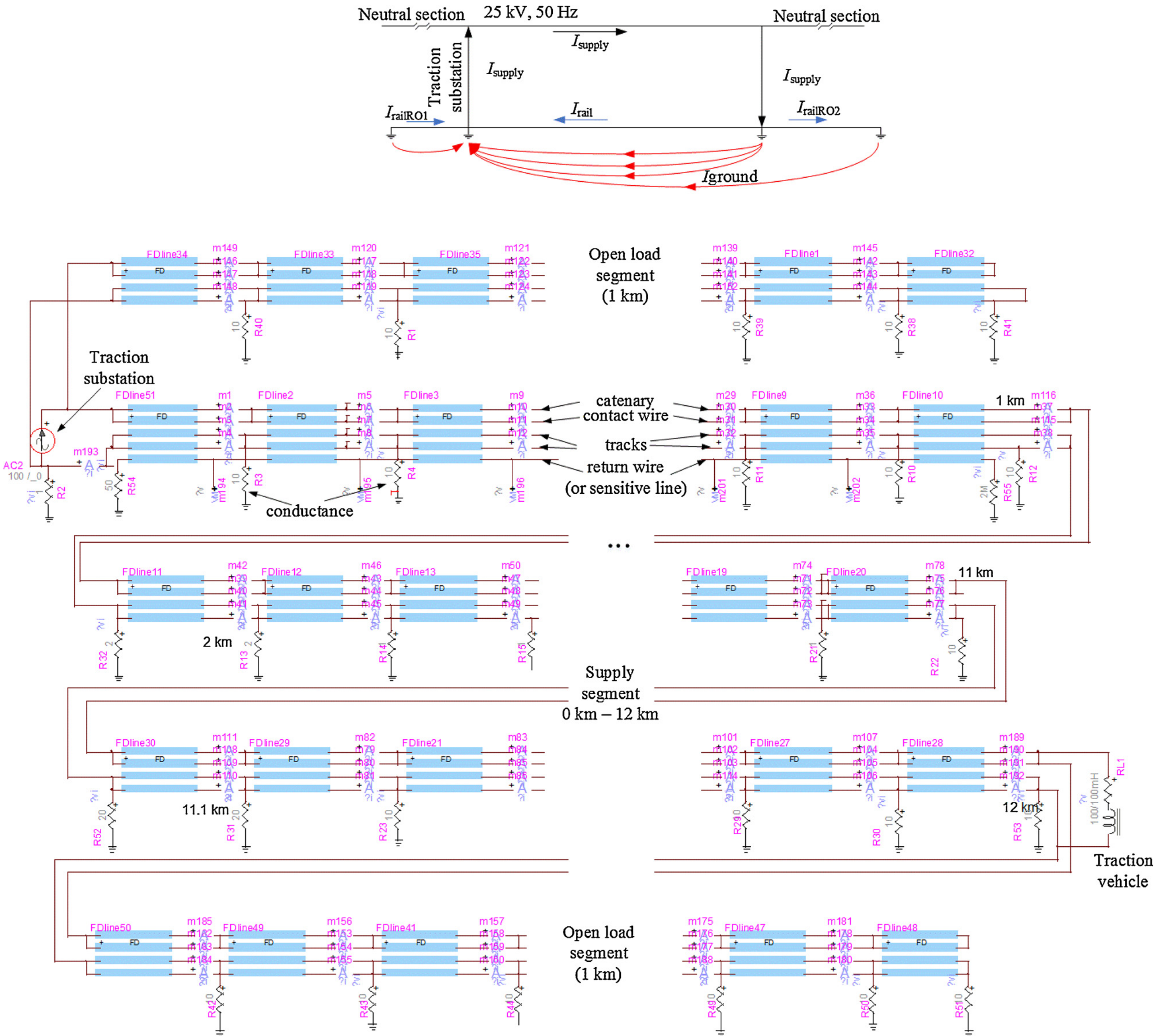

Fig. 3. Model of single-railed open railroad 25 kV, 50 Hz in EMTP.

to the ground. At the same time the current return to the substation through the rails in segment (I_{rails}) but also through the rails out of segment because of existing rail admittance ($I_{railRO1}$).

4. Current distribution in normal operation conditions

During the normal operation, the contact line is connected to an electric traction transformer. The supply current flows to consumer (electric vehicle) and returns through rails, return conductor and ground. The value of supply current is almost constant but the values of return currents are varying. The aim is to determine the values of current flowing through the rails, return conductor and ground. Therefore, the currents are calculated between each segment and the current variations are presented.

4.1. Single rail without return conductor

Electrified railways operate without return wire in the cases where the expected load is not so high. All the return current flows through rails and ground. The distribution of the return current depending on the soil resistivity is shown in Fig. 4.

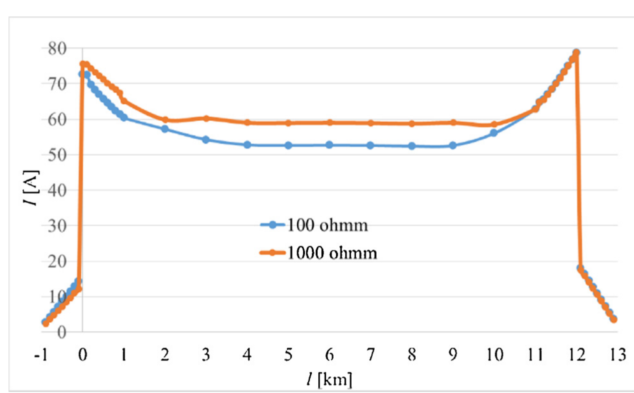

Fig. 4. Total return current in the rails on the system without return wire depending on soil resistivity.

The return current in the rails next to electric traction substation and locomotive is about 75% of the supply current and it decreases with a distance from the contact points. Return current amplitude changes significantly only next to the traction substation and traction vehicle. At the middle of the supply segment the return current value is almost

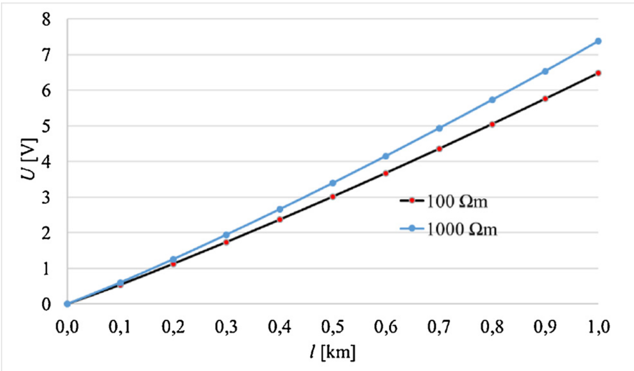

Fig. 5. Induced voltage on sensitive telecommunication line in case when railway system is not equipped with return conductor.

constant. It reaches 53% of the supply current when soil resistivity is 100 Ωm and 59% of the supply current when soil resistivity is 1000 Ωm. It is clear that the increase of soil resistivity results with higher value of return current. The return current in the rails out of supply segment (open load segment) is small but also increases by approaching the electric traction substation and traction vehicle.

A sensitive communication line has been set at the distance of 25 m from the railway line to verify the magnetic coupling. The induced voltage on the line is calculated using the FD line model. The communication line has been modelled in the first kilometre (ten FD line segments) and terminated by resistance of 2 MΩ. The soil resistivity of 100 Ωm and 1000 Ωm (worst case) was considered. Fig. 5 shows curves of induced voltage. The induced voltage is proportional to mutual inductance [12]. In the case when the soil resistivity is equal to 100 Ωm, the induced voltage and mutual inductance are 13.8% and 25.3% lower than in the case with 1000 Ωm, respectively. Although the induced voltage is proportional to mutual inductance, the percentage reduction is 11.5% lower because it is affected by increase of the return current.

4.2. Single rail with return conductor

Return conductor can be installed and directly connected to the contact network towers. Usually at least one rail is earthed by connection to tower fundament, so the return conductor has the same potential as rails. In this paper, it is assumed that both rails are earthed.

In the case with return conductor the impedance of return path is lower and the amount of return current is higher than in the case without return conductor.

The impedance of the rails has almost a constant value. It depends on the temperature and soil resistivity but the material and cross-section are always the same for the typical track construction. At the same time, the return conductor has a few typical constructions. In Table 1 the typical return conductor data are specified for the different constructions. For each material, the typical cross-section, radius, DC resistance and impedance are given.

The real part of the impedance depends directly on the material and radius of the return conductor, while the reactance is almost the same for all constructions. That means that the current in the return conductor has a low dependence on the construction of return conductor.

Table 1
Return conductor typical construction and electric parameters.

Material and cross-section	S [mm^2]	r [mm]	R [Ω/km]	Z [Ω/km]
Bronze 65 mm^2	65.8	5.25	0.3860	0.3860 + j0.753
ACSR 95 mm^2	93.3	6.25	0.4898	0.4898 + j0.742
ACSR 150/25 mm^2	173.1	8.55	0.1939	0.1939 + j0.723
Copper 95 mm^2	93.3	6.25	0.1949	0.1949 + j0.742

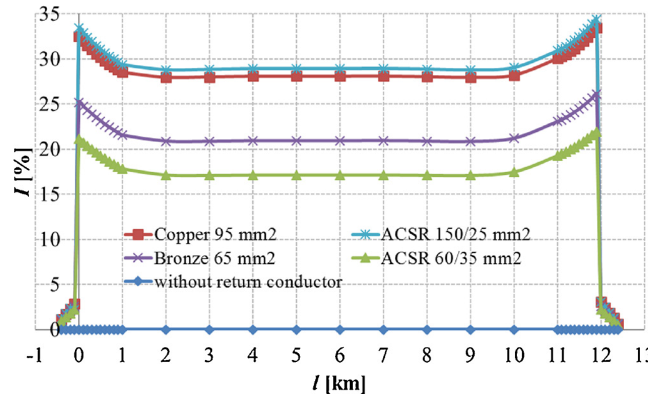

Fig. 6. Return current in the return conductors depending on conductor type.

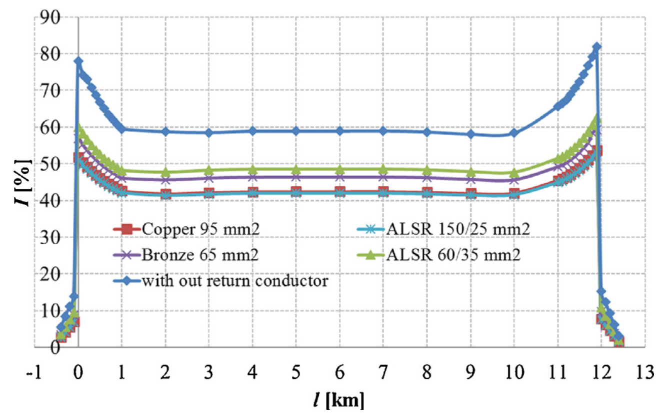

Fig. 7. Return current in the rails depending on return conductor type.

The different types of return conductors used in the railway system determine return current values as it is presented in Figs. 6 and 7. Depending on the material and return conductor cross section the total return current in the return conductor varies from 17% to 29% of the supply current (Fig. 6). The return current in the rails varies from 42% to 49%. As it is depicted in Fig. 7, the higher is the value of current in the return conductor, the smaller is the current through the rails.

The total return current value is higher if the impedance of the return conductor is smaller (Fig. 8). All the presented values are calculated for rail conductance 5 S/km. The total return current is from 59% in case without the return conductor to 71% in cases of low impedance of the return conductor (Cu 95 mm^2 and ALSR 150/25 mm^2).

Next to the traction substation and traction vehicle the return current in the rails and the return conductor has a value slightly smaller than the supply current. Some of the current is conducted to the ground

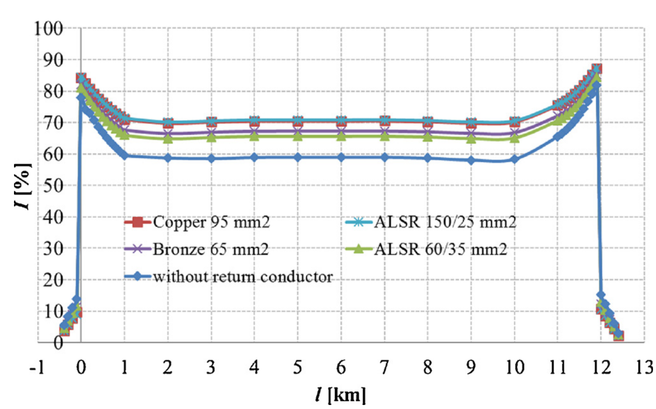

Fig. 8. Return current in the return conductors depending on conductor type.

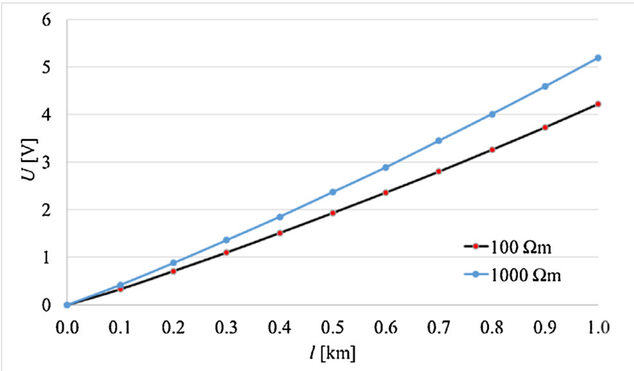

Fig. 9. Induced voltage on sensitive telecommunication line in case when railway system is equipped with return conductor.

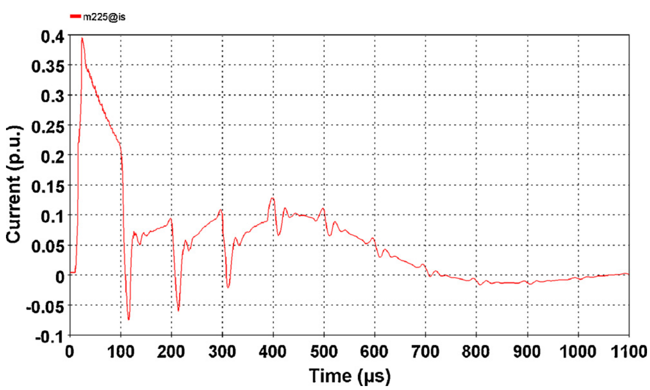

Fig. 10. Lightning current waveform next to the substation.

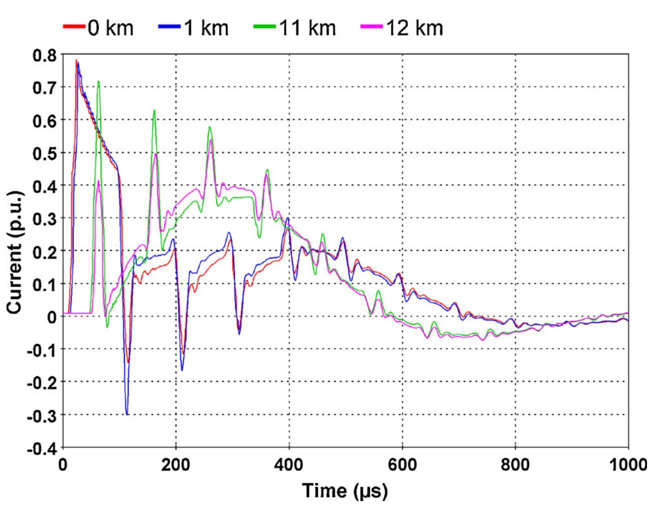

Fig. 11. Current waveforms on the different positions of contact network in case of lightning stroke next to the railway substation.

through the rails conductance and reaches almost constant value.

In this case, the induced voltage on the line is much lower in comparison with the case depicted in Fig. 5. For the soil resistivity of 1000 Ωm induced voltage is 54% lower (it decreases from 6.48 V to 4.22 V), and for 100 Ωm induced voltage is 42% lower (decrease from 7.38 V to 5.19 V). In Fig. 9 the curves of induced voltage on sensitive telecommunication line are presented in case when railway system is equipped with return conductor (bronze 65 mm^2).

The distance between supply conductors (contact wire and catenary conductor) and the return paths (return conductor and rails) is a few metres. The fact that two currents flow in the opposite way has the

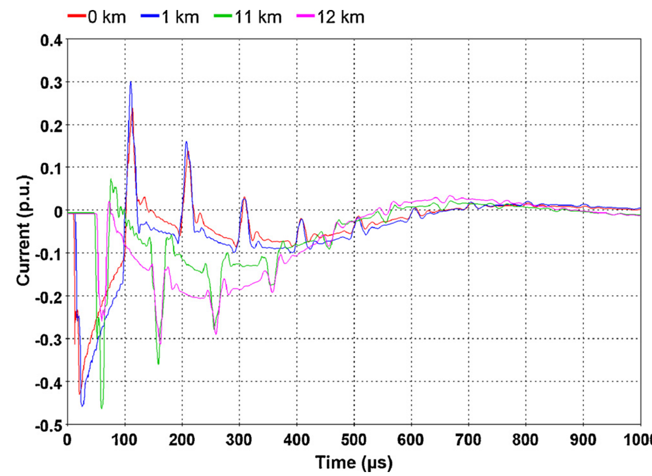

Fig. 12. Lightning current waveform on the different position of return path in case of impact next to the railway substation.

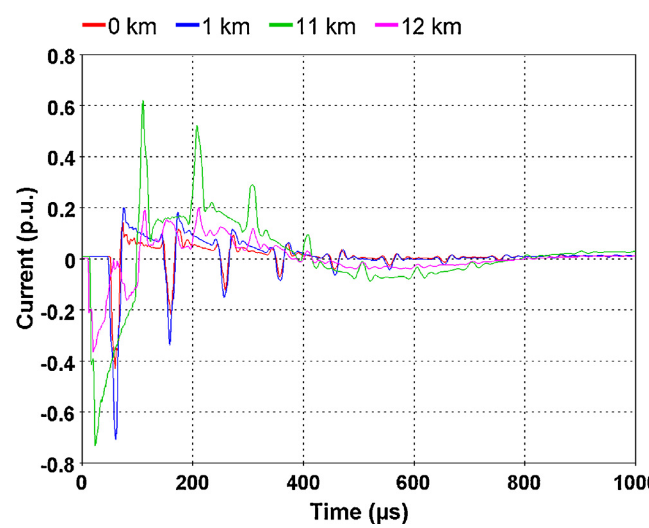

Fig. 13. Current waveforms on the different positions of contact network in case of lightning stroke next to the locomotive.

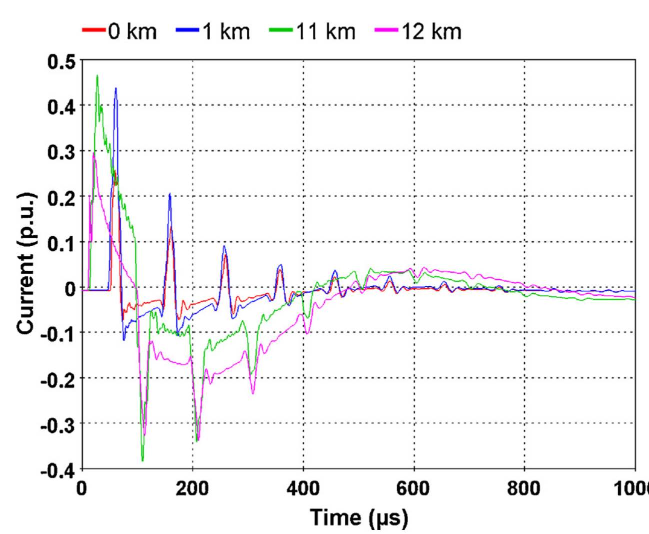

Fig. 14. Lightning current waveform on the different position of return path in case of impact next to the locomotive.

beneficial effects on electromagnetic coupling. The magnetic field values around the track decreases and the induced voltages in the sensitive circuits also decrease.

5. Current distribution in case of lightning stroke to railway line

Lightning stroke can occur at any point of the railway line. As can be seen from Fig. 2 the catenary conductor is directly exposed to lightning. The shielding effect of the return conductor, which can be considered as a ground wire on overhead line, is neglected. The towers of contact network can be a lightning terminal and down conductor.

Lightning current is modelled as Cigre concave lightning source connected directly to the catenary line (25 kV network). The current amplitude is 1 p.u., front time 1.2 μs, time to half value 50 μs and maximum steepness 9 p.u./μs. Since the goal was to obtain only the distribution of lightning current at 25 kV level, the part of railway network on the both sides from the impact point was modelled in detail, while the power transformer 25/110 kV can be neglected in the simulations.

The lightning current causes the potential rise and electromagnetic impulse propagation. For the electromagnetic compatibility calculations, it is important to know the current distribution through railway track elements. In this paragraph, the lightning stroke to catenary conductor is considered. The impact point is moved from the traction substation to the middle of the section and next to the locomotive. In all cases the current on the contact network (contact wire and catenary conductor), return conductor and rails are presented. The purpose of the model is to calculate lightning current distribution in the railway system including attenuation and reflections of the travelling waves.

Fig. 10 shows calculated lightning current waveform through catenary conductor at distance of 100 m away from the substation.

5.1. Current distribution in case of lightning stroke to contact network next to the railway substation

The lightning current source is connected to the point of AC current connection which corresponds to the lightning stroke to contact network next to the traction substation. The wave propagates through the line and attenuates.

Current waveforms are presented in Fig. 11. The first current measuring point is close to the impact point, just one FD line segment in direction of the locomotive. The first peak of current in catenary conductor and contact wire is 0.78 p.u. at the beginning of the segment. Almost the same value is in the contact network 1 km from impact point. On the long distance, 11 km from impact point is 0.71 p.u. in the first transit.

The model enables the calculation of current in the return circuit in case of lightning impact. In Fig. 12 the currents in rails and return conductor are depicted at the same distance as it is presented in Fig. 11. A current is induced in the return path as a consequence of a lightning stroke. In the first transit over current scopes it reaches 0.47 p.u. in the vicinity of the impact point and 0.14 p.u. close to the locomotive.

5.2. Current distribution in case of lightning stroke to contact network next to the locomotive

In this case the lightning current source is connected next to the locomotive. The fast front overvoltage wave propagates towards traction substation. The fast front current wave reaches the maximum value on the contact network elements near the impact point. In Fig. 13 the waveforms of current on contact network at different positions are presented. The maximum current value is 0.75 p.u. and it changes depending on distance, attenuations and reflections.

The currents in return paths (rails and return conductor) are depicted in Fig. 14. The total current in this paths reaches 0.47 p.u., the same as in the previous section.

Results show that an important amount of lightning current flows through rails and return conductor.

6. Conclusions

The paper presents the model for the estimation of current distribution in the electric railway system. The single track system is modelled with frequency dependent line segments in EMTP-RV software. The geometry of standard 25 kV, 50 Hz railway network is considered. Soil parameters are determined by field measurements. The model includes different constructions of railway network with and without the return conductor. The soil resistivity and rail conductance are varied parametrically.

While the supply AC current has a constant value, the return current changes at each point. At the points close to the traction substation and traction vehicle the return current in rails and return conductor is much higher than in the middle of the section. The magnetic field and induced voltages in sensitive circuits directly depend on the current value. The higher the value of return current, the lower is the magnetic field and induced voltage due to electromagnetic coupling effect. The magnetic field reduction is higher in the vicinity of the traction substation and traction vehicle.

The lightning stroke can occur at any point or element of the railway system. The most exposed elements are the tower, return conductor and catenary conductor. In all cases, the fast front current flows through conductors and rails which is attenuated and reflected at the points of discontinuity. Those currents affect the electromagnetic impulses that can cause voltage rise and potentially damage the sensitive circuits. Return paths reduce those effects and beneficially affects the system operation.

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