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Interaction between a DC Traction System and an AC Power System Through Earth-return Circuits

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Summary

The article describes a problem that occurs in electrified railway transportation, involving the interaction between the earth-return circuits of different power systems. One of the analysed circuits is the earth-return circuit of a high-voltage power grid, the other is the return path of a 3 kV DC traction power supply system. The paper presents the results of the field tests carried out so far and discusses a mathematical model developed in the Matlab-Simulink environment with the aim of determining the interaction between both of the said systems.

Keywords: earthing, traction substation, traction return system

1. Introduction

Earth-return circuits are all power circuits including earth in their structure. A phenomenon occurring in such circuits is the flow of electric current through the earth. In the domain of electrical engineering, the earth is defined as a homogeneous conductive half-space whose electric potential is assumed by default to equal zero at each of its points. At a particular – sufficient – depth, soil is considered reference soil, which means that its electric potential amounts to 0 at every point. This is an assumption adopted in energetics because despite the different soil resistivity levels, the cross section of such a "conductor" is infinite.

Every power supply line is a multi-element system, and earth is one of these elements. The author's experience with the analysis of traction power supply systems, the performed measurements in traction return systems, and the known case of faulty operation of railway and tramway traction substations motivate the author to propose the following research problem: There are interactions between the earth-return circuits of direct current traction systems and alternating current power supply systems. These interactions can be damaging, and may affect the reliability of the operation of both power supply systems.

The purpose of this article is to offer a presentation of the said research problem, make the reader familiar with the existing research conducted in the domain in question, and discuss a model developed in the Matlab-Simulink environment to simulate the interactions occurring between the two power supply systems.

2. Earth-return circuits in transmission grids

Professional energetics makes use of several types of transmission grids, as listed below. They differ in terms of the earthing effectiveness of the neutral points of power transformers as follows:

1. Power supply grids functioning with an effectively earthed neutral point of power transformers. These include high-voltage grids: 400 kV, 220 kV and 110 kV. 400 V low-voltage grids also function with an effectively earthed neutral point.
2. Power supply grids functioning with an ineffectively earthed neutral point of power transformers. These are medium-voltage grids: 30 kV, 20 kV, 15 kV and 6 kV. These grids are divided into grids with isolated neutral point and grids with earth fault current compensation involving the utilisation of a resistor or a Petersen coil.

Both structures include earth-return circuits whose specific feature is that the live conductors of

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these systems are isolated from the earth except for their terminals. Therefore, the currents in these conductors (in steady state) do not change over the distance from the power supply station point [5].

Another group of earth-return circuits are circuits whose live conductors are in contact with the earth along their entire length via a layer of insufficient insulation. An example of such an earth-return circuit is the return system in a DC traction power supply system. The currents in these conductors (running rails) change over the distance from the power supply station point [5].

3. Traction return system considered as an earth-return circuit

DC traction power supply systems are continuously being developed in order to meet the demands related to increased traffic and the growing power of traction vehicles. Traction substations are supplied with power via high-voltage transmission grids, and the traction substations' power levels are increased accordingly. As a result, the currents flowing in traction return systems reach high values, which leads to significant traction current leakages if the insulation is insufficient.

The value of the current flowing in a traction return system depends on: the power of the traction vehicles operated on a given route, the train sequence, the route profile, and the distances between traction substations. However, assuming that the above parameters are constant and that a traction vehicle draws a fixed amount of current along the entire route, the current in the traction return system will not have a fixed value as it also depends on the distance of the measurement point from the power supply substation and on the location of the traction vehicle on the line segment:

$$I_{SP} = f(L, L_{PT}),\ I_{PT} = const$$

Where:

I_{Sp} – current in the traction return system,
L – distance from the measurement point to the power supply substation,
L_{PT} – location of the traction vehicle on the powered section,
I_{PT} – traction vehicle current.

The main parameter determining the leakage of current from the traction return system over the distance from the power supply substation is the unit conductance of the traction return system, expressed in [S/km]. PN-EN 50122-2: 2011 [7] defines the acceptable levels of the traction return system unit conductance, considering the differences between cases of open track systems (ballast track and ballastless track, where rails are fixed above the track bed) and closed track systems (slabbed ballast track or rails sunk into the track bed). In the case of open-type track systems, the value of unit conductance should not exceed 0.5 S/km and the average rail potential should be less than or equal to +5 V; in the case of closed-type track systems, the unit conductance value should not exceed 2.5 S/km, and the average rail potential should be less than or equal to +1 V. When analysing traction return systems, evaluating the intensity of distribution of current leakage and the estimations of the values of earth faults and effective touch voltage may not be performed with the adoption of simplifications involving the unit conductance in a given traction return system being omitted [3, 6].

4. Field tests

The tests described herein involved examining the earth-return circuits located in close proximity to each other. One of the earth-return systems is a traction return system supplied with power from a 3 kV DC system. The other earth-return system is a set of earthed elements of a 110 kV power supply line powering a distribution substation located near the traction substation. The tested circuits along with their elements determining the values occurring in their interactions are presented in Figure 1.

The scope of the described tests involved, among others, recording the following: the voltage between the negative bus-bar (SM) and the main earthing busbar (GSU) of the traction substation, the current in the switch between SM and GSU, the current in the return cables. Results of typical measurement-taking sessions are shown in Figures 2, 3 and 4.

A compilation of the results of the performed measurements is provided in Table 1.

Upon analysing the obtained results, it is noticeable that in the cases with an earthed traction substation negative bus-bar, the stray currents flowing into the traction substation's negative bus-bar through the switch from the substation's main earthing busbar make up about 20% of the total traction current amount. The problem is particularly noticeable when the traction substation operates in the cabin mode, where the return currents flowing into the substation's negative bus-bar have relatively low values, i.e. approx. 400 A for cable group 1 and 220 A for cable group 2, and the value of the total traction current flowing into the negative bus-bar through the switch from the main earthing bus-bar is approx. 600 A.

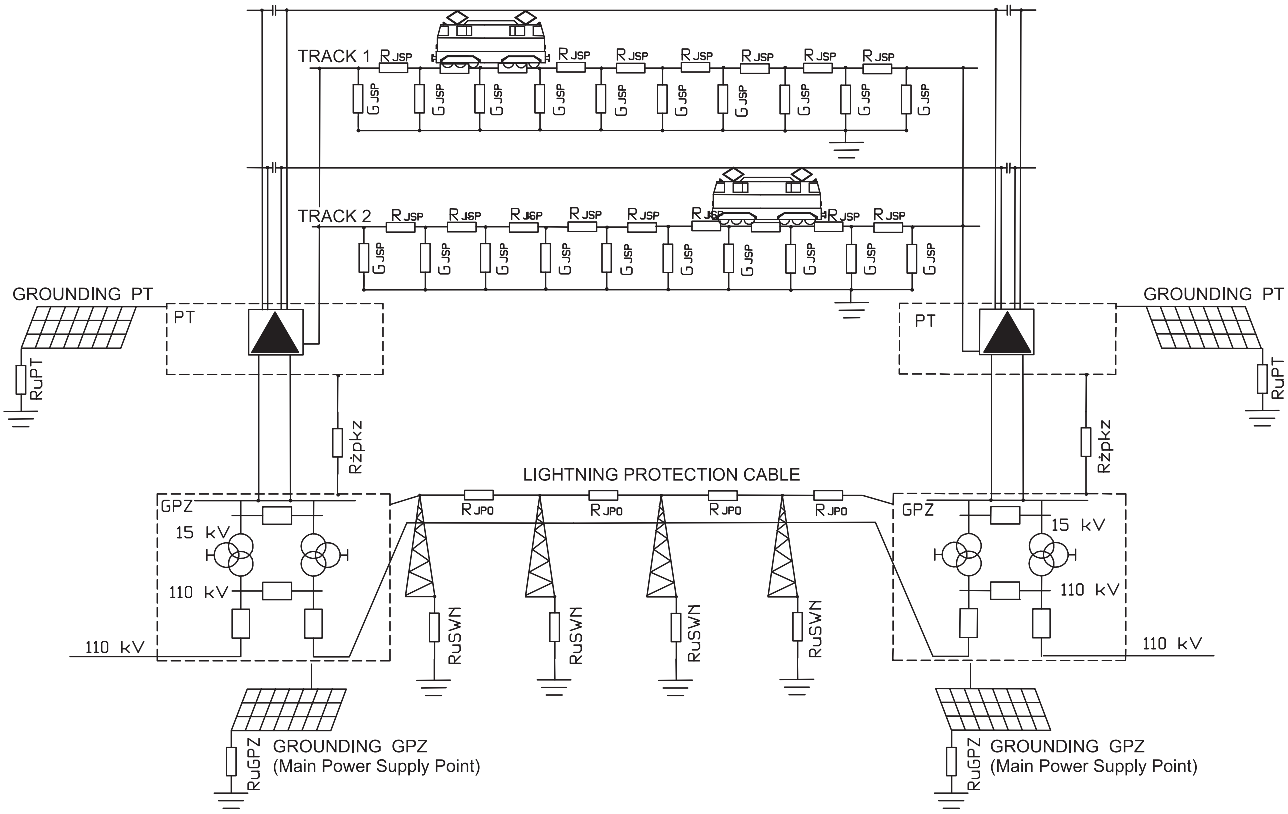

Fig. 1. The tested earth-return circuits: PT – traction substation, RJSP – earth-return system unit resistance, GJSP – earth-return system unit conductance, RuPT – traction substation earth resistance, GPZ – distribution substation, Rżpkz – resistance of metallic screens of power cables, RuGPZ – distribution substation earth resistance, RJPO – ground wire unit resistance, RuSWN – HV pole earth resistance [author's own work]

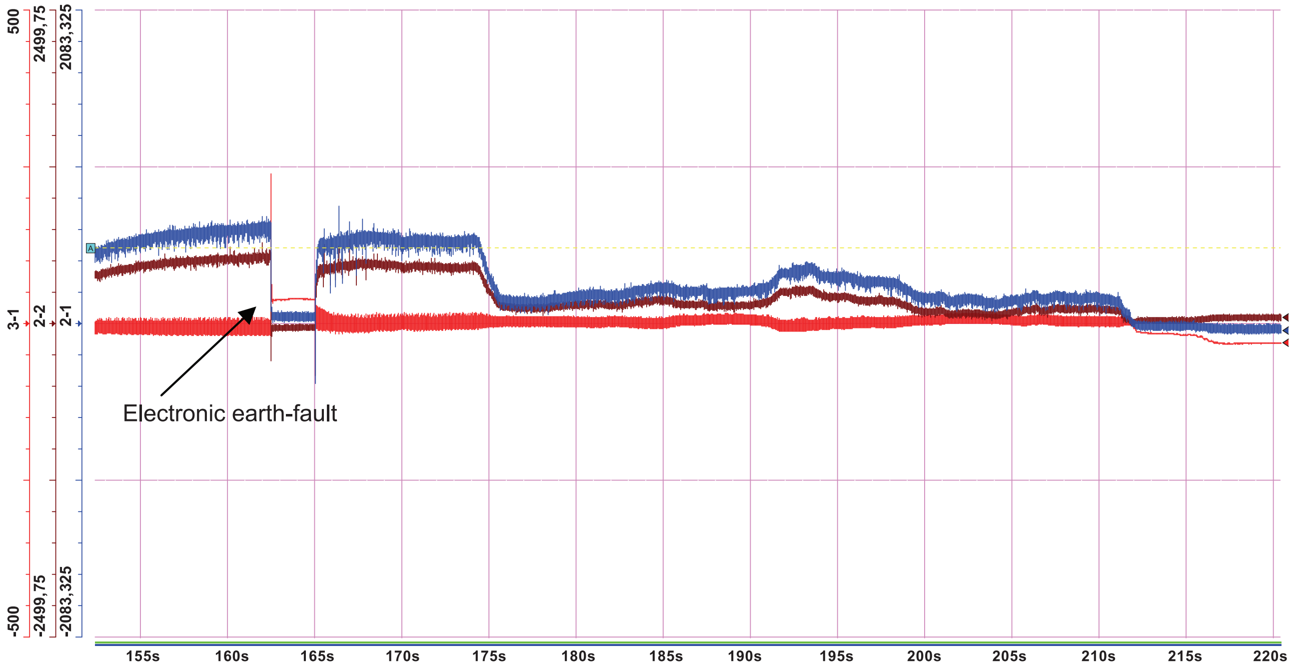

Fig. 2. An oscillogram of measurements performed during the operation of the traction substation with an unearthed negative bus-ba, ▬ CH2-1 return cable current – group 1, ▬ CH2-2 return cable current – group 2, ▬ CH3-1 electronic earth-fault protection device voltage [own elaboration]

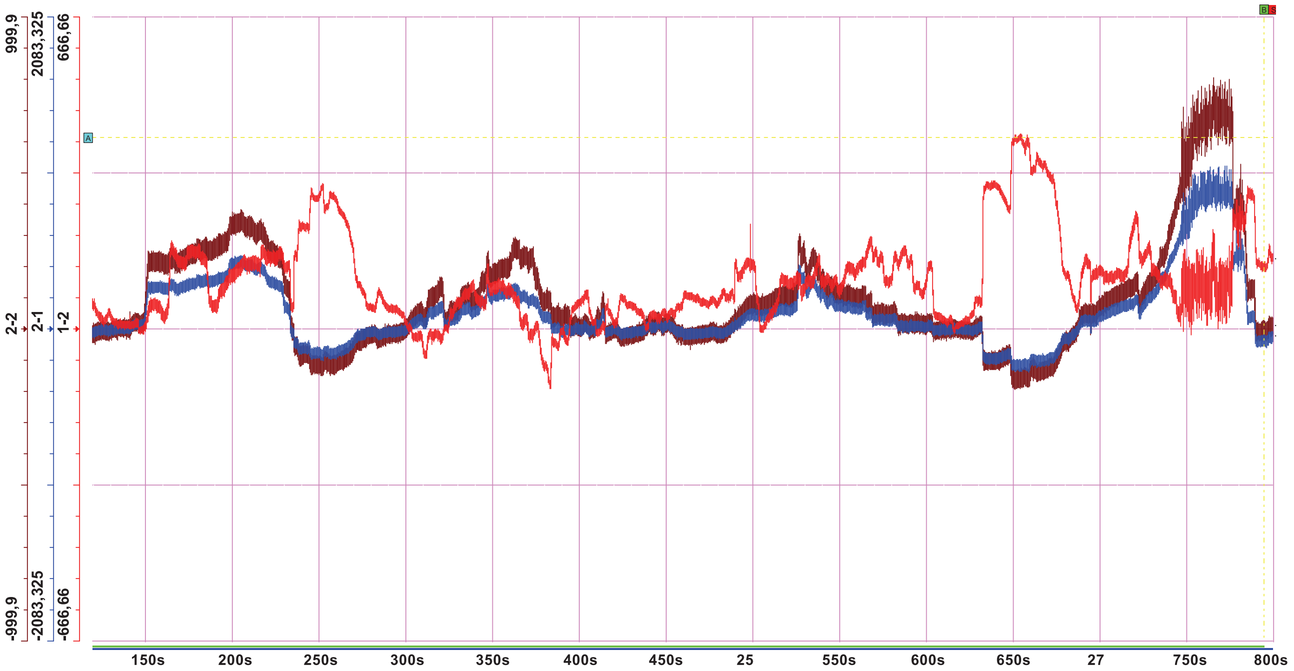

Fig. 3. An oscillogram of measurements performed during the operation of the traction substation with an earthed negative bus-bar, ▬ CH2-1 return cable current – group 1, ▬ CH2-2 return cable current – group 2, ▬ CH1-2 traction current flowing into the negative bus-bar through the switch from the substation's main earthing bus-bar [own elaboration]

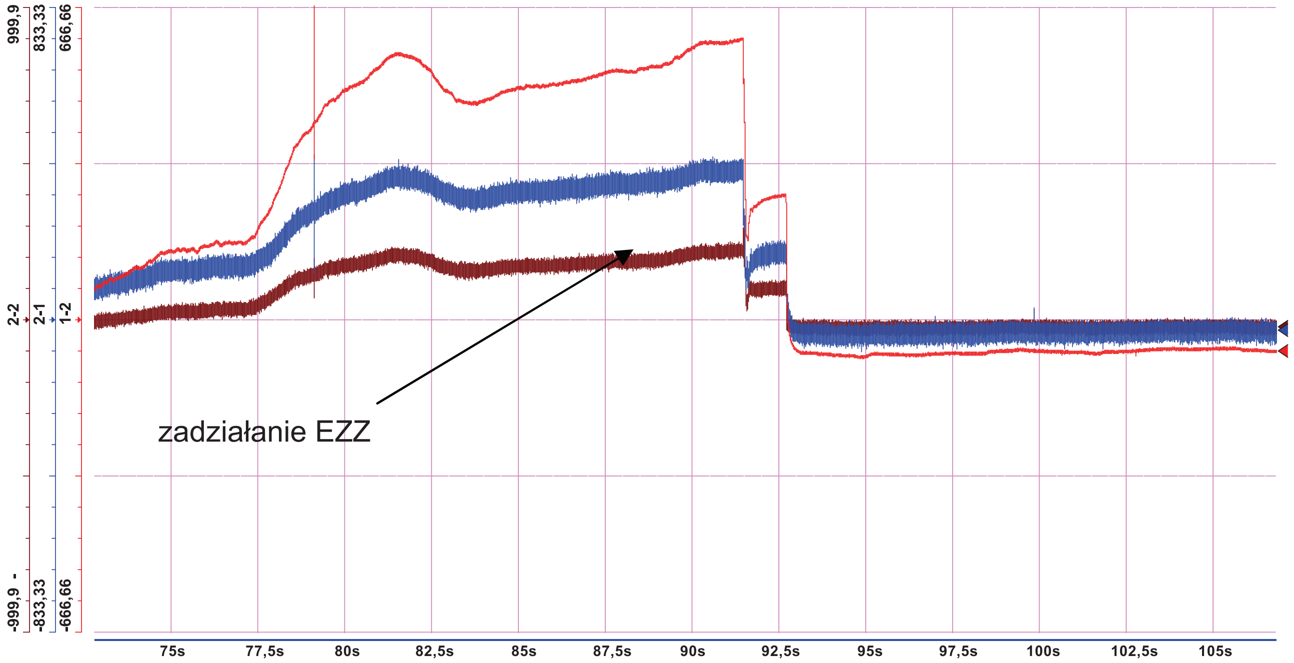

Fig. 4. An oscillogram of measurements performed during the cab operation of the traction substation with an earthed negative bus-bar, ▬ CH2-1 return cable current – group 1, ▬ CH2-2 return cable current – group 2, ▬ CH1-2 traction current flowing into the negative bus-bar through the switch from the substation's main earthing bus-bar [own elaboration]

Table 1

An overall compilation of the results of the performed measurements

Circuit description	No. of reg. ch. description of the measured value	Max value
Measurement results for the substation operation with an unearthed substation negative bus-bar; oscillogram shown in Figure 2	CH 2-1 [A], return cable current – cable group 1	618
	CH 2-2 [A], return cable current – cable group 2	423
	CH 3-1 [V], voltage between the unearthed negative bus-bar and the main earthing bus-bar of the substation	231
Measurement results for the substation operation with an earthed substation negative bus-bar; oscillogram shown in Figure 3	CH 2-1 [A], return cable current – cable group 1	960
	CH 2-2 [A], return cable current – cable group 2	700
	CH 1-2 [A], current in the switch between the unearthed negative bus-bar and the main earthing bus-bar of the substation	401
Measurement results for the cabin operation with an earthed substation negative bus-bar; oscillogram shown in Figure 4	CH 2-1 [A], return cable current – cable group 1	400
	CH 2-2 [A], return cable current – cable group 2	224
	CH 1-2 [A], current in the switch between the unearthed negative bus-bar and the main earthing bus-bar of the substation	595

[Own elaboration].

5. Calculation results

The circuit of a DC power supply section can be presented schematically in the form of a certain number of resistance and conductance elements [1, 2, 8]. A traction power supply section has been modelled in the Matlab-Simulink environment, together with a model of an earth-return circuit of an HV grid. Unlike typical substitute diagrams discussed in the literature, e.g. [2, 8], the diagram implemented in the model shown in Figure 5 was expanded with elements of the high-voltage earth-return system: RuSWN, which represent the grounding resistance of high-voltage supporting structures and Rpo elements representing the unit resistance of the earth wire of the high voltage line, and o resistance elements RuPT representing the earthing resistance of the traction substations. Since the purpose of the presented simulation is to determine the galvanic impacts originating from traction direct currents in steady states, the HV grid earth-return circuit model has been developed with the adoption of a simplification using resistance elements only. The lack of capacitive and inductive elements in the model used does not affect the accuracy of calculations in steady state network operation. For calculations in transient states, e.g. with short-circuit current, switching on or off the traction current, inductive and capacitive elements should be implemented. Simulation for this type of network operation is beyond the scope of this article. Similar results of measurements made during field tests with the results of calculations for correctly set input values confirm the adequacy of the implemented model. The following input data has been adopted in the presented analysis:

- distance between power supply substations: 20 km;
- traction system unit resistance: Rst = 0.04098 Ω/km;
- traction return system unit conductance: Gsp = 0.75 S/km;
- traction return system unit resistance: Rsp = 11.70 mΩ/km;
- traction substation equivalent resistance: RzPT = 0.13 Ω;
- resistance of return cables from one group: RzKP = 0.0075 Ω;
- traction vehicle current, constant along the entire route: IPoj tr = 3,200 A;
- voltage of an unloaded substation: UDC PT = 3,600 V;
- resistance of the earth of the distribution substation: RuGPZ = 0.1 Ω;
- resistance of the earth of traction substation: RuPT = 0.1 Ω;
- resistance of the earth of the set of HV poles along a 2-km section: RuSWN = 0.8 Ω.
- unit resistance of the earth wire of the high voltage line: Rpo = 0.2388 Ω / km (AFL6 120 wire).

The simulation has been developed for the substation operation mode of substations PT1 and PT2. The voltage occurring between the negative bus-bar (SM) and the main earthing bus-bar (GSU) in substations PT1 and PT2, the current in the switch between the SM and the GSU of both substations – with an earthed SM in PT1 and an unearthed SM in PT2 – have been estimated. The calculations have been conducted as a function of the distance between the traction vehicle and the traction substations. The results obtained from the simulation are presented in Figures 6 and 7.

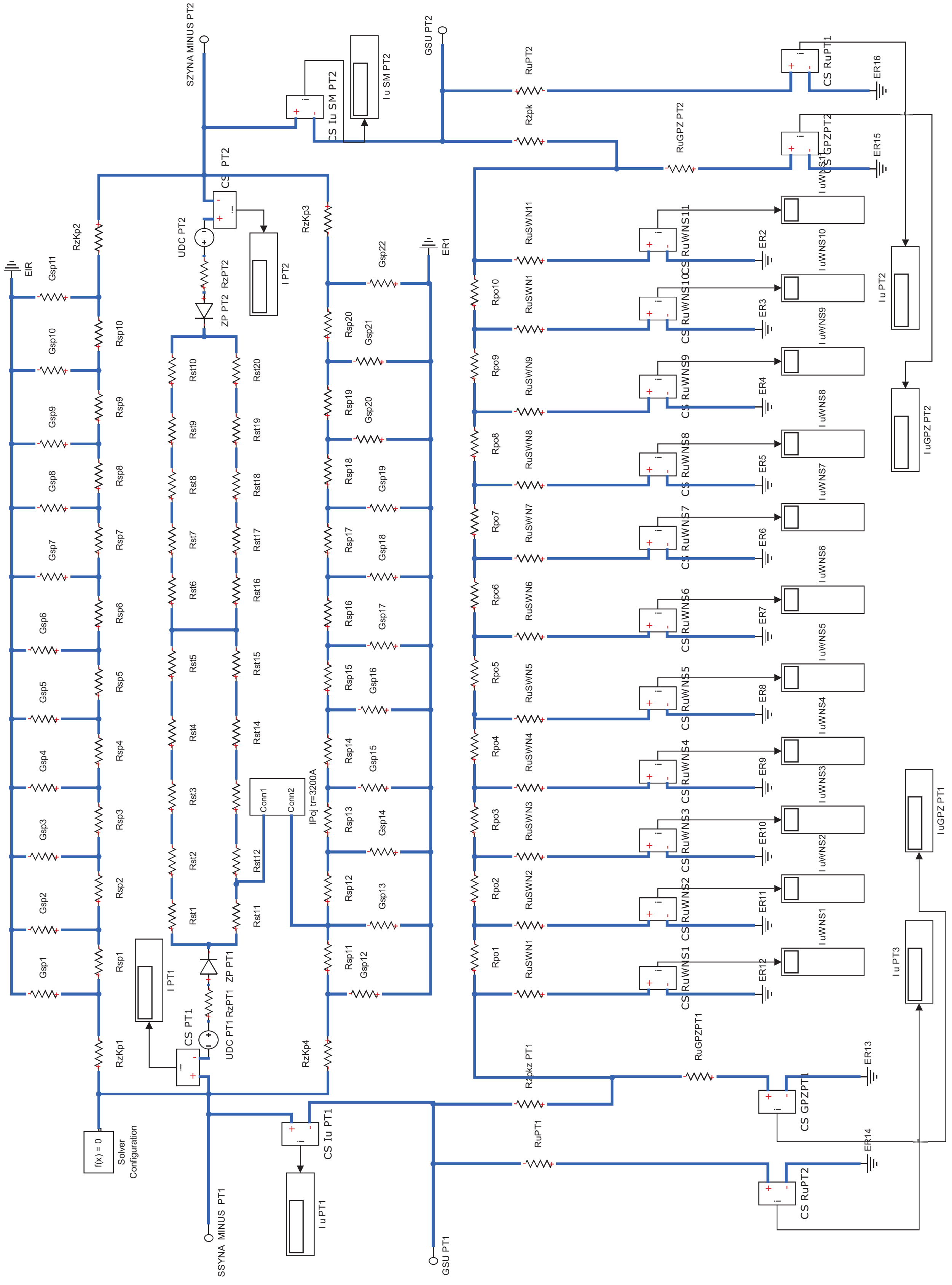

Fig. 5. A Matlab-Simulink model of the DC power supply section with an earth-return circuit of an HV power grid [own elaboration]

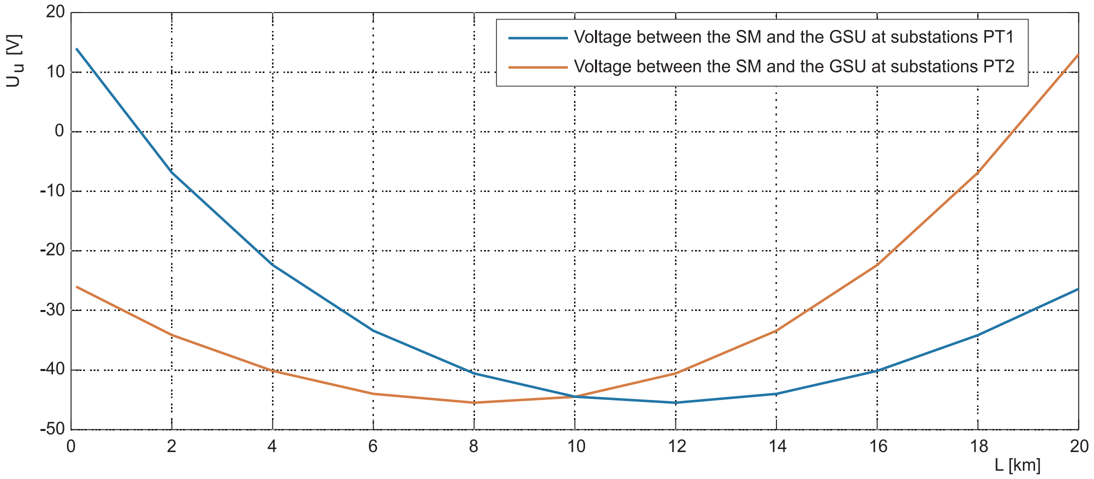

Fig. 6. Voltage between the SM and the GSU at substations PT1 and PT2 as a function of a moving traction vehicle drawing a direct current 3,200 A over the entire route [own elaboration]

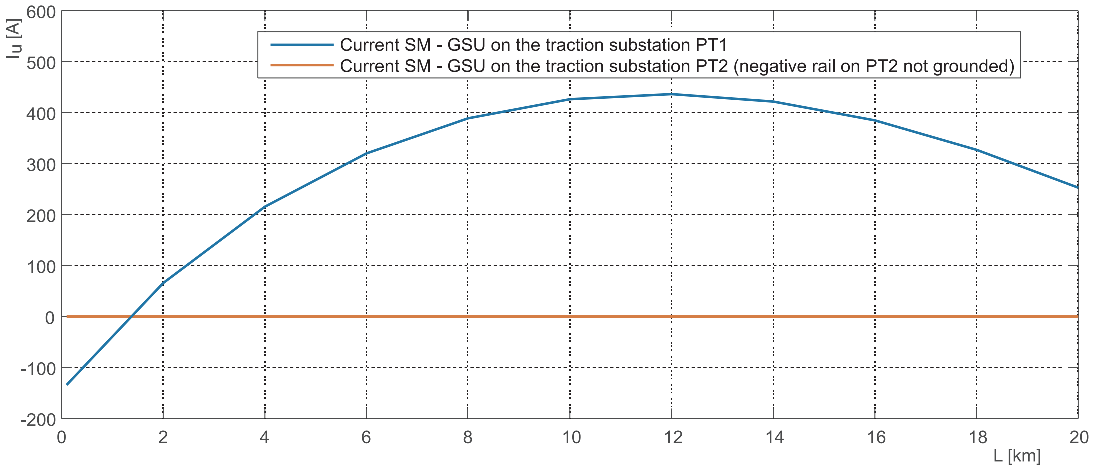

Fig. 7. Voltage between the SM and the GSU at substations PT1 and PT2 as a function of a moving traction vehicle drawing a direct current 3,200 A over the entire route. The SM shorted with the GSU at PT1, open at PT2 [own elaboration]

6. Conclusions

Traction return systems are components of traction power supply systems. The condition of a traction return system determines the effectiveness of electrical safety, the reliability of the

performance of RTC equipment and the entire system of traction power supply. In ideal conditions, the entire amount of the traction current should flow through the traction return system. However, this is impossible in practice as the traction return system – given its structure – is an earth-return circuit where live conductors – bare running rails – are in contact with the earth along the entire length via a layer of insufficient insulation.

There is often another technical infrastructure built in close proximity to electrified track systems, e.g. power supply lines or other technical facilities used to manage train traffic. These facilities contain their own earth-return circuits, which may interact with traction return systems. Depending on the operation mode and the type of utilised power supply or the type of transmitted energy, the occurring interactions may be electricity-based, induction-based or capacitance-based. The measurement results and calculations presented herein illustrate electricity-based interactions. As proven by the performed measurements and calculations, in the case of a standard power supply section along which an HV line running along it, with an earthed negative bus-bar, the traction current flowing into the negative bus-bar by means of the switch connecting it with the main earthing bus-bar reaches significant values. In addition, the voltage occurring between these traction substation elements may lead to traction substation electronic earth-fault protection device tripping.

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