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The railway devices modelling for the purpose of a lightning discharge analysis

Streszczenie. *Modelowanie urządzeń kolejowych w warunkach narażeń na przepięcia pochodzenia atmosferycznego z zastosowaniem metod numerycznych wymaga tworzenia modeli elementów składowych: sieć trakcyjna, sieć powrotna, słup, izolator, odgromnik, udar. Model sieci trakcyjnej opracowano z elementów reprezentujących odcinek 12, 8 km linii. Możliwości analizy z zastosowaniem czwórników typu PI i przykłady charakterystyk dynamicznych wybranych modeli przedstawiono w programie LTSPICE. W artykule do modelowania przyjęto wymuszenie prądowe 8/20 µs. (**Modelowanie urządzeń kolejowych w warunkach narażeń na przepięcia pochodzenia atmosferycznego**)*

Abstract. *The simulation of the railway devices for the purpose of lightning discharge by numerical method requires identification of indicated circuit elements: contact line, rail return, tower, insulator, lightning arrester, current impulse. A model of traction system was composed from elements witch represents 12.8 km section of contact wires. The possibilities of transient analysis with application PI sections models transmission line and examples of dynamic characteristics of the selected model are presented in the LTSPICE program. The article concerns an analytical work and presents the estimation of the values for the 8/20 µs impulse surge current.*

Słowa kluczowe: sieć trakcyjna, modelowanie cyfrowe, symulacje.
Keywords: catenary, numerical modelling, simulations.

Introduction

Railway installations are particularly endangered by direct and indirect atmospheric discharges in the supply system or a railway traffic control (rtc) and telecommunication equipment resulting from the influence of an impulse electromagnetic field [1]. This is a cause of disturbances in the service of the rtc equipment, the limitations of velocity due to the failure as well as additional costs carried out of [2]. The comparative analyses, introduced in the report of lightning damages data in Railway Lines Establishment, confirm the problem [3].

The simulation of overvoltage protection by a numerical method may be trustworthily carried out only after identification of indicated circuit elements traction system [4-7].

The article deals with analytical work but also presents the estimation of the values for the 8/20 µs impulse surge current.

Damageability of railway devices

Different systems of a static registration are put into practice worldwide. It is assumed that there are approximately twenty stormy days in Poland. Since the year 2000 data about static has been recorded by devices from three independent systems: PERUN (SAFIR), CELDN (Central European Lightning Detection Network), LINET [8]:

An analysis of different types of damage of railway devices as a consequence of various causes is executed at the PKP. This information is accumulated by different services. The exemplary data introduced in the report related to static damage of a traction system confirms the existence of the problem [3]. It allows the assessment of the repair costs, the frequency of damage occurrence and their distribution in the country. This data supplemented with the information pertaining to the producers of devices and overvoltage precautions constitute an extremely vital analytical base for PKP Polish Railway Lines JSC. Its compilation involves the work of many researchers.

For the purpose of the analysis the exemplarily accumulated data, in power engineering about the damage, was divided into three groups:

I damage depending on the traction system device,
II damage depending on electric power units and their service,
III other damage (not included in group I and II)

- atmospheric discharges
- a railway disaster, derailment of a rolling stock, crossing a loading gauge, a fire of a rolling stock
- breaking of the external carriage roof sheathing
- the ride of electric power unit with a lifted current collector down the electrified track into a non- electrified one (the inappropriate route)
- breaking of the protective platform on a viaduct, overturned tree, dropping of the power line, shifting of the track centre, scouring of the track
- working of outsiders and other causes independent from the railway
- the damage of a traction system in the period of warranty after the arranged reconditioning, modernising and investment activities.

Table 1. Number of damage of unit traction system in the summers of 2007-2012 as a result of atmospheric surges in Railway Lines Establishment of PKP Polish Railway Lines JSC [3,8]

Atmospheric discharges / km²	3.75 ÷ 7.49	3.75 ÷ 7.49	1.87 ÷ 3.74	3.75 ÷ 7.49	1.87 ÷ 3.74	3.75 ÷ 7.49	1.87 ÷ 3.74	3.75 ÷ 7.49	1.87 ÷ 3.74	1.87 ÷ 3.74	> 7.5	3.75 ÷ 7.49	0.46 ÷ 0.92	0.46 ÷ 0.92	0.93 ÷ 1.86	0.93 ÷ 1.86	0.93 ÷ 1.86	1.87 ÷ 3.74	0.93 ÷ 1.86	0.93 ÷ 1.86	0.93 ÷ 1.86	0.93 ÷ 1.86	0.46 ÷ 0.92	
Atmospheric discharges in Railway Lines Establishments	Warszawa	Łódź	Białystok	Siedlce	Lublin	Kielce	Skarżysko Kamienna	Kraków	Rzeszów	Nowy Sącz	Katowice (Sosnowiec)	Częstochowa	Tarnowskie Góry	Gdynia	Olsztyn	Bydgoszcz	Wrocław	Opole	Wałbrzych	Poznań	Ostrów Wielkopolski	Zielona Góra	Szczecin	Polish Railway Lines (PLK)
Year	Number of atmospheric discharges																							
2007	0	0	0	2	4	8	9	6	0	1	2	6	8	5	1	4	1	3	2	1	2	1	2	68
2008	1	2	1	0	2	7	8	6	0	0	9	9	10	4	3	4	1	3	0	1	5	0	1	77
2009	1	5	0	2	6	6	3	3	1	1	6	8	7	7	0	4	2	6	2	3	6	1	0	80
2010	2	1	0	2	4	0	4	7	0	0	7	9	11	8	3	3	5	5	0	1	3	3	2	89
2011	1	1	1	0	8	9	7	4	3	0	5	10	16	7	0	3	0	4	0	3	3	0	1	86
2012	1	4	0	0	3	8	10	5	0	1	5	2	21	7	9	15	3	6	1	7	4	1	3	116

Table 1 presents a number of unit traction system damage as a result of atmosphere originating surges in the chosen Railway Lines Establishment of PKP Polish Railway Lines JSC on the terrain of the country in the summers of 2007 and 2012 [3]. The average numbers of impulse waves per km^2 in year 2008 were taken from the materials and put in the upper unit of the table [1].

The quantity of damage as a result of atmospheric originating surges in individual years (1999 ÷ 2012) was compared with the general number of damage (Table 2). The participation of damage caused by atmospheric originating surges in group III does not exceed 11.75 %. For the total number of damage (group I ÷ III) its part is lower than about 7.24 %.

Table 2. The participation of damage as a result of atmospheric surges in the number of recorded damage of unit traction systems in the summers of 1999÷2012 Railway Lines Establishment of PKP Polish Railway Lines JSC [3], expressed in percentage.

Year	Group of damages			Atmospheric discharges	Percentage part of atmospheric discharges in group III	Percentage part of atmospheric discharges in group: I÷III
	I	II	III			
1999	410	105	384	32	8.33	3.56
2000	341	117	566	47	8.30	4.59
2001	227	186	730	56	7.67	4.91
2002	179	143	999	51	5.11	3.86
2003	264	134	757	39	5.15	3.38
2004	182	83	1381	34	2.46	2.07
2005	320	113	966	40	4.14	2.86
2006	265	166	1005	71	7.06	4.94
2007	226	106	1088	80	7.35	5.63
2008	218	156	935	88	9.41	6.72
2009	198	188	935	87	9.30	6.59
2010	226	217	1019	80	7.85	5.47
2011	261	290	1016	81	7.97	5.17
2012	367	248	987	116	11.75	7.24

Schemes model

The complexity of the electromagnetic compatibility issue in the railway environment is conditioned by [1,2]:
- a significant vastness of the area,
- mutual interaction of the circuits' low and high voltage devices with different supply systems
- joint running of the supply, signalling and telecommunication cables
- the complexity and common connection of subsystems, including devices of different generations
- the possibility of simultaneous interference interactions from many sources.

A traction system

The simulation of risks caused by electromagnetic impulse interferences requires creating a model considering *R*, *L*, *C* parameters and their variability in the frequency function [4]. In the analysis it should be taken into consideration that it is a circuit with the transmission model of the coupled lines parameters. The general scheme of the model railway supply network and rail return model accepted for the testing is presented in Figure 1 [5]. For the purpose of simplification it has been accepted for the analysis that the velocity of wave spreading is equal to the light velocity and the reflection of current waves from the peak of the initial stroke has not been taken into account.

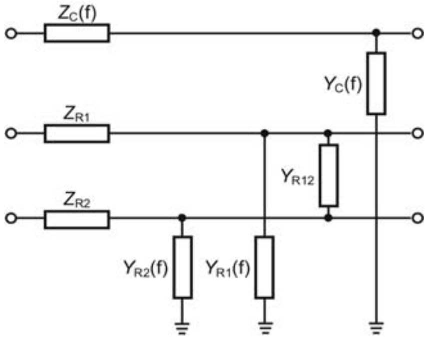

Fig.1. Line rail track impedance and admittance model [5]

For the frequency band regarded in these types of analyses, equalling a few kHz, the traction system has the length of quarter waves responding the section length between substations. According to the data presented in the paper [5], on the basis of the literature included in the paper, if the length of the overhead system section replaced with a four-terminal network does not exceed the wave length by 3%, then the error of such a model is smaller than 2.5 %. For the frequency accepted for the analysis, which is equal to 10 kHz length of a four-terminal network fulfilling this condition is 900 m. In the developed calculation model length of the four-terminal network responds to distance between two towers of an overhead system. The parameters calculated from the measurements included in the paper, for the *l* =72m overhead system section, as in Figure 2, regarding the frequency dependent characteristics of the electric traction and the suggested section parameters were: R_1 = 5.04 mΩ and L_1 = 97.35 μH, R_2 = 16.45 mΩ, L_2 = 12.39 μH, R_3 = 118.34 mΩ, L_3 = 4.19 μH, C_0 = 2.32 nF [11].

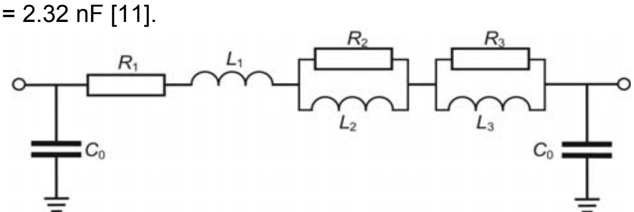

Fig. 2 A frequency- dependent PI section traction system model [5]

A simple but exact solution of the transmission line equations for lossless, coupled lines that is implementable in the SPICE circuit analysis programme. The multiconductor transmission line equations can be written in the matrix form [9].

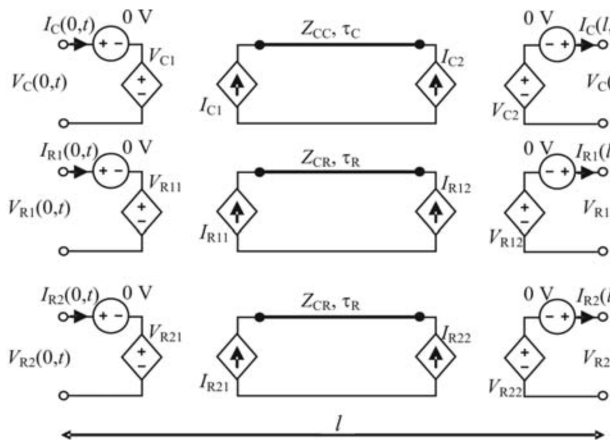

Fig. 3. The complete SPICE model for a three-conductor line [9]

To solve these equations one has to decouple them; that is, reduce the coupled pairs of lines to a set of tree-conductor lines that do not interact. In order to do this, we must define transformations that convert these desired line voltages and currents to mode voltages and currents.

These uncoupled mode lines can be modelled in the SPICE program using the exact, tree-conductor line model. The SPICE model for the mode voltages and currents along the line is solved, and the mode currents and voltages at the endpoints of the line, can be converted to the actual line currents and voltages by implementing the transformations. This can be implemented with voltage-controlled voltage sources and using current-controlled current sources as shown in Figure 3. Zero volt voltage sources are necessary in SPICE to sample the controlling current for current-controlled sources.

A rail network and electrical track parameters

The rail parameters calculated on the basis of measurements results included in [5] calculated for the length of the 72 m four-terminal network equalled (Fig. 4): R_1 = 0.576 Ω, L_1 = 0.0576 mH, G_{12} = 0.115 S, C_{12} = 1.44 μF. In a similar way the substitute parameters of the four-terminal network describing a rail network section while taking into account their changeability in the frequency function (rail 1): G_1 = 6.24 mS, C_1 = 3.98 μF, G_2 = 6.07 mS, C_2 = 0.37 mF, G_3 = 13.3 mS, C_3 = 5.94 μF, G_4 = 0.305 S, C_4 = 3.06 μF were determined. The same values were accepted for the second four-terminal network connected with rail 2. The cross-bonding of rails by around 300 m was taken into account.

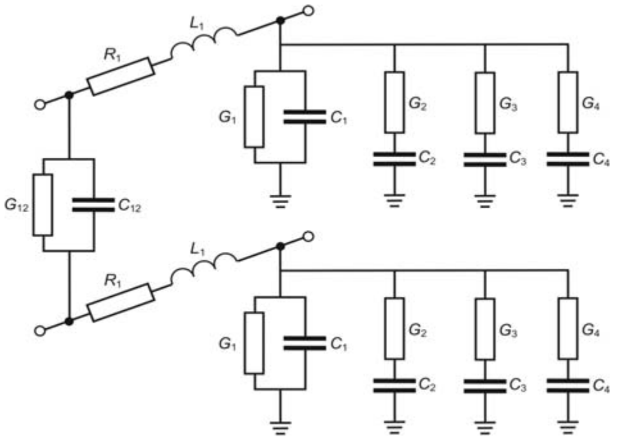

Fig. 4. Scheme of a section of a railway track regarding the influence of the ground [5]

For the analysis in the LTSPICE programme the accepted section of a traction system was composed of 178 four - terminal networks with a length of 72m.The Impulse wave was applied to the tower number 93.

A substation model

As a substation model the parameters regarding: substation voltage U_p = 3450 V, substation inductance and supply system L_p = 4.774 mH [7] have been accepted (Fig. 5).

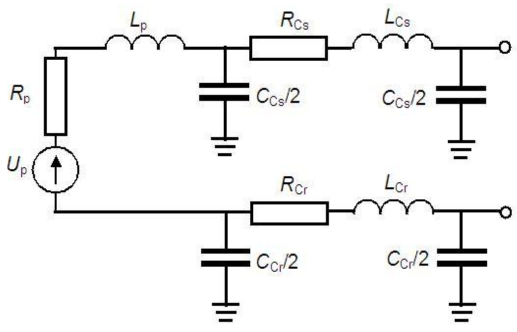

Fig. 5. The scheme of the substations and connections cable [7]

The parameters of the return and supply cable have been accepted according to the measurement results included in the paper [7] for the frequency 10 kHz and the length of the cable equal to 200m as: R_{Cs} = R_{Cr} = 3 Ω, L_{Cs} = L_{Cr} = 0.3 mH, C_{Cs} = C_{Cr} = 0.4 μF. This model introduced into calculations as a four-terminal network may be expanded in further simulations.

Towers

In the analysis of atmospheric discharges a tower model may be realized as a row connection of inductance and resistance. Assuming the unit inductivity L_0 = 1.67 μH/km calculated using the following formula:

(1) $$L = 0.2\,\mu_r\,\frac{2h}{r}\quad [\mu\text{H/km}]$$

where: μ_r - relative magnetic penetration (for air μ_r = 1), h – height of the tower, r – cable radius.

The tower inductance was accepted as L = 20.28 μH, and tower impedance as R = 10 Ω. As the connection to rail of the tower inductance L = 5 μH was accepted.

For the purpose of the analysis, the switch controlled by 90 kV voltage was used as the insulator model in the tower model. The model of a horn lightning arrester was used as the switch controlled by voltage of 12 kV of spark-over voltage and spark gap of 100 MΩ impedance. Horn lightning arresters used to protect the railway feed system are installed every 1.200 m or 600 m (in areas with more than 30 thunderstorm days). In the analysis, the distance was 600 meters.

Declaration of current sources 8/20 μs

It analysis in article was subjected the scheme of contact wires with input current waveform maximum values I_m = 25 kA and shapes 8/20 μs [11,12]. The waveform 8/20 μs suggested by [5] was assigned by the relationship :

(2) $$i(t) = A I_m t^3 \exp(-t/\tau)$$

where: A – correction factor, I_m – is peak value of the short-circuit current.

The value of time constant for 8/20 μs current impulse time constant assumes: A = 0.01243 $(\mu s)^{-3}$; τ =3.911μs.

The results of modelling

In the article the scheme of contact wires with input current waveform maximum values I_m = 25 kA and shapes 8/20 μs was a subject of the analysis. A model set of traction system was composed of the described elements which represent the 12.8 km section of contact wires. The calculations for two traction systems models were executed as: a set without a model from Fig. 3 (Fig. 6 and Fig. 8) same as an arrangement with a traction system model from Fig. 3 (Fig. 7 and Fig. 9).

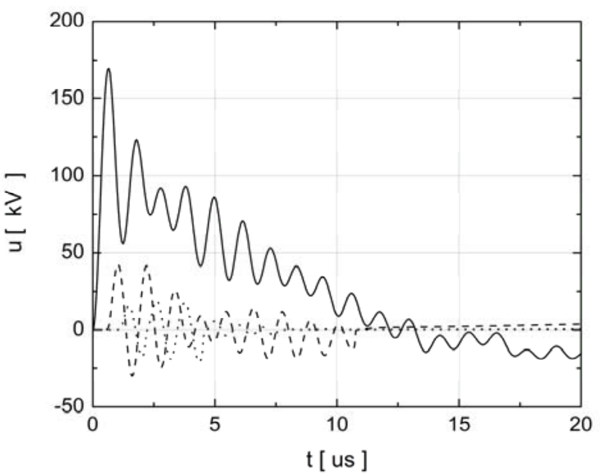

Fig. 6. The courses of voltages for tower in place of lead of impulse wave (the full line) as well as the next one in a distance of 72 (the lined line) and 144m (dotted line) without the traction system model from Fig. 3

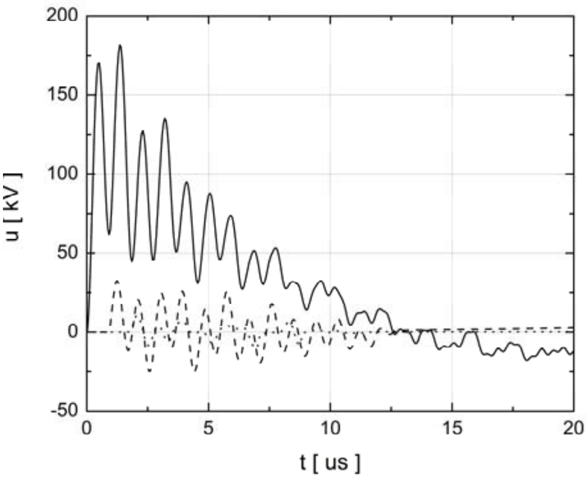

Fig. 7. The courses of voltages for tower in place of lead of impulse wave (the full line) as well as the next one in a distance of 72 (the lined line) and 144m (dotted line) for the traction system model from Fig. 3

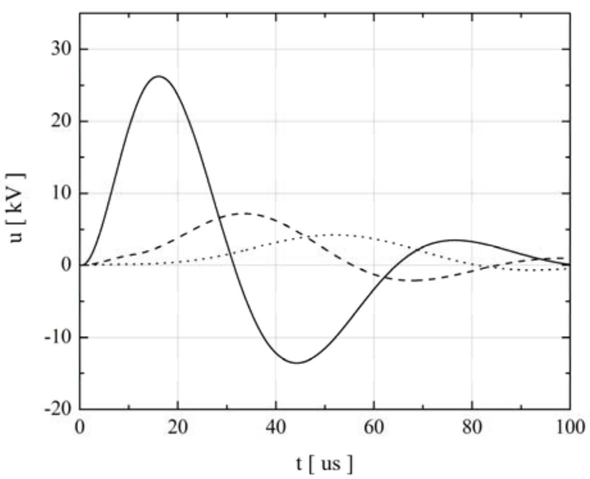

Fig. 8. The courses of voltages for towers from Fig. 6 in splice from rail without the traction system model from Fig. 3

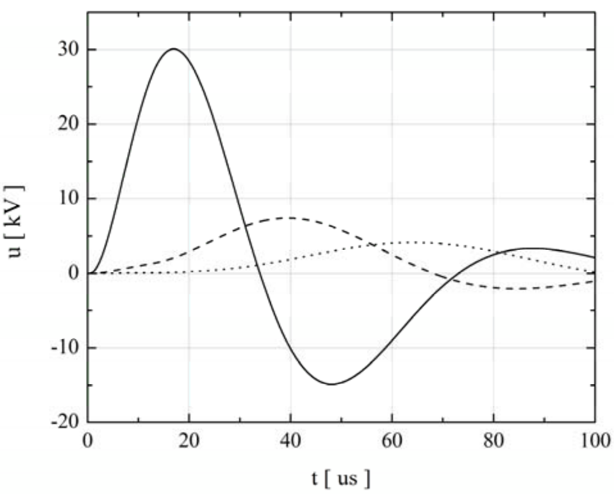

Fig. 9. The courses of voltages for towers from Fig. 7 in splice from rail for the traction system model from Fig. 3

Conclusions

The data presented in table 1 shows that large threat comes from direct static discharges. These discharges, as the result of formed surges, cause the decay of the railway traffic control devices (rtc) and telecommunication equipment. Therefore, it is necessary to carry out a profound investigations, including with usage of the models, which encompass the mutual coupling of lines as well as taking into account the dependence of traction and rail parameters on the frequency. The presented results of traction system modelling executed in the LTSPICE programme illustrate their usefulness if it comes to the surges of atmospheric origin as well as while designing the overvoltage protection.

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