Modeling of 25 kV Electric Railway System for Power Quality Studies

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Abstract—**25 kV, 50 Hz single-phase AC supply has been widely adopted in the long-distance electrified railway systems in many countries. Electrical locomotives generate harmonic currents in railway power supply systems. Single-phase traction loads also inject large unbalance currents to the transmission system and cause voltage unbalance subsequently. As the amount of rail traffic increases, the issue of power quality distortion becomes more critical.**

Harmonic currents and unbalanced voltages may cause negative effects on the components of the power system such as overheating, vibration and torque reduction of rotating machines, additional losses of lines and transformers, interference with communication systems, malfunctions of protection relays, measuring instrument error, etc.

Therefore, the harmonic current flow must be assessed exactly in the designing and planning stage of the electric railway system (ERS). Harmonic current flow through the contact line system has to be accurately modeled to analyze and assess the harmonic effect on the transmission system.

This paper describes the influence of electric railway system on power quality in 110 kV transmission system. Locomotives with diode rectifiers were analyzed. Electric railway system was modeled using EMTP-RV software. Currents and voltages were calculated in 110 kV and 25 kV network. Power quality measurements were performed on 110 kV level in 110/35/25 kV substation and analyzed according to IEC 61000-3-6.

Keywords: Electric Railway System, Power Quality, Modeling, Measurement

I. Introduction

Constant technological development requires the electrification of main railway lines due to the advantages of electric traction over diesel traction, such as: increase in speed, safety, efficiency and environmental acceptability.

However, electric railway system has a negative influence on facilities to which it is connected and on surrounding facilities. The negative influence of the electric railway system is manifested in the form of unbalanced loading [1] and generation of harmonic voltages and currents [2]-[3] at the point of connection. Unbalanced loading occurs due to the fact that the transformers in electric traction substations, feeding the contact line, are connected between two phases of the transmission grid. This generates current loading at the 110 kV voltage level at the point of connection of the electric traction system, thus creating voltage drops at the transmission branch impedances, which leads to voltage unbalance.

Besides voltage and current unbalance, electric railway system also causes voltage and current harmonic distortion at the point of connection due to operation of power electronics used for train control and drive systems [4]. In order to calculate the distorted voltages and currents caused by electric traction at the point of connection to the transmission grid, a model of diode locomotive was created using the EMTP-RV software. The calculated harmonic voltages and currents were compared to the values measured at the electric railway substation.

II. Electric Locomotives With Diode Rectifiers

Majority of electric locomotives in Croatian electric railway system 25 kV, 50 Hz are equipped with DC motors and diode rectifiers. Diode rectifier bridge causes current waveform distortion and as a consequence voltage distortion in transmission power system.

Diode locomotive consists of an autotransformer, diode rectifiers and four DC motors. The autotransformer 25/1.06 kV connects contact wire with diode rectifiers and DC motors. Figure 1 shows the electrical scheme of diode locomotive.

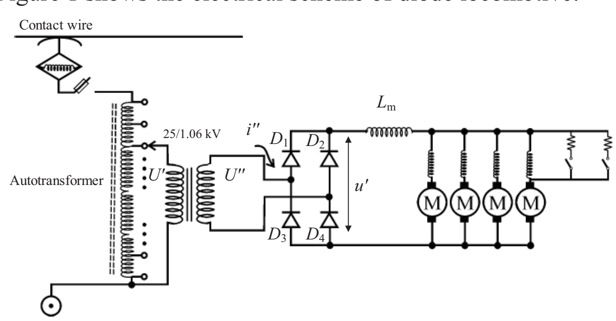

Fig. 1. Electrical scheme of the diode locomotive

Figure 2 shows voltage *U*” and current *i*” waveforms entering the diode rectifier [5]. Diode rectifier has one commutation over one semi-period of voltage.

The Figure 2 also shows conducting sequence of individual diodes in the rectifier bridge as well as commutation when all diodes simultaneously conduct in a short time period (in Fig. 2 this time period is enlarged).

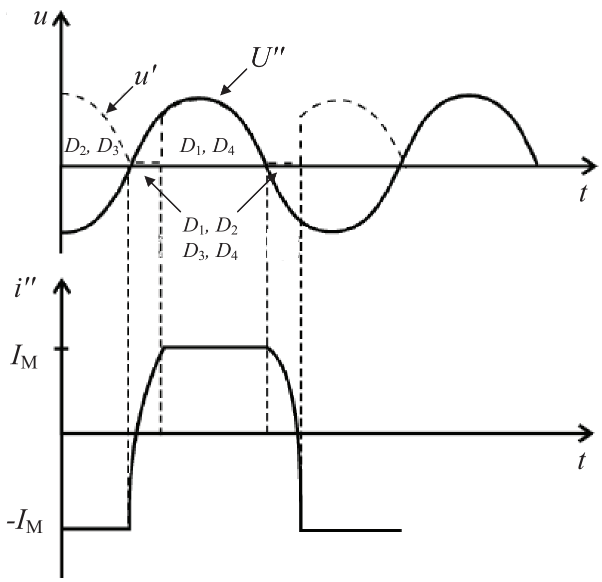

Fig. 2. Diode rectifier voltage and current waveforms

Odd current harmonics (3rd, 5th, 7th, 9th,…) are characteristic for diode bridge rectifiers.

III. Modeling of Electric Railway System

A model of electric railway system connected to 110 kV network was developed in order to determine power quality parameters of voltage and current. A model consists of electric railway substation and contact line feeding electric locomotives equipped with diode rectifiers. Figure 3 shows the model in EMTP-RV software [6] which is used for analysis of electromagnetic transients.

An electric railway substation consists of one 110/25 kV transformer with rated power 7.5 MVA which is connected to the transmission grid. The transformer impedance was calculated from the manufacturer data. 110 kV transmission network is represented by Thevenin equivalent (impedance in series with voltage source). The positive and zero sequence impedance was calculated from single-phase and three-phase short-circuit currents.

Figure 4 shows a 25 kV catenary system which consists of a messenger wire and contact wire.

The catenary system was modeled using a frequency-dependent J. Marti model which is based on the approximation of the line characteristic impedance $Z(\omega)$ and propagation function $A(\omega)$ by rational functions of the higher order. Ground resistivity was assumed 100 Ωm.

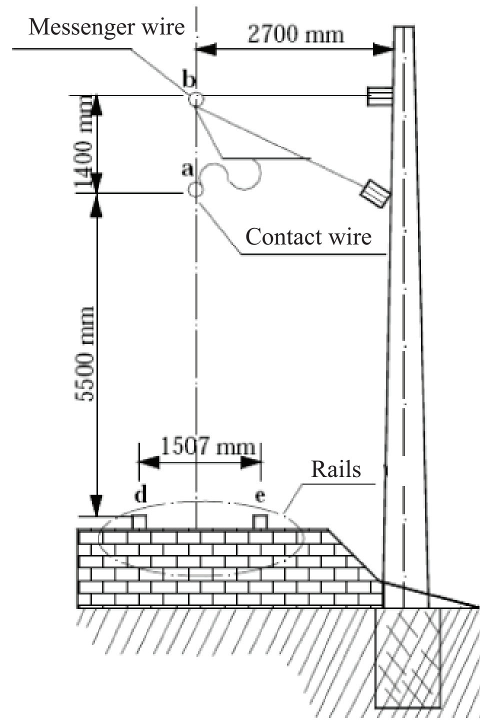

Fig. 4. Configuration of the 25 kV, 50 Hz catenary system

The parameters of the catenary system are shown in Table I.

DC motor model consists of main field inductance, armature and commutating pole resistance and back electromotive force [7]-[9].

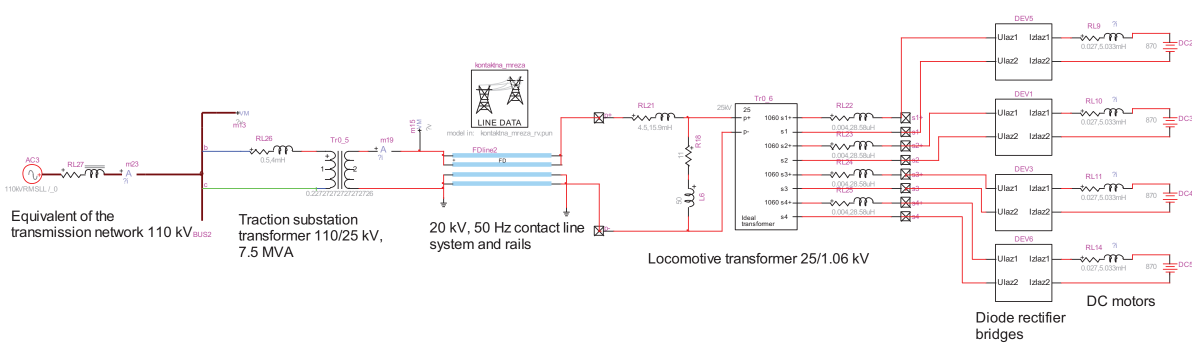

Fig. 3. EMTP-RV model of electric railway system

TABLE I
PARAMETERS OF THE CATENARY SYSTEM

	Contact wire	Messenger wire
DC resistance (Ω/km)	0.1759	0.153
Radius (mm)	6	6.18
Cross section (mm^2)	100	120

Regarding the rectifier bridge it is represented with the series resistance of the diodes and the parallel RC elements. To smooth the direct current a series reactor is connected between the rectifier bridge and the motor. This reactor together with its resistance was also taken into account in calculations. Diode rectifier bridge is shown in Fig. 5.

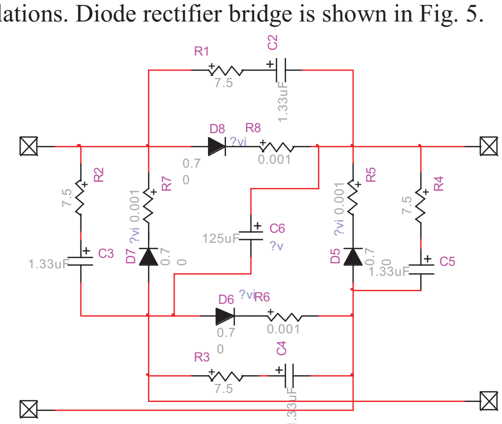

Fig. 5. Diode rectifier bridge

IV. ANALYSIS OF THE SIMULATION RESULTS

Constant speed of the diode locomotive was analyzed. Electric railway system is connected between phase L2 and L3 of the 110 kV network. All calculated values relate to the single diode locomotive 1 km away from the electric railway substation. Voltage and current waveforms were calculated on 25 kV and 110 kV level at the railway substation.

The diode electric locomotive causes voltage distortion in the 25 kV catenary system. Fig. 6 shows voltage waveform and Fig. 7 current waveform on 25 kV side of railway substation transformer.

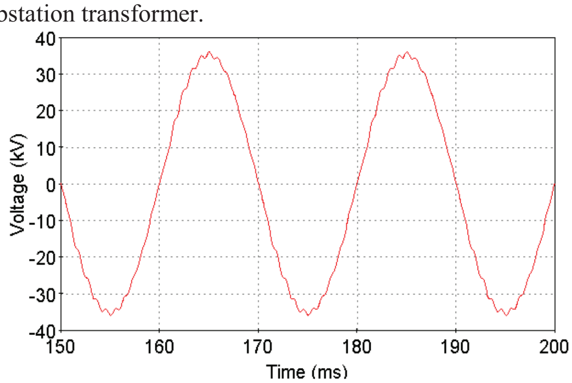

Fig. 6. Voltage waveform on 25 kV side of railway substation transformer

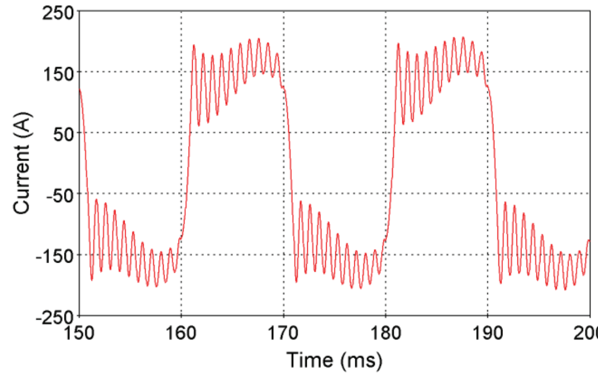

Fig. 7. Current waveform on 25 kV side of railway substation transformer

Fig. 8 shows voltage waveform and Fig. 9 voltage harmonic spectrum at 110 kV side of railway substation transformer. The voltage and current harmonics in 25 kV catenary system is shifted through 110/25 kV transformer in electric traction substation to the 110 kV voltage level.

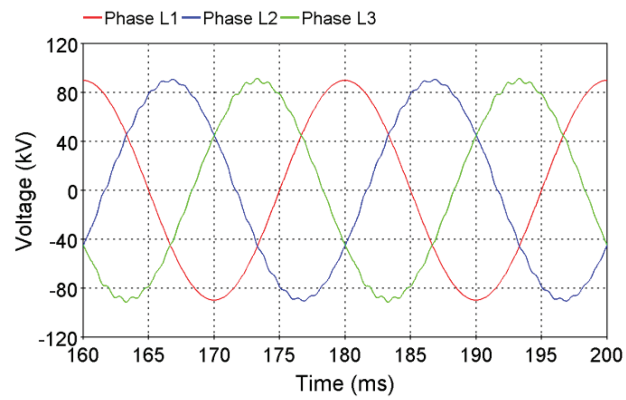

Fig. 8. Voltage waveform at 110 kV side of railway substation transformer

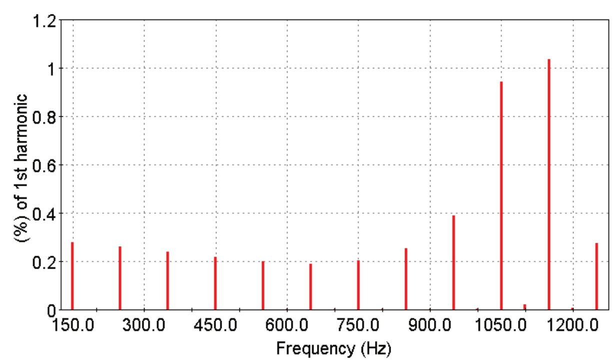

Fig. 9. Voltage harmonics at 110 kV side of railway substation transformer

There is a significant part of higher odd harmonics (23rd and 21st harmonic are the highest).

Fig. 10 shows current waveform and Fig. 11 current harmonic spectrum at 110 kV side of railway substation transformer. The harmonic distortion of 110 kV voltage is significant only in L2 and L3 phases to which the electric railway system is connected.

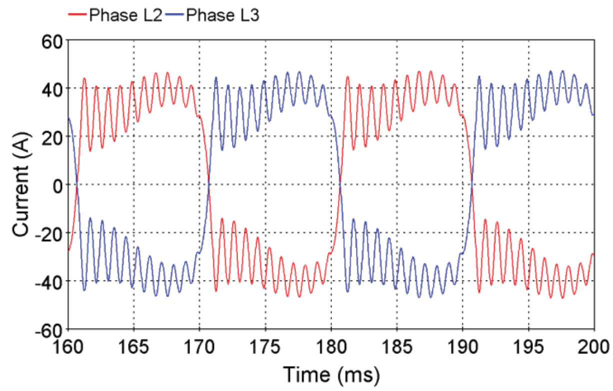

Fig. 10. Current waveforms on 110 kV side of railway substation transformer

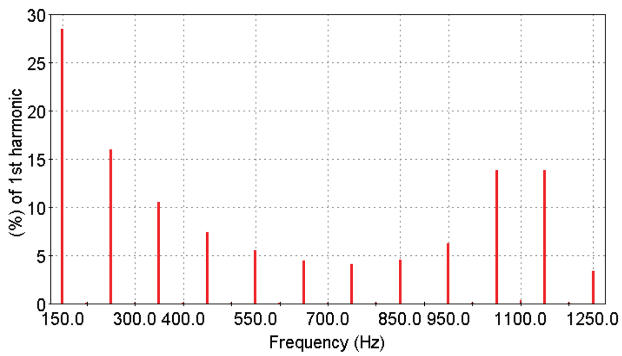

Fig. 11. Current harmonics on 110 kV side of railway substation transformer

The 3rd, 5th, 21st and 23rd harmonic contribute the most to the total current distortion.

Simulations showed that total harmonic distortion (THD) of voltage and current is the highest at the point of connection of the locomotive to contact line. Calculated current and voltage THD at 110 kV and 25 kV level is shown in Table II and harmonics at 110 kV level are shown in Table III.

TABLE II
CURRENT AND VOLTAGE THD AT 110 KV AND 25 KV LEVEL

Voltage	THD *U*	THD *I*
110 kV	1.63 %	41.83 %
25 kV	2.06 %	

TABLE III
CURRENT AND VOLTAGE HARMONICS AT 110 KV AND 25 KV LEVEL

Harmonic number	25 kV		110 kV	
	U (V)	*I* (A)	*U* (V)	*I* (A)
1st	35280	194	89560	40.1
3rd	125.1	35.2	251.2	11.4
5th	116.7	31.0	234.4	6.4
7th	107.7	10. 5	216.4	4.2
21st	421.0	26.7	931.4	5.5
23rd	462.0	26.7	841.8	5.5

V. MEASUREMENT OF POWER QUALITY

Power quality parameters were measured for the period of seven days in 110/35/25 kV substation shown in Fig.12 [10].

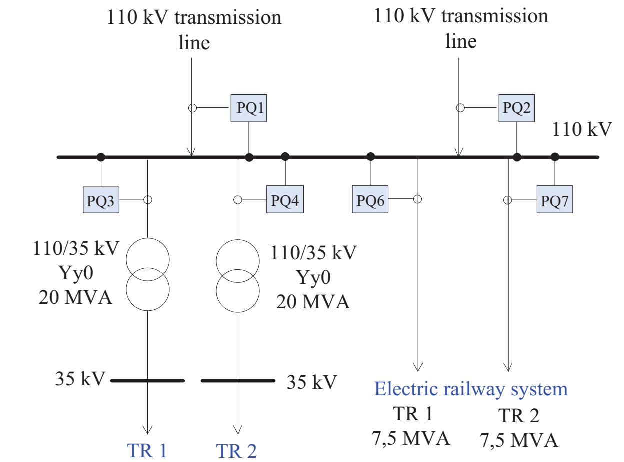

Fig.12. 110/35/25 kV substation with indicated measuring points where power quality (PQ) analysers were connected

110 kV power system is supplied from hydro power plant over two transmission lines. Voltage harmonic distortion at 110 kV level occurs due to the fact that two electric railway transformers and two distribution transformers are connected to 110 kV level. Electric railway transformers are connected to phases L2 and L3 of the 110 kV system. All measurements were time synchronized. Measurement system collected 10-minutes mean RMS values of voltage at 110 kV system and currents in electric railway drain (phase L2). Diode and thyristor locomotives were operating in the electric railway system during the measurement period [11].

3rd voltage harmonic in the observed period of one week are significantly higher in L2 and L3 phases than in L1 phase (Figure 13).

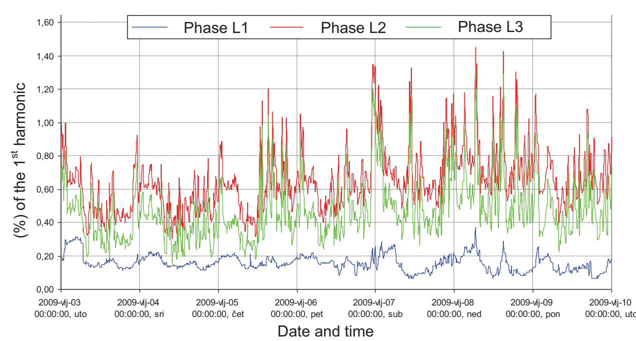

Fig. 13. 3rd voltage harmonic at 110 kV level

During 95 % time of the week the maximum value of third voltage harmonic was 0.9 % in phase L2 and L3 and 0.3 % in phase L1. Besides the 3rd voltage harmonic, the 3rd current harmonic was also increased in L2 and L3 phases of electric railway drains. Fig. 14 shows 3rd current harmonic in phase L2 of both railway substation transformers. The 3rd current harmonic is characteristic for diode and thyristor electric locomotives.

5th voltage harmonic in all three phases is approximately equal (Fig. 15) due to the fact that the 5th harmonic is characteristic for the loads in distribution network as well as for the railway system. During 95 % of the week, the maximum value for all phases was 0.6 %.

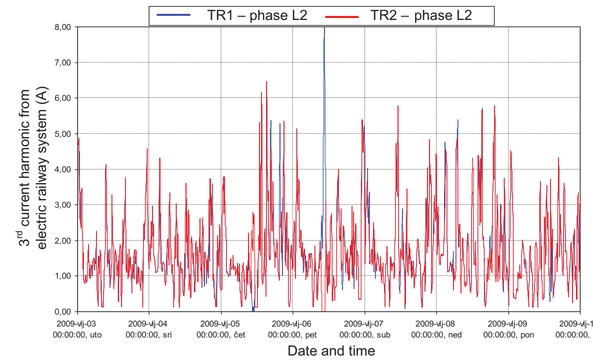

Fig. 14. 3rd current harmonic in phase L2 of the both electric railway transformers at 110 kV level

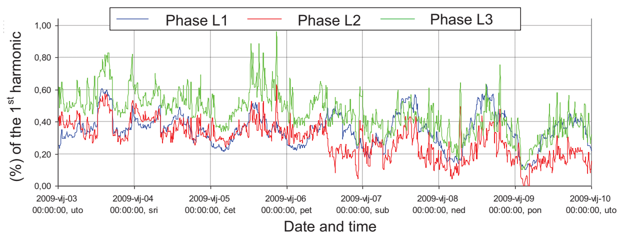

Fig. 15. 5th voltage harmonic at 110 kV level

The 5th current harmonic is shown in Fig. 16.

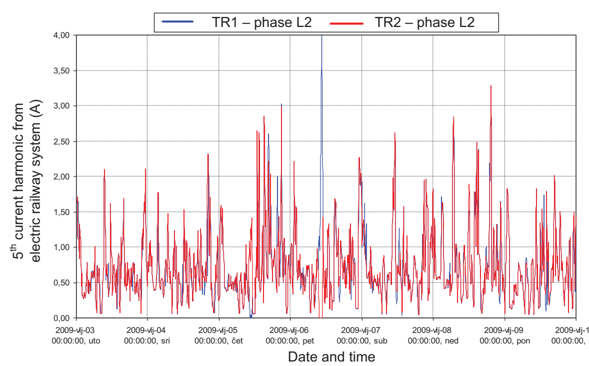

Fig. 16. 5th current harmonic in phase L2 of the both electric railway transformers at 110 kV level

9th voltage harmonic in phase L2 and L3 was also higher than in phase L1 (Figure 17). During 95 % time of the week the maximum value in phase L2 and L3 was 0.3 %.

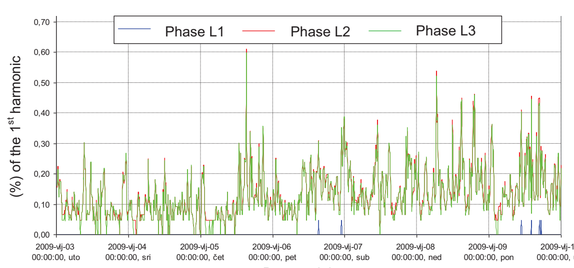

Fig. 17. 9th voltage harmonic at 110 kV level

According to Fig. 18 it can be concluded that the increased 9th current harmonic in phase L2 and L3 of electric railway drain causes increase of 9th voltage harmonic in the same phases at 110 kV level.

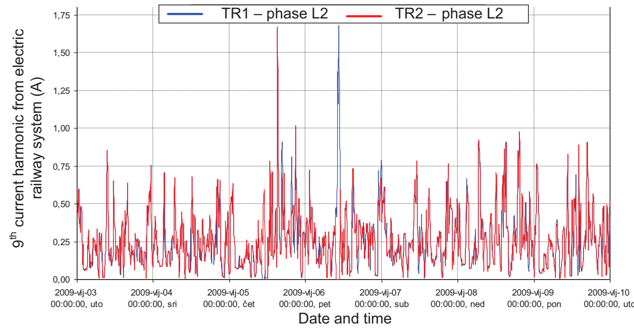

Fig. 18. 9th current harmonic in phase L2 of the both electric railway transformers at 110 kV level

3*n* harmonics are specific for diode and thyristor locomotives. During 95 % of the week the maximum value of the 21st voltage harmonic in phase L2 and L3 was 0.5 %, while in phase L1 was zero (Fig. 19). The 21st current harmonic is shown in Fig. 20.

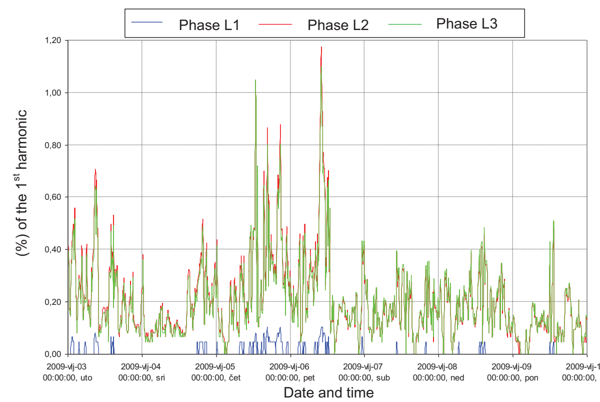

Fig. 19. 21th voltage harmonic at 110 kV level

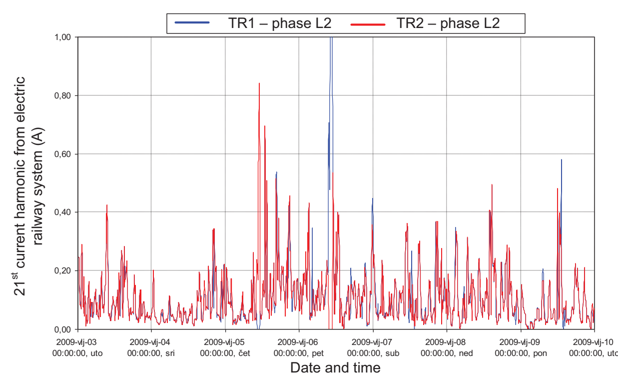

Fig. 20. 21th current harmonic in phase L2 of the both electric railway transformers at 110 kV level

The comparison between measured values and planning levels for harmonic voltages according to [12] is shown in Table IV.

TABLE IV
COMPARISON OF MEASUREMENTS AND PLANNING LEVELS FOR HARMONIC VOLTAGES ACCORDING TO IEC 61000-3-6: 2008

	Measurements on 110 kV busbars		Planning levels for HV
	Phases L2, L3	Phase L1	
THD	1,8 %	0,8 %	3 %
U_{h3}	0,9 % U_{h1}	0,3 % U_{h1}	2 % U_{h1}
U_{h5}	0,6 % U_{h1}	0,5 % U_{h1}	2 % U_{h1}
U_{h7}	0,5 % U_{h1}	0,2 % U_{h1}	2 % U_{h1}
U_{h9}	0,3 % U_{h1}	0,0 % U_{h1}	1 % U_{h1}
U_{h11}	0,6 % U_{h1}	0,3 % U_{h1}	1,5 % U_{h1}
U_{h13}	0,8 % U_{h1}	0,4 % U_{h1}	1,5 % U_{h1}
U_{h15}	0,4 % U_{h1}	0,1 % U_{h1}	0,3 % U_{h1}
U_{h17}	0,4 % U_{h1}	0,2 % U_{h1}	1,2 % U_{h1}
U_{h19}	0,4 % U_{h1}	0,1 % U_{h1}	1,1 % U_{h1}
U_{h21}	0,5 % U_{h1}	0,0 % U_{h1}	0,2 % U_{h1}
U_{h23}	0,6 % U_{h1}	0,3 % U_{h1}	0,9 % U_{h1}
U_{h25}	0,8 % U_{h1}	0,3 % U_{h1}	0,8 % U_{h1}

These values refer to the maximum 10-minute mean RMS values during 95 % of the time. The 15th and 21st voltage harmonic exceeds the planning level. The calculation results cannot be directly compared with the measurements because only one diode locomotive was analyzed in the calculations, while during the measurements several diode and thyristor locomotives were in operation. However, both measurements and calculations show railway-specific 3*n* order odd harmonics.

VI. CONCLUSION

This paper describes the influence of electric railway system on power quality in 110 kV transmission system. Electric railway system with diode locomotive was analyzed and modeled using EMTP-RV software. Currents and voltages were calculated in 110 kV and 25 kV network. Power quality measurements were performed on 110 kV level in 110/35/25 kV substation with connecion to electric railway system. Measurements were analyzed according to IEC 61000-3-6.

Calculation results and measurements show that the impact of the electric railway system on power quality in transmission system is especially expressed in form of railway-specific harmonics - 3*n* order odd harmonics. 3*n* harmonics are higher on phases between which the electric railway system is connected.

Future work will focus on experimental verification of diode locomotive model, development of thyristor locomotive model and analysis of harmonic propagation in transmission system.

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