

SCIENTIFIC PAPERS
OF THE UNIVERSITY OF PARDUBICE
Series B
The Jan Perner Transport Faculty
15 (2009)

**EXPERIMENTAL MEASUREMENT AND SIMULATION OF HARMONIC
FREQUENCY INCURRED FROM CZECH RAILWAY NETWORK**

František RAJSKÝ

Department of Electrical Power Engineering and Environmental Engineering,
Faculty of Electrical Engineering, University of West Bohemia in Pilsen

Eva VEJVODOVÁ

Department of Technologies and Measurement,
Faculty of Electrical Engineering, University of West Bohemia in Pilsen

1. Introduction

The electrified railway system supplies electrical energy to electric railway tractive stock and multiple unit trains so that they can operate without having an on-board prime mover. There are several different electric traction systems in use throughout the world.

Former electric railway systems used the low-voltage DC network. Electric motors were supplied directly by contact line, and speed of motors was controlled by combination of resistors. Motors in combination of parallel or series connection were operated via switch or relays depending on a type of railway tractive stock.

Nowadays, the DC power supply system is 1500 V and 3 kV in the railway network. In the 20th century, the twelve-pulse diode rectifier was put in operation to convert utility (mains) AC power (22 000 V at 50 Hz) to the required DC voltage at the feeder stations. Today, only one research study on usage of semiconductor rectifiers to transform the voltage down from the utility supply is available.

Another power supply system in railway network is AC 25 kV at 50Hz uses only one phase of the normal three-phase power supply. This voltage is transmitted from

110 kV distribution network via a one-phase transformer. Consequently, railway stock having DC motors which are supplied from AC network needs the rectifier.

A traction sub-station or a traction current converter plant is an electrical substation that converts electric power from the distribution network (22 kV or 110 kV) to appropriate type of voltage and current, and frequency to supply railways.

2. Model of Distribution and Traction Network

2.1 Distribution and Traction Network

A model of the distribution network is often based on simulation of Π network. This model uses the following mathematical equations describing the low voltage network:

$$Z = R \cdot l + j \cdot k \cdot \omega_l \cdot L \cdot l \ (\Omega) \quad (1)$$

$$Y = (G \cdot l) + j \cdot k \cdot \omega_l \cdot C \cdot l \ (S) \quad (2)$$

Resistance R (Ω /km), inductivity L (MH/km), capacity C (nF/km) and inducement G (MS/km) are passive parameters. Values can be found e.g. in supplier prospects of contact line or cables, as it is shown in the Table 1.

Table 1 – Passive parameters

	Network 22kV	Network 110kV	Traction network
Inductivity L [mH/km]	0,94	1,24	1,00
Resistance R [Ω /km]	0,30	0,39	0,4
Capacity C [nF/km]	12	9,44	15
Susceptance G [mS/km]	3,76	2,96	100

For the purpose of this paper, the model of the distribution network and traction network is based on lossy line.

The Lossy line model is used for simulation of harmonic frequencies of voltage and current in the traction network. Additionally, simulation can be run for the single frequency, the model based on Π network shows all frequencies through FFT. Accuracy of the model depends on impedance of network, especially on length of overhead line. The first model gives accurate results only for short distances because it implements only one Π block which does not take into account a reflected wave of current and voltage. On the other hand, more than one Π block is implemented in the Lossy line model, resulting in more accurate results of particular harmonic frequencies of current and voltage in comparison with the model introduced before. The number of Π blocks needed for simulation can be obtained by followings equations based on calculation of diffusion constant γ which takes into account all passive parameters of the distribution and traction network:

$$|\gamma| \cdot l \ll 1, \text{ where } (-) \quad (3)$$

l is length of overhead line (km).

For short distances, the following equation can be used:

$$\sinh(\gamma \cdot l) \cong \gamma \cdot l \quad (-) \quad (4)$$

$$\tanh(\gamma \cdot l) \cong \gamma \cdot l \quad (-) \quad (5)$$

$$\gamma = \sqrt{(R + j \cdot \omega \cdot L) \cdot (G + j \cdot \omega \cdot C)} = \alpha + j \cdot \beta \quad (\text{m}^{-1}) \quad (6)$$

When the lengths of overhead line l_{MAX} and frequency f_{MAX} are given, speed of propagation will be following:

$$l_{\text{max}} \leq 0,03 \cdot \lambda = \frac{0,03 \cdot v}{f_{\text{MAX}}} \quad (\text{m}), \text{ where} \quad (7)$$

λ is a wave length for frequency f_{MAX} (m).

$$v = \frac{\omega}{\text{Im}\{\gamma\}} = \frac{\omega_{\text{MAX}}}{\beta_{\text{MAX}}} \quad (\text{ms}^{-1}) \quad (8)$$

$$\beta \cong \omega_{\text{MAX}} \cdot \sqrt{L \cdot C} \quad (\text{m}^{-1}) \quad (9)$$

$$l_{\text{max}} \leq \frac{0,03}{f_{\text{MAX}} \cdot \sqrt{L \cdot C}} \quad (\text{m}) \quad (10)$$

The last equation clearly shows that simulated frequency depending on lengths of overhead line l_{MAX} gives the number of Π blocks:

$$\text{number_of_block} = \frac{\text{requested_frequency}}{f_{\text{MAX}}} \quad (-) \quad (11)$$

2.2 Filtration Compensation Equipment

When the number of PI blocks is known, another step is simulation of Filtration Compensation Equipment.

Filtration Compensation Equipment (FCE) changes power factor $\cos \varphi$ from 0,95 to 1,00. If compensate power is lower than needed the power factor is also decreasing. Compensation is shown on the right side of the Figure 1.

FCE eliminates 3rd, 5th and 7th harmonic current and voltage harmonic frequency. Filtration is shown on the left side of the Figure 1.

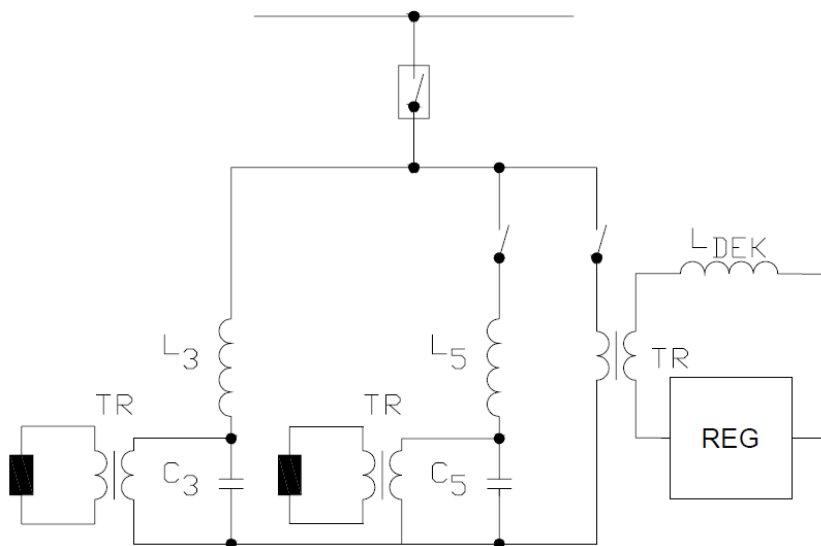


Figure 1 – Filtration Compensation Equipment

For the purpose of this paper, the following values were used (FCE in the sub-station Bohatice) for simulation of FCE: $L_3 = 0,137mH$, $C_3 = 8,5\mu F$, $L_5 = 0,169mH$, $C_5 = 2,4\mu F$, $L_{DEK} = 0,596H$.

2.3 Rectifier and Transformer on DC Network

For simulation of the DC traction network, modeling of the rectifier is essential. The model of rectifier goes together with the model of a three-phase transformer.

The mathematical model of the transformer is given by following equation:

$$L_{TT} = \frac{U_{ef.sdr.}^2 \cdot u_k}{100 \cdot \pi \cdot S_{TT} \cdot 100} \text{ (H), where} \tag{11}$$

L_{TT}	is inductivity of traction transformer	(H)
U_{ef}	is phase voltage at secondary part	2 050V
u_k	is short circuit voltage	5%
S_{TT}	is traction transformer power	4MVA
L_{TV}	is contact line inductivity	10mH

Based on given values (sub-station Hoštka), $L_{TT} \cong 250\mu H$.

Modeling of the rectifier is difficult because a phase shift 30° electrical degree between the both of secondary voltages is needed, as it is explained in the Figure 2. The

phase shift was created between Way and Delta connection of secondary part of the transformer.

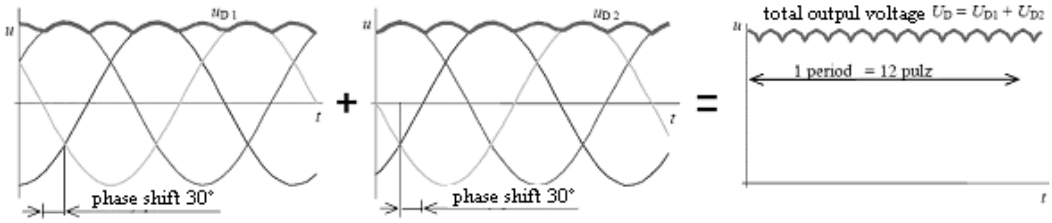


Figure 2 – Phase shift 30°

This shift is also shown on the twelve-pulse rectifier, occurring after connecting secondary and tertiary part of the transformer. The third part of the Figure 2 shows voltage in time domain simulated on contact line. For better understanding see the Figure 8.

Time behavior of currents in diodes is similar to time behavior of voltages (Figure 2).

The first current i_{L4} flows out of Way connection and the second current i_{L5} flows out of Delta connection. For the calculation of the total current flowing to contact line, the current from the transformer i_{L1} is necessary.

$$I_{CELK} = i_{(L1)} + \frac{i_{(L4)} - i_{(L5)}}{\sqrt{3}} \text{ (A)} \quad (12)$$

2.4 Transformer on AC Network

The AC traction network is currently connected to the distribution network. The transformer working on AC is the one-phase transformer. This transformer reduces voltage from 110 kV to 27 kV with frequency at 50 Hz. The model of the transformer is described by following equations:

$$Y = \frac{i_0}{100} \cdot \frac{S_N}{U_N^2} \text{ (S)} \quad (13)$$

$$Z = \frac{u_k}{100} \cdot \frac{U_N^2}{S_N} \text{ (\Omega)} \quad (14)$$

Where:

- i_0 is transformer open circuit current (%)
- S_N is nominal power (MVA)
- U_N is nominal voltage (kV)
- u_k is transformer short circuit voltage (%)
- Z is impedance (Ω)
- Y is admittance (S)

2.5 The AC Load Line

Last part in modeling of the AC traction network is load of electric railway tractive stock. This load is very difficult to be predicted because a single phase AC motor vehicle is not automatically operated since its speed is controlled by a driver. It could be concluded that load is highly influenced by a human factor.

For getting more accurate results of simulation, it is recommended to use values of experimental measurement of real load. In this paper, the measurement was carried out in the traction sub-station Bohatice, results are shown in the Figure 3. Measured data were used as input to a current generator to obtain values for simulation of load.

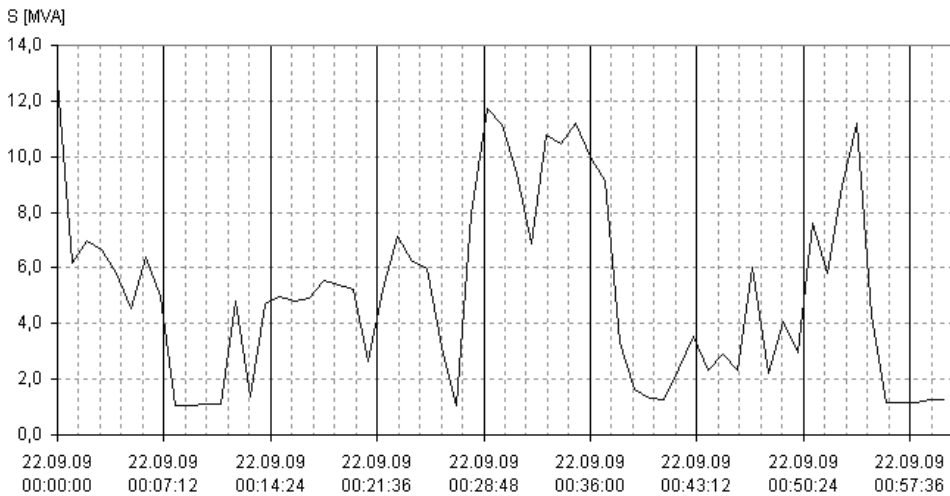


Figure 3 – AC load

2.6 The DC Load Line

As it was explained in the previous chapter, load of railway tractive stock is difficult to be modeled. For the scope of this paper, a method published in 1977 (6) and 1980 (7) was used to obtain the load model. Today, this method is not used and previous implementation in real measurements is un-known to the authors of this paper. According to the methodology, the model of load is based on characteristics of railway track and electric railway tractive stock; especially on type of railway tractive stock, lateral inclination of stock, terrain uprising and downgrade, placement of runway signaling devices, railway tractive stock speed and weight.

Firstly, railway track between Hoštka and Mělník was chosen because of suitable terrain characteristics. Secondly, measurements of load were carried out at the traction current converter plant Hoštka. Thirdly, load simulation (based on type of railway tractive stock) was done. Measured and simulated data were compared (see the Figure 4) to evaluate accuracy of used method.

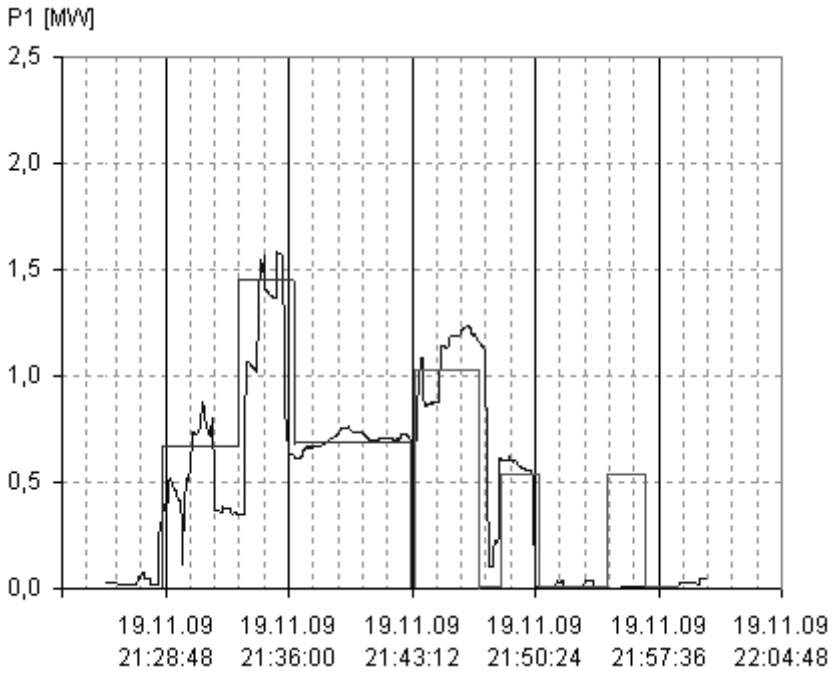


Figure 4 – DC load

The Figure 4 shows that used method does not give accurate results. Based on those results, it was concluded that only experimental data would be used for the DC traction network model.

3. Simulation of Sub-stations

3.1 The AC Sub-station

The following figure (Figure 5) describes simulation of the distribution network connected to the AC traction network. The power source of 110 kV is shown on left side with the loss network representing the distribution network. The one-phase transformer reducing voltage from 110 kV to 27 kV is placed next to this network. The AC traction network is situated in the middle of the figure and it is spited into two parts (for simulation of stock movement). The right part of the figure deals with load of the railway tractive stock.

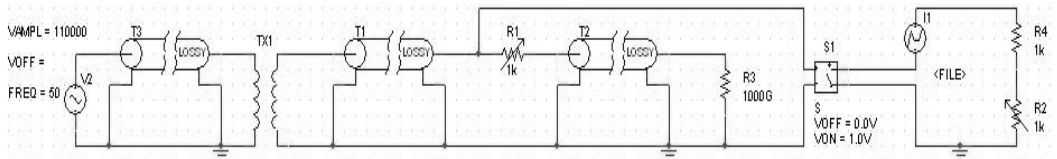


Figure 5 – Schema of AC sub-station

When the model of the AC sub-station was done, harmonic frequencies of currents flowing from railway tractive stock to the distribution network were simulated, as it is shown in the Figure 6.

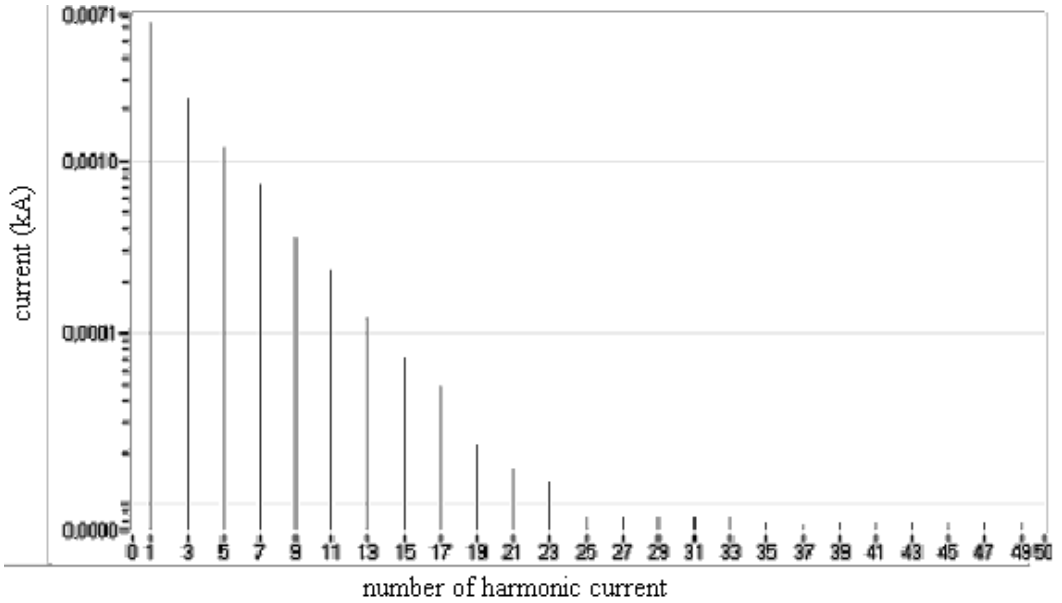


Figure 6 – The simulation of harmonic frequencies – AC sub-station

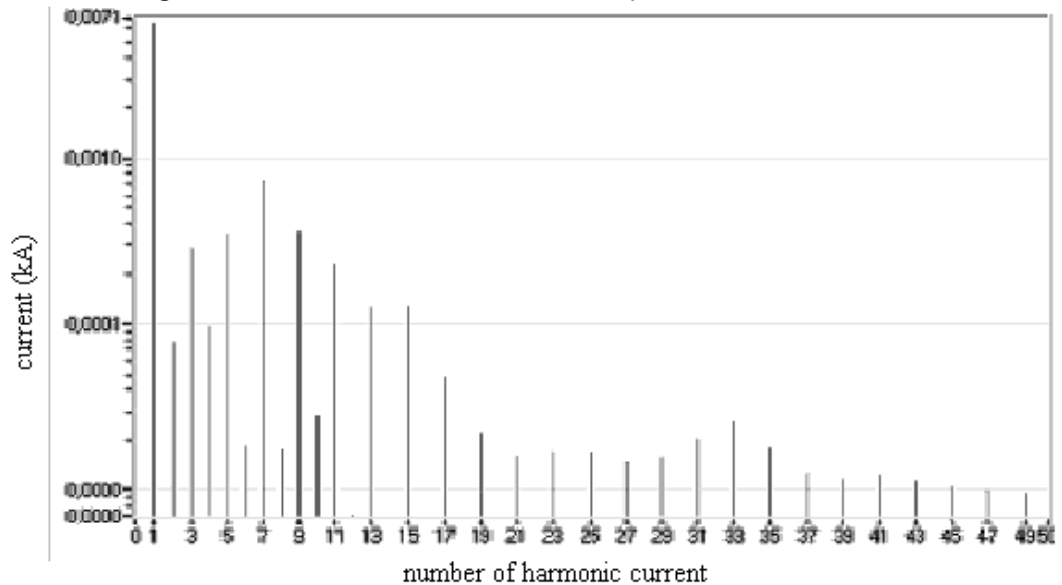


Figure 7 – The measurement of harmonic frequencies – AC sub-station

Simulated data were compared to measured data (measurements were carried out at the traction sub-station Bohatice), see the Figure 7.

The different results at 3rd and 5th harmonic frequencies could be explained as impact of FCE - compensation was higher than assumed. The results at 31st, 33rd and 35th harmonic frequencies in the Figure 6 are low because the traction sub-station was switched-off due to measurement of surroundings conditions.

3.2 The DC Sub-station

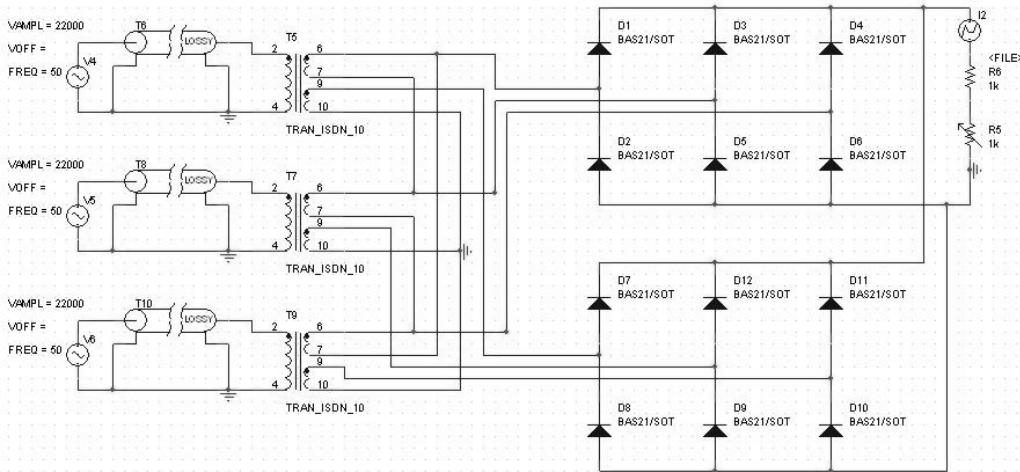


Figure 8 – Schema of DC sub-station

The figure 8 describes simulation of the three-phase distribution network connected to the one-phase DC traction network. The distribution network of 22 kV is situated on the left side of this figure. The three-phase three-wire transformer is situated in the middle of this figure. The transformer has primary wire connected in way none grounded system with clock number 0. The secondary wire consists of two parts: the first is connected in way none grounded system with clock number 0, the second is connected in delta system with clock number 1. The twelve-pulse rectifier is shown next to this transformer. This rectifier changes voltage of 2500 V at 50Hz to DC system of 3 kV. The model of railway tractive stock load is situated on the right side of the Figure 8.

When the model of the DC sub-station was done, harmonic frequencies of currents flowing from railway tractive stock to distribution network were simulated, as it is shown in the Figure 9.

Simulated data were compared to measured data (measurements were carried out at the traction sub-station Hořtka), see the Figure 10.

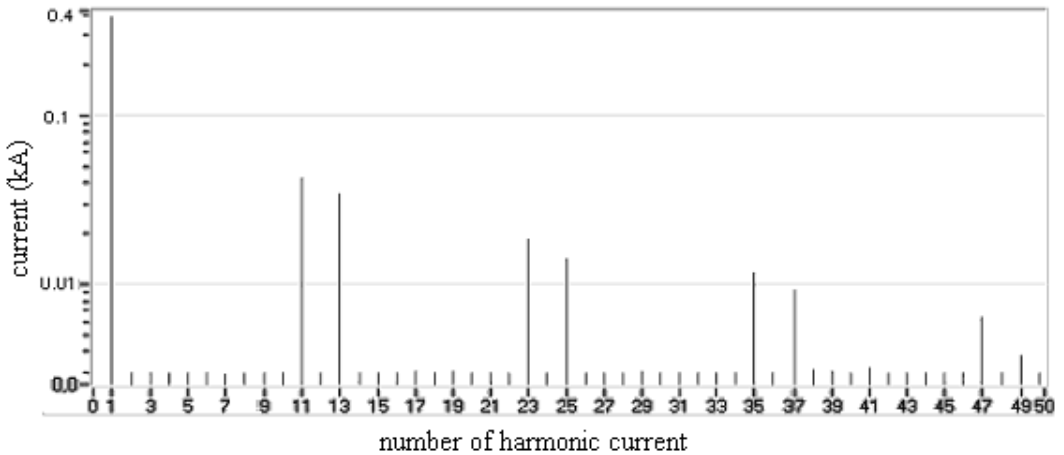


Figure 9 – The simulation of harmonic frequencies – DC sub-station

The different results at 3rd, 5th and 7th harmonic frequencies could be explained as impact of loaded distribution network (it occurred during taking real measurement). The results at 17th and 19th harmonic frequencies in the Figure 9 are zero because the traction sub-station was switched-off due to measurement of surroundings conditions.

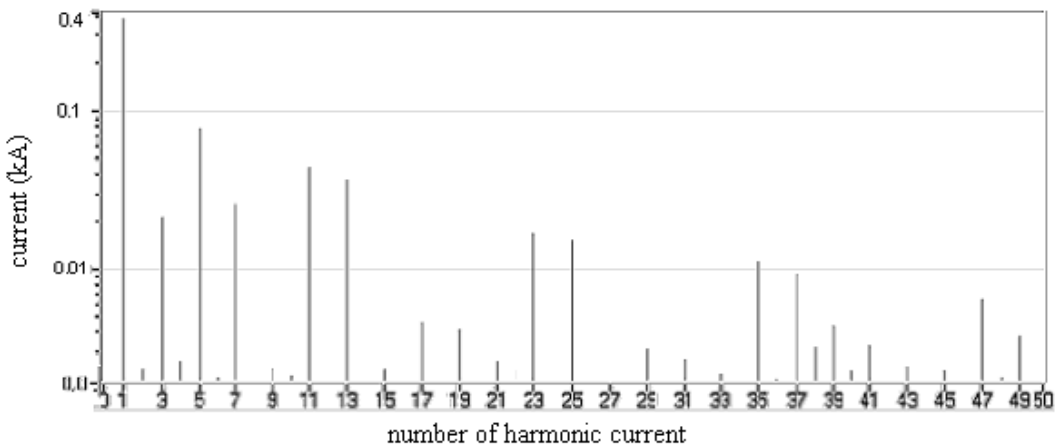


Figure 10 – The measurement of harmonic frequencies – DC sub-station

4. Discussion of Results

Software PSpice was employed to obtain simulations of particular components. Based on comparison of measured and simulated data of AC and DC traction network it was shown that current harmonic frequencies take similar values, particular differences are discussed in the previous chapter. In the end, measured and simulated data were compared to limits given by standards PNE 33 3430 and ČSN IEC 61000 -3 -4 (for harmonic frequencies of current) and the standard ČSN EN 50 160 ed.2 (for harmonic

frequencies of voltage). It was concluded that data do not meet limits stated in the standards.

5. Conclusion

The paper deals with modeling and simulation of processes in the distribution network of electric energy. The point of connection of distribution network to the traction network was chosen as the point where measurements were taken and simulation was done. Results of those simulations were compared with experimental measurements which were taken at the railway lap of traction current converter plant Hoštka – Mělník (for DC traction network) and at the railway lap of the traction sub-station Bohatice (for AC traction network).

Based on comparison of measured and simulated data of AC and DC traction network it could be concluded that current harmonic frequencies take similar values, particular differences are discussed in the paper. Another conclusion is that measured and simulated data do not meet limits for harmonic frequencies of current given by standards PNE 33 3430 and ČSN IEC 61000 -3 -4. Limits for harmonic frequencies of voltage stated in the standard ČSN EN 50 160 ed.2 are not exceeded.

6. Acknowledgement

The authors would like to thank to Ing. Jiří Krupica, in memoriam, for valuable comments, ideas and feedback.

Submitted: 26. 03. 2010

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Resum3

EXPERIMENT3LN3 M3RN3 A MODELOV3N3 HARMONICK3CH FREKVENC3 GENEROVAN3 PROVOZEM 3ESK3CH DRAH

František RAJSK3, Eva VEJVODOV3

Tento 3l3nek se v3nuje problematice modelov3n3 a simulov3n3 d3j3 v distribu3n3 s3ti ovlivn3n3 3elezni3n3m provozem. Z d3vodu 3irok3ho rozsahu tohoto t3matu je z3u3en pojem simulov3n3 d3j3 na simulaci kvality elektrick3 energie, hlavn3 na harmonick3 frekvence nap3t3 a proudu. Jako modelovan3 a m3řen3 bod distribu3n3 soustavy bylo vybr3no m3sto p3ipojen3 distribu3n3 soustavy k trak3n3 proudov3 soustav3, p3i3em3 3l3nek re33 stejnosm3rnou i jedno f3zovou st33d3vou trak3n3 proudovou soustavu.

V 3vodu 3l3nku je pops3n sou3asn3 stav problematiky stejnosm3rn3 i st33d3v3 trak3n3 proudov3 soustavy. 3l3nek se detailn3 zaob33r3 problematikou modelov3n3 jednotliv3ch 33st3 distribu3n3 a trak3n3 proudov3 soustavy, jakou jsou: venkovn3 veden3, trak3n3 veden3, filtra3n3 kompenza3n3 za33zen3, dvan33ti-pulzn3 m3ni3, trojvinu3ov3 trojf3zov3 transform3tor, trak3n3 transform3tor a spot3eba elektrick3 energie elektrick3ch hnac3ch vozidel. V3sledkem sestaven3 matematick3ch model3 jednotliv3ch 33st3 je model p3ipojen3 stejnosm3rn3 trak3n3 proudov3 soustavy k distribu3n3 s3ti 22 kV a model p3ipojen3 jednof3zov3 st33d3v3 trak3n3 proudov3 soustavy k distribu3n3 s3ti 110 kV.

Simulace jednotliv3ch matematick3ch model3 byly prov3d3ny pomocí softwaru PSpice. V3sledky z t3chto simulac3 byly porovnan3 s experiment3ln3mi m3řeními, kter3 prob3haly na 3seku trak3n3 m3n3rny Ho3tka – M3ln3k (pro stejnosm3rnou trak3n3 proudovou soustavu) a na 3seku trak3n3 transformovny Bohatice ((pro jednof3zovou st33d3vou trak3n3 proudovou soustavu). Porovnan3m simulov3n3ch a nam3řen3ch dat jednotliv3ch trak3n3ch proudov3ch soustav bylo zji33t3no, 3e proudov3 harmonick3 frekvence nab3v3j3 podobn3ch hodnot, p33padn3 odchylky jsou podrobn3n3 vysv3tleny v 3l3nku. Nam3řen3 ani simulovan3 hodnoty nep3ekra3uj3 soubor norem PNE 33 3430 a normu 3SN IEC 61 000 -3 -4 stanoven3 limity pro harmonick3 frekvence proud3. Hodnoty pro harmonick3 frekvence nap3t3, kter3 stanov3 norma 3SN EN 50 160 ed.2, nebyly takt33 p3ekro3eny.

Summary

EXPERIMENTAL MEASUREMENT AND SIMULATION HARMONICAL FREQUENCY INCURRED FROM CZECH RAILWAY

František RAJSK3, Eva VEJVODOV3

This paper deals with modeling and simulation of processes in the distribution network of electric energy. For the scope of this paper, the simulation means the simulation of quality of electric energy with the main focus on voltage and harmonic frequencies of current in distribution network. The point of connection of distribution network to the traction network was chosen as the point where measurements were taken and simulation was done.

Introduction part deals with AC and DC traction network. Then the article discusses the problem of modeling of different parts of the distribution network and traction network, such as: overhead line, contact line, Filtration Compensation Equipment, twelve-pulse rectifier, three-phase three-wire transformer, traction transformer and load of railway tractive stock. The mathematical

František RAJSK3 and Eva VEJVODOV3:

model of each part was drawn-up leading in a complex model of DC traction network connected to the 22 kV distribution network and the complex model of the one-phase AC traction network to the 110 kV distribution network.

Software Pspice was employed to obtain simulations of particular components. Results of those simulations were compared with experimental measurements which were taken at the railway lap of traction current converter plant Hoštka – Mělník (for DC traction network) and at the railway lap of the traction sub-station Bohatice (for AC traction network).

Based on comparison of measured and simulated data of AC and DC traction network it could be concluded that current harmonic frequencies take similar values, particular differences are discussed in the paper. Another conclusion is that measured and simulated data do not meet limits for harmonic frequencies of current given by standards PNE 33 3430 and ČSN IEC 61 000 -3 -4. Limits for harmonic frequencies of voltage stated in the standard ČSN EN 50 160 ed.2 are not exceeded.