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Some results of research into harmonics in the high voltage networks with distributed nonlinear loads

***Abstract**. The paper presents the results of the analysis of harmonic parameters that were measured at the nodes of connecting railway substations to the feeding network. Traction load is nonlinear, unbalanced and stochastic. The 3-rd and 5-th harmonics are dominant in the current of the traction load. The paper shows some properties and specific features of the measured parameters of 3-rd and 5-th harmonics.*

***Streszczenie.** W artykule zaprezentowano rezultaty analizy harmonicznych zmierzonych na węzłach połączeń podstacji kolejowych z siecią zasilającą. Sieć trakcyjna jest nieliniowa, niezrównoważona i stochastyczna. Dominują trzecia i piąta harmoniczna. (**Rezultaty badania harmonicznych w sieci trakcyjnej z nieliniowym obciążeniem**)*

Keywords: harmonic, measurement, railway substation, traction load.
Słowa kluczowe: sieć trakcyjna, harmoniczne

Introduction

Researchers have conducted very many experimental studies on harmonic conditions in the electric networks. The results of their analysis are presented in [1-11]. The studies aimed to analyse the properties and specific features of the harmonic conditions.

The presented paper gives some results of the measurements and analysis of the 3-rd and 5-th harmonic parameters at railway substations. The railway substations receive power from the 110-220 kV public networks with a frequency of 50 Hz. The feeding network is almost radial. The railway substations are distributed along the feeding network. The traction loads affect one another.

The objective of the research was to study the properties of harmonic behaviour in the network with distributed traction loads for identification of regularities. The obtained information will be used further to develop models of nodal loads for the calculation of nonsinusoidal conditions in the high voltage network.

Object of research

Electrified railway in Russia has been a source of harmonics for many years. It is very extended. In East Siberia railway occupies a special place since it is part of the Trans-Siberian railway. The railway runs across the territories with sparse population and small electric loads. At the same time the railway traffic is heavy. The time interval between trains varies from 5 to 20 minutes. The railway substations are as a rule located at a 40-60 km distance from one another, i.e. they are quite evenly distributed along the feeding network. Each section of railway between two substations receives power from two sides. The railway substation has two 40 MVA three-winding transformers. One of them is a reserve transformer. The 25 kV winding of the transformer supplies power to the traction network, whereas 6 (11) kV winding supplies power for auxiliary needs of the substation and to non-traction consumers located near the substation.

Electric locomotives receive power from the traction network. They are driven by DC engines. The engines are powered through single-phase two-pulse rectifier circuits. The rectifier circuits in the traction network cause harmonic currents. The currents of the 3-rd and 5-th harmonics have the largest value. The harmonic currents penetrate through transformers into the 110-220 kV feeding network and cause a distortion of the voltage waveform. Thus, the traction load for the feeding network is nonlinear, unbalanced and distributed. The measurements show that the voltage nonsinusoidality at the nodes of connecting railway substations to the feeding network exceeds the standard limits established in Russia [12].

The considered railway section is situated in East Siberia between the substations Mysovaya and Novoilinsky. The section contains 9 railway substations. Measurements were taken at four substations: Mysovaya, Tataurovo, Zaigraevo, Novoilinsky. For simplicity, we will denote the substations by letters M, T, Z and N respectively. The substations are located as follows: the substation T - in 126 km from the substation M, the substation Z - in 86 km from the substation T, the substation N - in 47 km from the substation Z. Arrangement of the substations relative to each other is presented in Fig. 1, where EPS – electrical power system.

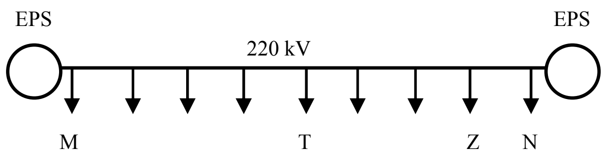


Fig.1. Arrangement of the railway substations

The measurements were carried out at the points of common coupling of railway substations to the feeding network, i.e. on the high voltage side of the transformers. Measurements were performed with the aid of the device "OMSK", which measures not only the indices of power quality but also currents, powers and other parameters. Each measurement was performed during 24 hours. The parameters were measured mainly in an interval of 1 minute. For voltage measurements the device was connected through voltage transformers to the high voltage buses. For current measurements the device was connected to current transformers installed at the inputs of high voltage transformers.

Measurements were made for three connection schemes of the railway substation:

- scheme I – traction network feeder is connected, i.e. traction network receives electric energy from the 25 kV transformer winding at the railway substation;
- scheme II – traction network feeder is disconnected, i.e. traction network does not receive electric energy from the 25 kV transformer winding at the railway substation;
- scheme III – passive filter in the traction network is disconnected at the railway substation.

The disconnection of the traction network feeder at either of the two substations means that the section of traction network receives electric energy only from one substation. Passive filter is tuned to absorb the 3-rd and 5-th harmonic currents. Fig. 2 shows the scheme that explains connection of transformer and circuit breakers for three schemes during measurements. The number near the circuit breaker corresponds to the number of the scheme in which the circuit breaker was switched on.

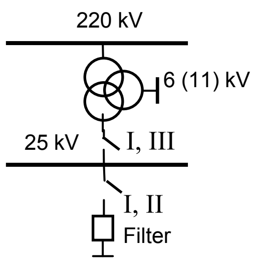


Fig.2. Connection scheme of transformer and circuit breakers

Harmonic voltages in terms of the standard requirements

The measurements show that the standard limits [12] are considerably exceeded at 3-rd and 5-th harmonics. The values of measured harmonic voltages U_3, U_5, that represent the values with a probability of 95% are presented in Table 1. The values exceeding the limits are highlighted in bold.

Table 1. Measured values of U_3, U_5 [%]

Sub-station	Scheme	Phase A		Phase B		Phase C	
		U_3	U_5	U_3	U_5	U_3	U_5
M	I	1.2	**2.0**	1.3	**2.1**	**1.6**	**2.2**
	II	1.2	**1.9**	1.4	**2.1**	1.4	**1.8**
T	I	**2.7**	**2.5**	**2.5**	**3.6**	**2.1**	**3.2**
	II	**2.2**	1.4	**1.9**	**1.6**	**2.1**	1.2
Z	I	1.1	1.3	1.1	1.2	**1.7**	1.0
	II	1.0	1.4	0.9	1.4	**1.8**	1.3
	III	1.1	1.5	1.0	1.5	**1.7**	1.4
N	I	0.9	1.3	0.9	**1.6**	**1.6**	**1.7**
	II	1.3	**1.8**	0.9	**2.1**	**1.8**	**1.9**
	III	**1.7**	**1.8**	1.3	**1.8**	**2.7**	**1.7**
Limits	95%	1.5	1.5	1.5	1.5	1.5	1.5

Table 1 shows that:

- disconnection of traction network feeder at substation M increased insignificantly the 3-rd harmonic voltage in phase B, but decreased it in phase C, and decreased the 5-th harmonic voltage in all phases;
- disconnection of traction network feeder at substation T decreased voltage at all harmonics in all phases;
- disconnection of feeder at substation Z decreased the 3-rd harmonic voltage in two phases (A, B) and increased it in phase C, increased the 5-th harmonic voltage in all phases; disconnection of passive filter decreased the 3-rd harmonic voltage in all phases but increased the 5-th harmonic voltages;
- disconnection of both traction network feeder and passive filter at substation N increased the voltage of the 3-rd and 5-th harmonics in all phases.

High harmonic voltages at disconnected traction network feeder testify to the fact that they are formed not only by the currents from the traction network but also by the currents drawn in the feeding network from other nonlinear loads. The decrease in the 3-rd harmonic voltage after disconnection of passive filter at substation Z is the evidence of passive filter malfunction.

The obtained results confirm that the harmonic conditions are complex, unpredictable and require thorough research before modelling them.

Active and reactiv powers of the fundamental frequency

Fig. 3 shows the curves of active and reactive powers for phase B for schemes I and II for substation N. They demonstrate a typical character of change in the powers at railway substations. The curves of active and reactive powers at all substations are very similar. When the traction network feeder is connected, the powers are highly variable (Fig.3a). When traction load is disconnected, the curves of powers are ordinary (Fig.3b). The highly variable character of powers at connected traction network feeder occurs as a result of summing up the powers of a large amount of electric locomotives that operate simultaneously. In Fig. 3b a long-term decrease in powers corresponds to the night time. The power curves at connected feeder represent the total powers consumed by electric locomotives and non-traction loads. At the same time the powers of traction loads exceed the power of non-traction loads by 2-4 times.

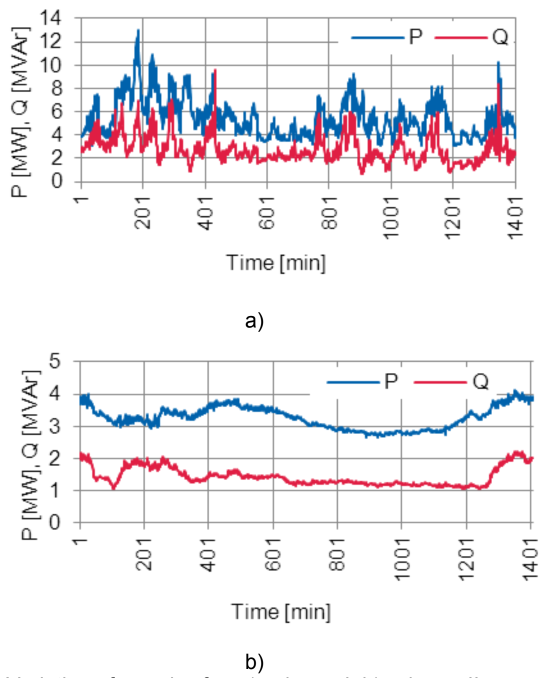


Fig. 3. Variation of P and Q for: a) scheme I, b) scheme II

The 3-rd and 5-th harmonic currents

Daily measurements of the harmonic currents represent time-series of values (Fig.4).

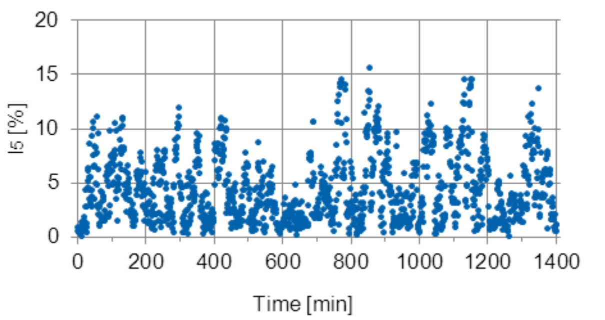


Fig. 4. Scatter plot of the 5-rd harmonic current as function of time

The analysis of the measured time-series of harmonic currents shows that they are non-stationary.We present the results of stationarity analysis of the time-series for the 5-th harmonic current at phase A for substation Z as an example. The time-series was divided into 4 equal intervals of 360 elements each. The mean value and variance were calculated for each interval and are presented in Table 2. The data of the Table 2 show that the mean values and variances for each interval differ in value, which gives evidence of non-stationary time-series. Analysis of the measured currents of the 3-rd and 5-th harmonics at the other substations has showed that their time-series are also non-stationary.

Table 2. Mean values and variances

Series interval	1	2	3	4
Mean value	4.96	4.01	5.35	4.02
Variance	1.58	1.89	1.70	2.01

The current curves closely resemble the above given power curves, but have a different shape. In the majority of the studied cases the values of correlation coefficients between harmonic powers and currents are low, which testifies to the weak correlation. However, in some cases there is a noticeable and high correlation, even with an opposite sign. The correlation coefficients between the active and reactive powers and the 3-rd and 5-th harmonic currents for substation N are presented in Table 3 for the sake of illustration.

Table 3. Correlation coefficients between I_3, I_5 and P, Q

Scheme	Harmonic	Phase A		Phase B		Phase C	
		$r_{P,I}$	$r_{Q,I}$	$r_{P,I}$	$r_{Q,I}$	$r_{P,I}$	$r_{Q,I}$
I	3	0.49	-0.04	0.31	**0.56**	0.32	0.18
	5	**-0.61**	0.49	0.23	-0.17	-0.26	-0.09
II	3	**-0.65**	-0.46	-0.08	-0.02	-0.32	-0.14
	5	**-0.87**	**-0.68**	**-0.85**	**-0.69**	**-0.88**	**-0.66**
III	3	0.40	0.32	0.47	**0.56**	**0.71**	**0.68**
	5	-0.22	**0.58**	**0.59**	**0.74**	0.25	0.47

In scheme II the correlation coefficient in phase C equals -0.88, which is vividly shown in Fig.5. The 5-th harmonic current decreases with the active power increase and increases with its decrease. The curve of the 3-rd harmonic current changes less sharply than the curve of the 5-th harmonic current. At the same time, we clearly see the sections, where with the increase of active power the current value decreases, and vice versa. The correlation coefficient in phase C between the active power and the 3-rd harmonic currents is equal to -0.32.

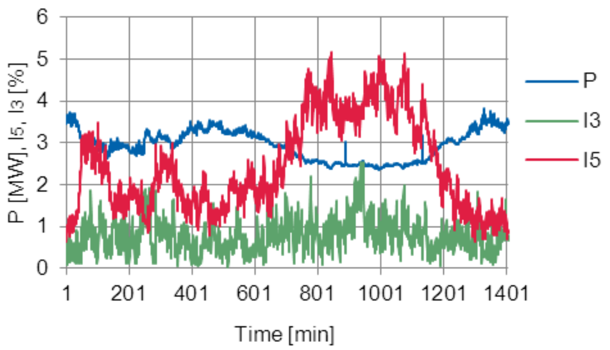
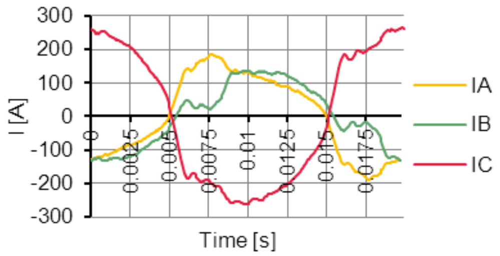
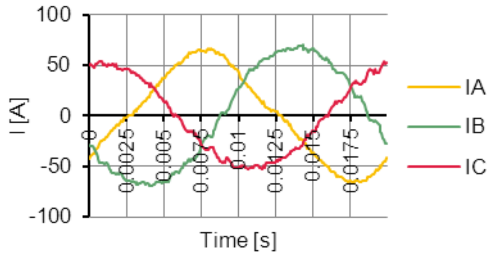


Fig. 5. Variation of the harmonic currents and the active power

The current waveform is much distorted. It changes with time, but in general, it remains typical despite the great variety. Fig. 6 presents the oscillograms of currents for the connected feeder and disconnected feeder at substation M. The current waveforms are much less distorted, when the feeder is disconnected.



a)



b)

Fig.6. Current oscillograms for: a) scheme I, b) scheme II

The analysis of harmonic composition of the traction load current shows that the value of the 3-rd harmonic current varies from 25% to 30% of the fundamental frequency current, and the value of the 5-th harmonic current is within the range from 8% to 10% of the fundamental frequency current. Table 4 presents the statistical estimates of the 3-rd and 5-th harmonic currents in one of the phases of each substation. The obtained values are of approximately the same order of magnitude at all the substations

Table 4. Statistical estimates of the 3-rd and 5-th harmonic currents

Substation	Harmonic	Maximum value	Minimum value	Mean value	Standard deviation
M	3	52.31	0.53	12.59	8.49
	5	34.27	2.72	12.74	5.14
T	3	23.86	0.35	9.61	4.23
	5	16.12	4.25	9.68	1.95
Z	3	15.78	0.19	5.02	3.14
	5	7.65	0.68	3.74	1.38
N	3	18.59	0.18	6.14	3.87
	5	9.94	1.13	4.35	1.39

The curves of powers and currents demonstrate a largely probabilistic character of harmonic behaviour. Fig. 7 presents the histogram of the 3-rd harmonic current in phase A, which is measured at substation N in scheme I. This histogram has one peak.

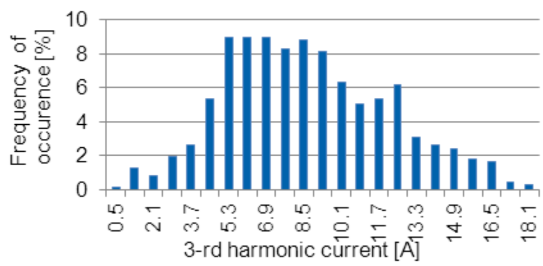


Fig. 7. Histogram of the 3-rd harmonic current

The histogram of the 5-th harmonic current in Fig. 8 has two peaks. The histograms are constructed to get an idea of the distribution function form of the measured currents of the 3-rd and 5-th harmonics. Suitable models describing the probability distribution functions of the measured harmonic parameters are to be yet chosen at a later date.

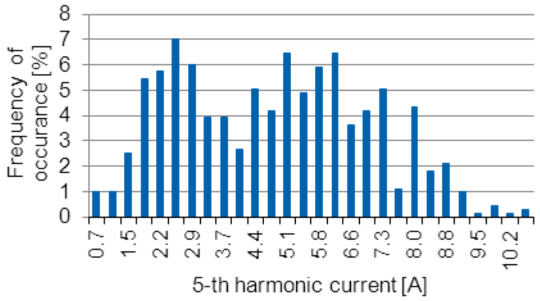


Fig. 8. Histogram of the 5-th harmonic current

The properties of active and reactive components of harmonic currents are of particular interest for constructing models of non-linear loads. The histograms in Fig. 9 present the values of active and reactive components of the 5-th harmonic current. The histogram of the active current components has several faint peaks (Fig.9a). The histogram of the reactive current components (Fig.9b) has two peaks as well as the histogram of the current module in Fig. 8. The histograms of the values of active and reactive current components are the probability density functions of different forms.

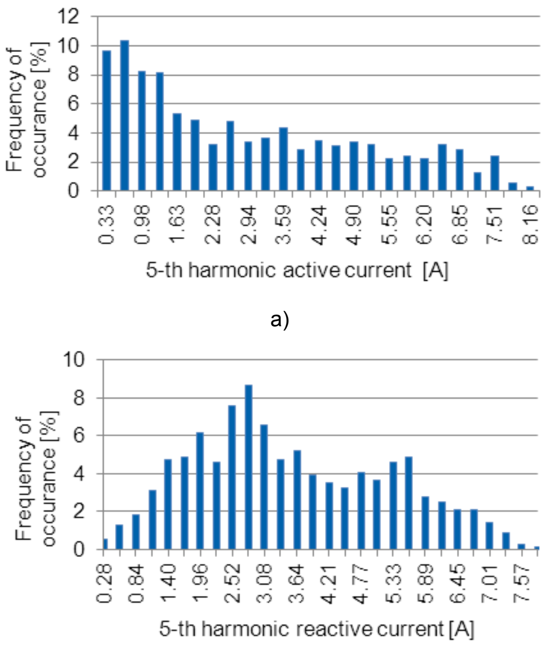


Fig. 9. Histograms of active a) and reactive b) components of the 5-th harmonic current

Fig. 10 presents the currents of the 3-rd harmonics in phase A of substation N for schemes I and II in the form of scatter plots on a complex plane. The diagrams make it possible to evaluate the phase angles of currents. The distributions of phase angles for 3-rd harmonic in schemes I and III differ very little from each other. The phase angles for the 3-rd harmonic are within the range from 0 to π. The phase angles for the 5-th harmonic are within the range from π/2 to 2π. Disconnection of the traction substation feeder considerably changes the phase angles. The changes take place in the scatter plots and ranges of phase angles. The phase angles for the 3-rd harmonic are distributed within the range from 0 to 2π, and for the 5-th harmonic – within the range from –π/2 to π/2.

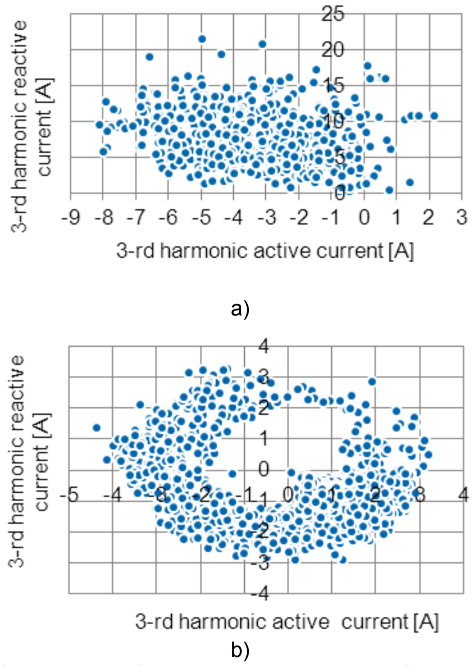


Fig. 10. Scatter plots of the 3-rd harmonic currents for: a) scheme I, b) scheme II

Analysis of the interrelation between voltages and currents of the 3-rd and 5-th harmonics

The values of harmonic voltages at the points of common coupling are largely determined by the values of currents of loads connected to the node. The influence of harmonic currents passing through the substation transformers on the values of corresponding voltages is assessed by the correlation coefficients in Table 5.

Table 5. Correlation coefficients between I_3, U_3 and I_5,U_5

Substation	Scheme	Phase A		Phase B		Phase C	
		$r_{U3,I3}$	$r_{U5,I5}$	$r_{U3,I3}$	$r_{U5,I5}$	$r_{U3,I3}$	$r_{U5,I5}$
M	I	0.13	0.41	0.12	0.06	-0.06	0.13
	II	0.14	0.26	0.31	-0.04	-0.38	**-0.56**
T	I	0.29	0.20	0.37	**0.53**	**0.63**	0.45
	II	0.05	-0.06	-0.04	-0.07	0.08	-0.12
Z	I	0.24	0.06	0.12	-0.01	-0.11	0.03
	II	**0.52**	**0.68**	**0.64**	0.46	**0.89**	**0.61**
	III	0.22	0.25	0.25	-0.06	-0.19	0.21
N	I	0.28	0.14	**0.60**	0.07	0.33	0.45
	II	-0.35	**0.64**	0.23	**0.72**	-0.07	**0.71**
	III	0.4	0.13	0.54	0.24	**0.57**	0.23

The correlation coefficients are determined for all the schemes given in Table I. The values of correlation coefficients that correspond to the noticeable and high values are shown in bold. There is a considerable linear relationship between the voltages and currents of the 3-rd and 5-th harmonics at substation Z in scheme II and of the 5-th harmonic at substation N in scheme II. In most of the other cases the relationship is weak, which indicates a strong influence of the harmonic currents of other nonlinear loads on the voltage. The harmonic voltage at the substation arises due to the effect of numerous nonlinear loads connected to the feeder.

Resonance conditions at the 3-rd and 5-th harmonics

The measurements at substation T that were made by metering device demonstrated a sharp increase in the 3-rd and 5-th harmonic voltages. Fig. 11 shows a range of measured 5-th harmonic voltages in which resonance conditions are well seen. A sharp increase in voltage occurs after the 15-th measurement. It turned out that at this moment a 44 MVAr capacitor bank was switched on at the substation of power supply organization, which is located in the area of railway substation T, to maintain the fundamental frequency voltage.

Further analysis and calculations showed that after switching the capacitor bank a resonance loop occurred between the capacitor bank and network at the 3-rd and 5-th harmonics. Before the connection of capacitor bank the input conductance at the network node at the 3-rd harmonic was inductive, whereas after the connection its value decreased almost by 4 times. At the 5-th harmonic the input conductance became capacitive but of a very low value. The capacitor bank compensated the inductive conductance of the network node. The 3-rd and 5-th harmonic conditions are unbalanced. Unbalance of voltages and currents increased after the connection of capacitor bank.

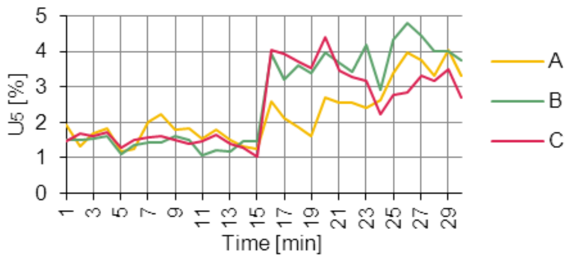


Fig. 11. Change in the 5-th harmonic voltages after connection of capacitor bank

Conclusions

At all the substations, where the measurements were taken, the standard limits harmonic voltages were exceeded. The limits of the 3-rd and 5-th harmonic voltages were exceeded most frequently and to a greater degree.

Oscillograms of phase currents essentially differ from sinusoidal form when feeders of traction network are switched on. Currents are considerably unbalanced.

Traction load introduces a significant probabilistic component to the harmonic behaviour in the network. The harmonic currents in the network with numerous distributed nonlinear loads are conditioned by the effect of numerous loads.

Currents of the 3-rd and 5-th harmonics represent non-stationary time-series. They are weakly correlated with fundamental frequency active powers in the scheme with connected feeders of traction network. A greater extent of correlation is observed in the schemes with disconnected passive filters. Considerable correlation occurs in the schemes with disconnected feeders of traction network. Strong correlation between harmonic currents and voltages is revealed in the schemes with disconnected feeders of traction network at all substations except for T.

Probability distributions of currents of the 3-rd and 5-th harmonics have single- and double-peaked histograms, whose forms usually differ from the normal distribution. Histograms of active and reactive current components have different forms of probability density functions.

In the general case the phase angles of currents of the 3-rd and 5-th harmonics are within the range from 0 to 2π and change at disconnection of the traction network feeder.

Connection of capacitor bank resulted in resonance conditions at the 3-rd and 5-th harmonics, which increased voltages and currents of the 3-rd and 5-th harmonics.

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