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Experimental Analysis of Electrical Modes in a Residential Estate Electrical Power Supply System

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Abstract: The modern structure of power supply system is characterized by an expanding non-linear load which has a pulse nature of electrical energy consumption, a wide range of higher harmonics and a low electromagnetic compatibility with the supply mains. Unsymmetrical load due to single-phase power-consuming electrical receivers has also a negative impact on the electrical power supply system which leads to unbalance current flow in a neutral wire. In this regard, the power consumption modes experimental analysis was carried via measuring with the aid of certified devices "Energomonitor-3.3T1" and "C.A 8335" as well as by means of simulation modeling using matlab simulink software package. Experiment and simulation results confirmed the presence of the higher harmonic components of currents and voltages as well as the unbalance of loads caused by the presence of non-linear electrical receivers and unbalance of loads per the phases. It was drawn the conclusion that for improving the power factor within the microdistrict electrical power supply system as well as improving electric power quality, it is necessary to develop such compensation methods that would simultaneously solve the problems of improving the electric power quality in case of random changes in load parameters within the microdistrict electrical power supply system.

Key words: Electromagnetic compatibility, nonsinusoidality, unbalance, harmonics, power quality

INTRODUCTION

It is essential that information about changes of basic parameters through time, specifically: operating values of currents and voltages in all phases and in neutral conductor; capacities; spectra of upper harmonics; unbalance ratios, etc., should be available in order to optimize the electrical modes in the electric power supply systems of residential estates. The main methods of obtaining information about the parameters of electric power supply system modes are the measurement with the help of special instruments, simulation modeling and analytical calculations. The first two ways of information gaining are used in this study. The fragment of a residential estate electric power supply system is presented in Fig. 1.

Household Electrical Receivers (ER), outdoor lighting are the main consumers of a microdistrict. The most common ER with non-linear current-voltage characteristics are as follows: computer equipment personal computers, laptops, internet-equipment; consumer electronics-LCD TV sets, audio systems, charging devices; energy-saving sources-compact fluorescent and LED lamps for indoor and outdoor lighting (Yanchenko, 2014). The presence of ER with non-linear current-voltage characteristic deteriorates the quality of electrical power in the building estate electric power supply system as they are the generators of upper harmonics of currents and voltages (Meyer *et al*., 2011; Cuk *et al*., 2010; Rodriguez *et al*., 2009; Averbukh *et al*., 2015). An unbalanced load caused by uneven load distribution in phases also has the negative impact on a building estate power supply system which leads to the asymmetry of currents and voltages in three-phase four-wire electrical power supply system and the flow of unbalance current in a neutral wire (Loskutov *et al*., 2013).

MATERIALS AND METHODS

To evaluate the basic parameters and indices of electric power quality in a building estate power supply system in accordance with GOST 32144-2013 (GOST, 2013) specifically: the harmonic components of the voltage up to the 40th of the order $K_{U(n)}$ as a percentage of the voltage of main harmonic component U_1 at the supply terminal;

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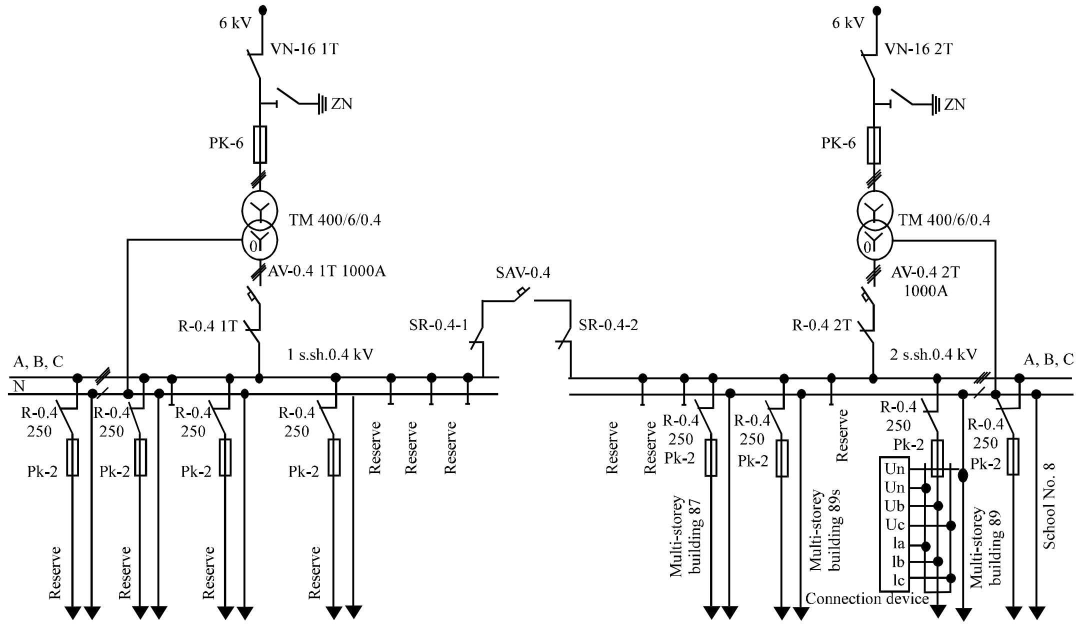

Fig. 1: Fragment of a residential estate electric power supply system

total ratio of voltage harmonic components (the ratio of root-mean-square value of the sum of all harmonic components up to the 40th order to the root-mean-square value of the main component) K_U (%) at the supply terminal; voltage unbalance factors based on the reverse sequence K_{2U} and of voltage unbalance based on the null sequence K_{0U} at the supply terminal averaged within the time interval of 10 min should not exceed 2% during 95% of the time interval per 1 week; factors of voltage unbalance based on the reverse sequence K_{2U} and of voltage unbalance based on the null sequence K_{0U} at the supply terminal averaged within the time interval of 10 min should not exceed 4% during 100% of the time interval per 1 week, the measurements were performed for a period of 24 h by means of instruments "Energomonitor-3.3T1" and C.A 8335 (Qualistar +) (Esfahani *et al*., 2013). The appearance of the instruments and connection diagram is shown in Fig. 2.

The metrological characteristics of the instruments are presented in Table 1. Current measurement channels were being connected through the clamp-on meters per 100 A. Voltage measurement channels were being connected directly to the controlled network. The procedure for measuring is as follows:

- Connect the power and measurement cables to the instruments Energomonitor-3.3T1 and C.A 8335 in accordance with the scheme of Fig. 2

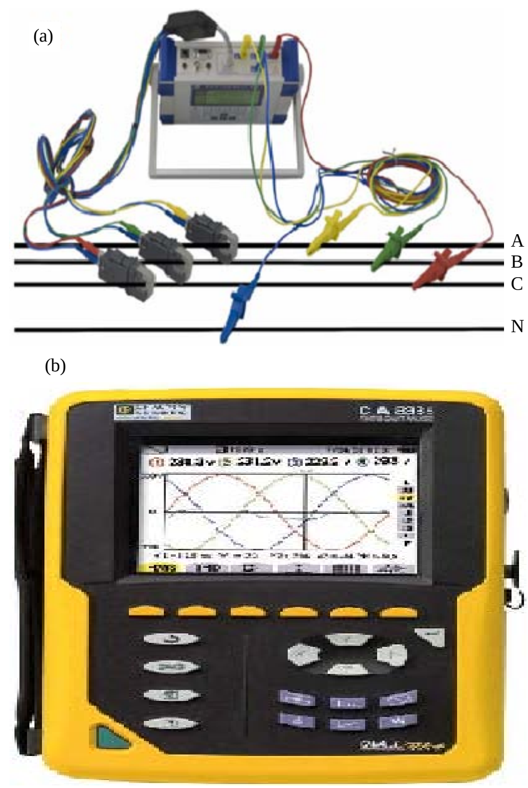

Fig. 2: The appearance of the instruments and diagram of connection to four-wire network 0.4 kV; a) Energomonitor-3.3T1 (No. 1) and b) C.A 8335 (Qualistar +) (No. 2)

Table 1: Metrological characteristics of the instruments

	Measuring range		Maximum error (%)
Measurement parameters	No. 1	No. 2	No. 1 and 2
Frequency	40-400 Hz	40-69 Hz	± (1 least significant digit value)
Phase voltage	10-1000 V	10-1000 V	± (0.5%)
Line voltage	10-1000 V	10-1000 V	± (0.5%)
Current	10-6500 A	10-6500 A	± (0.5% +1 A)
Active power	0-9999 kW	0-9999 kW	± (1.5%+) 0.5≤cosφ<0.8
Reactive power	0-9999 reactive kilovolt-ampere	0-9999 reactive kilovolt-ampere	± (1.5%) 0.2≤sinφ<0.5
Power factor	-1-1	-1-1	± (1.5%) 0.2≤cosφ<0.5
Total Harmonic Distortion (THD)	0- 999.9%	0-999.9%	± (1%)
Distortion factor	0-999.9%	0-999.9%	± (1%)

(a)

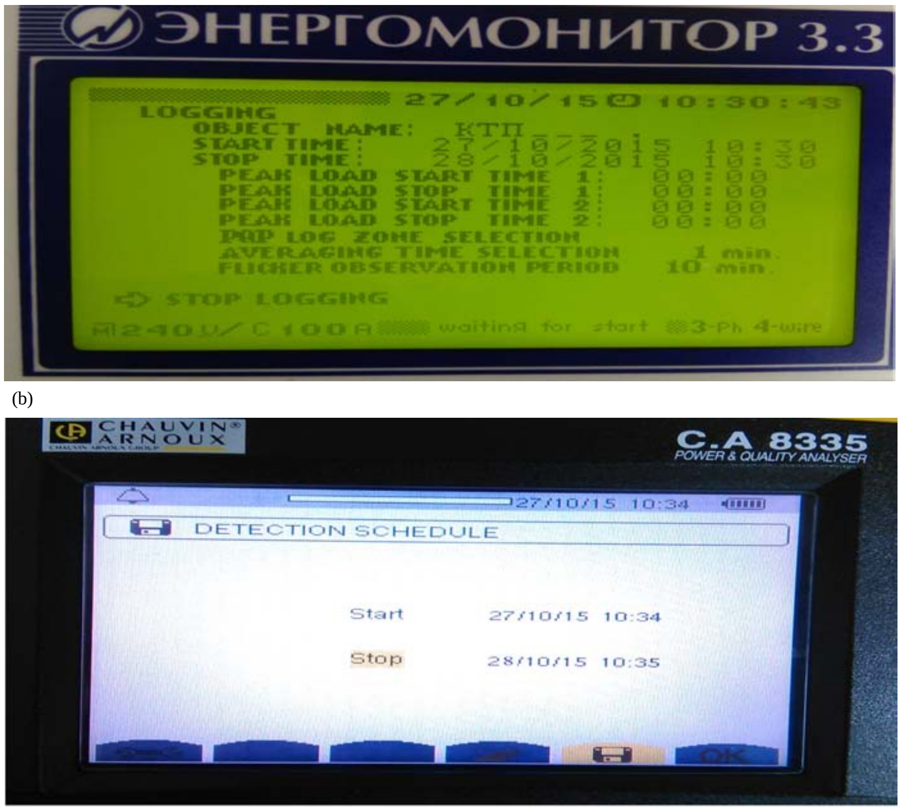

Fig. 3: a, b) The screen of the instruments during registration of PQI

- Turn off the power from the substation busbars via an automatic circuit breaker
- Set the required recording parameters and the measurement range of current and voltage on the measuring instruments
- Connect the clamp-on meters and voltage inputs to the substation busbars
- Apply power to the transformer substation busbars
- Activate the mode of electricity mains parameter recording (current, voltage, power) and electromagnetic compatibility indicators within 24 h
- De-energize the generator and disconnect the instrument from their secondary windings upon completion of recording time

The screenshots of the instrument screens Energomonitor-3.3 T1 and C.A 8335 during registration of Power Quality Indices (PQI) are shown in Fig. 3. The measurement results are presented in the form of graphs and tables which were being documented in the report and signed by the specialists of the district network. The measurements were being performed with a time interval of 1 min within 1 day.

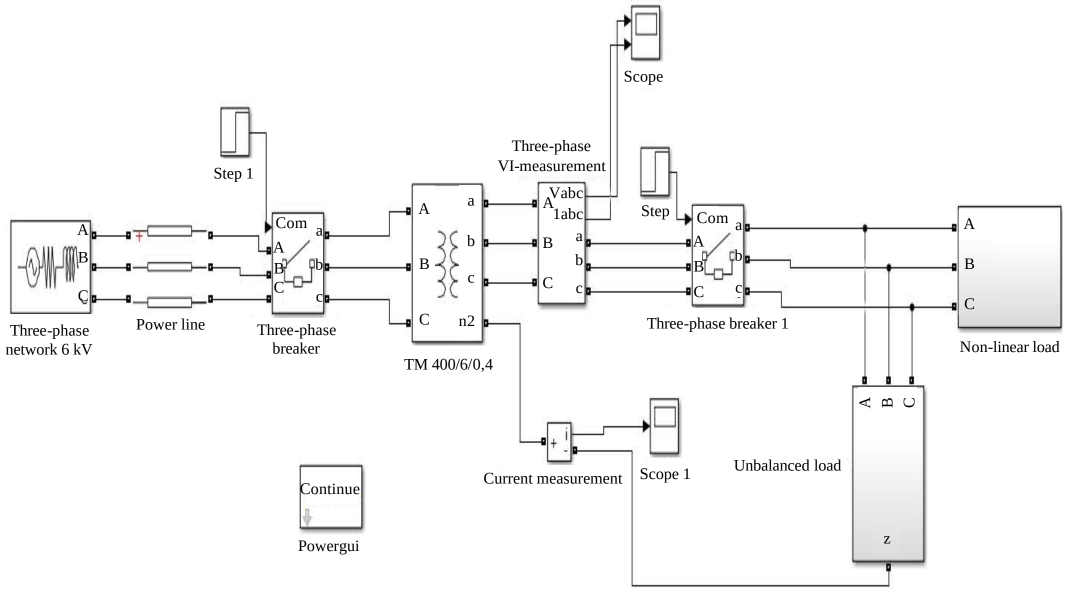

Fig. 4: Virtual model of a fragment of a building estate electric power supply system in matlab simulink package

The reliability of measurement results was checked by simulation modeling. The Matlab software package 7 was chosen as a medium for model development. The fragment of a building estate electricity mains model is shown in Fig. 4. This model supplemented with Powergui block makes it possible to research the spectral content as well as the voltage unbalance and load currents. The simulation model is constructed according to power supply scheme Fig. 1 and contains the equivalent units of the three-phase voltage source, communication line with the voltage of 6 kV, step down transformer and the load in the form of ER with non-linear volt-ampere characteristics and unsymmetrical distribution in phases.

3-Phase Source block is used as a power supply source comprising three ac voltage sources connected in star. Measurement units of single-phase and three-phase current and voltage (voltage measurement, current measurement, three-phase V-I measurement) take measurement of the instantaneous value of current (voltage) flowing through the connecting line. Simulink normal signal which is then displayed on an oscilloscope is an output signal. The positive direction of current (voltage) is set by the signs "+" and "–" on the block icon. Simulation of three-phase double-winding transformer (TMP-400/6/0.4) is performed by means of block three-phase transformer (Two windings) built based on three single-phase transformers (Tahmassebpour, 2017).

RESULTS AND DISCUSSION

The measurement results by means of Energomonitor instrument are presented in Table 2. It follows from the measurement results that the load falling on each phase is asymmetric. The difference of active powers of the phase A and C is 79%, the difference of the phase B and C is 73% and the difference of the phase B and A is 93% which also confirms the presence of an asymmetric work mode. The value of aggregate coefficients of harmonic components by voltage and current within 24 h falls within the limits of: K_I = 15.8-29.33%; K_U = 2.4-2.71%. At the same time, total coefficients of harmonic components based on voltage do not exceed the permissible values of 5%. The results of measurements by the instrument CA 8335 and simulation are presented in Table 3.

Unbalance of phase voltages is inconsiderable but phase currents may differ from each other by 100% which causes sufficiently large current flow in the fourth wire. The spectra of upper harmonics of currents and voltages in a building estate electrical network are shown in Fig. 5. The maximum total current nonsinusoidality ratio is about 30% but the total voltage nonsinusoidality ratio does not exceed 3% at the same time. However, this is only due to low resistance of the measurement circuit. Since, the circuit resistance from the measuring point to the secondary winding of step-down transformer is taken into account in the instrument when measuring. However,

Table 2: Indications of the instrumentEnergomonitor 3.3 T1

Measurement No.	K_{UA} (%)	K_{UB} (%)	K_{UC} (%)	K_{IA} (%)	K_{IB} (%)	K_{IC} (%)	U_A (V)	U_B (V)	U_C (V)
1	2.6	2.4	2.1	20.8	20.45	20.8	225.1	224.8	223.4
2	2.5	2.4	2.1	23.0	21.38	18.9	225.7	224.4	223.4
3	2.5	2.4	2.1	23.6	22.56	18.5	225.2	224.4	224.5
4	2.6	2.4	2.1	22.3	23.08	11.8	224.7	225.6	223.4
5	2.6	2.4	2.1	21.6	22.96	13.0	224.3	225.5	223.2
6	2.6	2.4	2.1	21.2	23.72	13.9	225.0	225.8	223.3
7	2.7	2.4	2.2	21.2	29.33	16.5	225.2	226.0	223.4
8	2.6	2.4	2.1	19.7	25.63	15.8	225.8	226.4	222.9
9	2.6	2.4	2.2	20.9	24.26	22.6	226.0	225.7	223.8
10	2.6	2.4	2.2	20.8	23.33	23.5	226.1	226.6	223.1
No.	U_{AB} (V)	U_{BC} (V)	U_{CA} (V)	P_A (W)	P_B (W)	P_C (W)	Q_A (var)	Q_B (var)	Q_C (var)
1	387	387	390	2483	2170	3007	553	957	1133.80
2	387	388	390	2316	2136	3041	570	911	1247.80
3	387	388	391	2247	2158	3155	586	917	1247.40
4	387	388	390	2250	2178	4766	571	944	1275.30
5	387	387	390	2184	2143	4411	526	929	1150.40
6	388	388	391	2167	2082	4347	543	925	1149.30
7	388	388	391	2245	1833	4297	527	715	954.51
8	388	388	391	2383	2119	4428	513	620	1118.90
9	388	389	391	2331	2186	3075	522	642	1075.20
10	389	389	392	2320	2245	3078	521	690	1061.60

K_U: aggregate coefficient of harmonic components by voltage (%); K_I: aggregate coefficient of harmonic components by current (%); $U_{A, B, C}$: phase voltages; $U_{AB, BC, CA}$: line voltages; $P_{A, B, C}$: active power in each phase; $Q_{A, B, C}$: reactive power in each phase

Table 3: Indications of the instrumentEnergomonitor C.A 8335 and results of the simulation

	Parameters obtained from measurement/simulation								
No.	K_{UA} (%)	K_{UB} (%)	K_{UC} (%)	K_{IA} (%)	K_{IB} (%)	K_{IC} (%)	U_A (V)	U_B (V)	U_C (V)
1	3.2/3.8	2.9/3.2	2.5/2.9	15/2.8	2.9/2.5	3.1/2.5	225.8/218.2	226.1/217.8	224.1/217.7
2	3.1/3.6	2.9/3.5	2.5/2.9	15.4/13.1	5.9/5.1	4/3.3	225.8/218.2	225.9/218.2	224.6/218.2
3	3/3.8	2.8/3.5	2.4/2.9	15.7/13.2	7.4/5.9	4.3/3.6	226.1/218.7	225.8/218.2	224.6/218.2
4	3/3.5	2.8/3.5	2.4/3	12.1/10.4	6/5.9	4.2/3.6	225.7/218.6	225.4/219.1	225.8/218.5
5	2.9/3.5	2.7/3.6	2.4/2.9	11.2/10.8	3.8/3.4	4/3.2	225.3/218.3	225.1/218.7	226.8/219.5
6	2.9/3.5	2.7/3.7	2.4/2.9	12.4/11.1	3.9/3.4	4/3.3	225.4/219.1	224.8/218.1	226.9/220.2
7	3/3.9	2.8/3.8	2.5/3.1	14.7/13.2	6.3/5.5	4.2/3.3	224.9/218.8	225.4/219.2	227/220.6
8	3.1/4.1	3/3.8	2.5/3.1	14.6/13.2	6.6/5.8	4.2/3.2	224.9/218.8	225.5/219.1	226.2/220.2
9	3.1/4.1	2.9/3.8	2.3/2.8	14.6/13.3	7/6.2	4.2/3.1	225.7/218.7	225.9/219.8	225.3/219.3
10	3.1/3.9	3/3.7	2.4/2.8	14.7/13.4	2.8/2.7	4/3.1	226.1/219.3	225.5/219.7	226.1/218.9
	Parameters obtained from measurement/simulation								
No.	U_{AB} (V)	U_{BC} (V)	U_{CA} (V)	P_A (W)	P_B (W)	P_C (W)	Q_A (var)	Q_B (var)	Q_C (var)
1	1841.3/1823.3	4780.9/4758.6	4951.1/4932.2	1896.8/1875.6	1389.6/1362.3	1054.4/986.8	11.6/10.5	22/20.8	22.4/21.4
2	1798.4/1768.6	3523.6/3511.4	5235.6/5213.4	1777.2/1749.8	1426.1/1401.3	1086.5/985.8	11.2/10.5	16.8/14.9	23.5/21.8
3	1773.2/1761.4	2769.1/2745.3	5398.2/5368.8	1754.8/1733.5	1417.6/1392.3	1091.8/986.3	11.1/10.5	13.6/13.1	24.2/22.1
4	2315.7/2288.4	3744.3/3714.5	5302.9/5286.7	2299.1/2272.3	1430.5/1408.3	1089.5/979.6	14.6/14.3	17.6/16.4	23.921.3
5	2281.4/2267.6	5328.2/5302.1	5227.7/5200.1	2451.3/2433.6	1464.3/1442.3	1089.1/989.7	14.9/13.5	24.1/23.2	23.7/21.2
6	2185.1/2156.8	5284.7/5248.4	5307.7/5278.9	2257.9/2233.7	1454.8/1432.7	1148.1/993.5	14/13.1	24/22.8	24/22.1
7	1853.3/1833.6	3341.8/3312.7	5357.2/5332.5	1840.8/1822.5	1425.8/1703.8	1174.3/997.8	11.6/10.5	15.9/14.2	24.2/22.1
8	1842.5/1823.4	3006.5/2992.4	5291.1/5271.4	1843.5/1823.3	1419.1/1402.3	1102.1/991.2	11.6/10.5	14.5/13.6	23.9/21.8
9	1834.9/1812.8	2769.8/2742.6	5226.9/5201.4	1831.7/1823.3	1403.9/1386.8	1069.2/996.8	11.6/10.5	13.5/12.3	23.6/21.9
10	1823.3/1814.8	1013.4/1002.4	5212.2/5196.3	1800.3/1803.2	537.2/529.8	1087.2/992.7	11.6/10.5	5/5.5	23.6/21.9

the load current third harmonic commensurates with the current fundamental harmonic which means that the energy losses from the third harmonic commeasure with the energy losses of the fundamental harmonic. It is also confirmed by the results of experimental investigations on the quality of electric power described by GOST (2013, 2014). The power lines of the examined objects turned out to be characterized by the constant spectral structure of upper harmonics of the current in electric lines.

Thus, the development of such compensation methods that would simultaneously solve the problems of improving electric power quality in case of random changes in load parameters within the micro-district electric power supply system is needed for improving power factor in a building estate electric power supply system and increasing electric power quality. The losses of energy from the load unbalance in phases should be added to this.

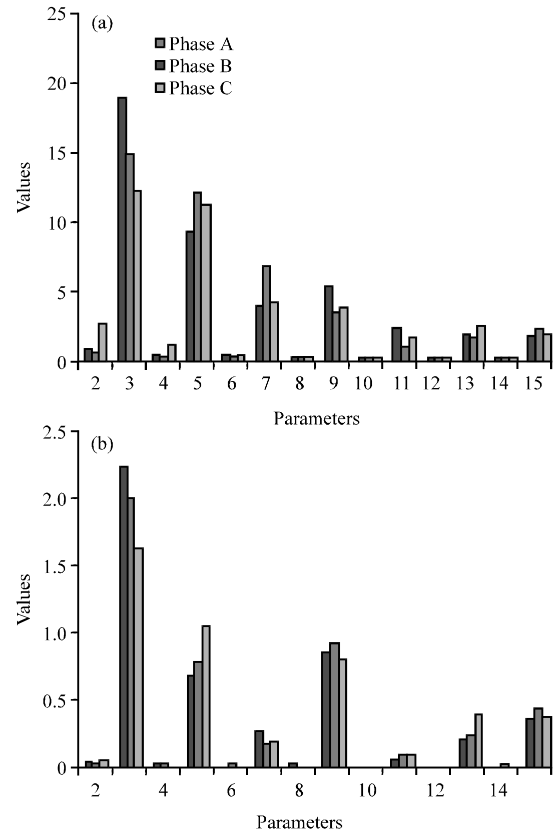

Fig. 5: a, b) Spectrum of current and voltage harmonical componentsup to the fifteenth harmonics

CONCLUSION

The measurements of mode basic parameters in the electric power supply systems of residential estates and unified power quality indices determining electromagnetic compatibility conducted via certified instruments Energomonitor-3.3 T1 and C.A 8335 showed the presence of upper harmonics of currents and voltages and the total current nonsinusoidality ratio was about 30% in such case. The simulation model constructed in Matlab 7 environment via Simulink and sim power system packages makes it possible to determine the mode parameters and unified power quality indices determining the electromagnetic compatibility for a wide variety of loads in the electric power supply system of a residential estate. It is possible to measure the level of upper harmonics and radiant quantities by means of developed simulation model at the sections of electric power supply system at different voltage level and when connecting additional electrical receivers (Rao, 2011).

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