FACTA UNIVERSITATIS
Series: **Electronics and Energetics** Vol. 33, N° 2, June 2020, pp. 261-271
https://doi.org/10.2298/FUEE2002261K

DEPENDENCIES OF CURRENT HARMONICS OF SOME NONLINEAR LOAD DEVICES ON RMS SUPPLY VOLTAGE

Lidija M. Korunović, Ivan Anastasijević

Faculty of Electronic Engineering, University of Niš, Niš, Serbia

Abstract. *The paper deals with the determination of current harmonic dependencies of some nonlinear load devices on the rms supply voltage. These dependencies are based on the laboratory experiments that include the variations of rms supply voltage in relatively wide ranges. The experiments were performed on some representatives of nonlinear load devices. Both current harmonic amplitudes and their angles are recorded during the voltage changes, and corresponding dependencies on rms voltage are obtained by curve fitting. The results are related to actual devices that are typically used in residential load sector. The obtained dependencies are the indices of potentially significant effects of rms voltage variation on current harmonics in low voltage installations.*

Key words: *load device, voltage variation, current harmonics, power quality, harmonic distortion*

1. INTRODUCTION

In up-to-date power networks, there is a significant increase of the use of nonlinear load devices in all characteristic load sectors such are industrial, commercial and residential [1], [2]. For example, residential load sector typically includes the following nonlinear devices: energy efficient lighting – LED lamps and fluorescent lamps with electronic ballast; switch-mode power supplied loads – laptop computers, TV sets, mobile chargers; air conditioners; direct drive washing machines; refrigerators and freezers. All nonlinear devices inject current harmonics into the network nodes, and numerous problems can arise [3], [4]. Therefore, the limitation of harmonic emission is needed [5], as well as adequate modelling of individual and/or aggregate nonlinear loads for proper harmonic analysis [6], [7].

For the correct harmonic analyses of low voltage networks, load devices should be properly modelled. In [8], modelling of low voltage devices that is based on simulations is presented. These simulations use equivalent electric circuits that represent analytical models of the devices, with typical parameter values. However, the parameters of the devices are

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Received September 2, 2019; received in revised form September 20, 2019
Corresponding author: Lidija M. Korunović
Faculty of Electronic Engineering, Aleksandra Medvedeva 14, 18000 Niš, Serbia
E-mail: lidija.korunovic@elfak.ni.ac.rs

almost impossible to get from the manufacturers. Thus, although the results presented in [8] regard real and reactive power and power factor, as well as total harmonic distortion of the current obtained for different rms values of supply voltages, these can not be adopted for the load devices that belong to the same load category when they consist of different circuits or of the same circuits with different parameters. Also, for harmonic power flow analysis information regarding particular current harmonics is needed.

On the other hand, there is the group of references that present individual harmonic distortions of currents that can be used for harmonic studies. Thus, [9] provides these distortions of some load devices used in households, obtained by measurements and simulations, while individual harmonic distortions of currents and current harmonic angles obtained by measurements are listed in [10]. The significant influence of harmonic distortion of the supply voltage on current harmonic distortion of low voltage devices is found in many references, e.g. [6] and [11]-[13]. It indicates that network operating conditions hardly influence current harmonic emissions.

However, published references do not analyse measured current harmonics of low voltage devices when rms supply voltage changes in relatively wide range that can appear in various network operating conditions. Therefore, this paper presents the results of experiments performed on some typical low voltage devices used in residential load sector, in order to obtain proper dependencies of current harmonics and their angles, on rms supply voltage. For this purpose the results of experiments performed in time periods when the harmonic distortions of supply low voltage network voltage were almost constant, are selected for the presentation.

It is presumed that current frequency component dependencies of a device, and the dependencies of their angles, are not always similar to each other. This assumption is proven in this paper, since mentioned dependences expressed in the form of mathematical functions, demonstrate significant mutual differences for the same load device. The presented approach to determining dependencies of current harmonics on rms supply voltage is applicable to any low voltage load, and obtained dependencies have numerous potential applications.

The rest of the paper is organized as follows: typical nonlinear residential load devices are listed in Section 2, description of experiments is presented in Section 3, Section 4 discusses experimental findings of current harmonic dependencies on rms supply voltage in detail, Section 5 summarises the functions that represent these dependencies, while the main conclusions are drawn in Section 6. The paper ends with the References, and with data of load devices used in experiments that are listed in Appendix.

2. Representatives of Nonlinear Load Devices in Residential Load Sector

The group of linear load devices used in residential load sector consists of resistive load devices such are: cooker hot plates, water and space heaters. The participation of these devices in total energy consumption of residential load sector is reducing, due to the increased usage of other energy sources for cooking (natural gas) and heating (e.g. heat pumps and central heating), while the consumption of nonlinear load devices is increasing constantly.

The group of nonlinear load devices used in residential load sector consists of devices that belong to different types of load. One of these types is nonlinear indoor lighting load whose use increases. Namely, linear indoor lighting loads – incandescent lamps, have very low efficiency [14], [15], and therefore are progressively being replaced with more efficient nonlinear lighting sources. In some of the developed countries they are even forbidden. Nonlinear lighting load applied in residential load sector includes compact fluorescent lamps (CFL) with electronic ballasts, as well as light-emitting diode (LED) lamps. Since compact fluorescent lamps are rapidly being replaced with light-emitting diode lamps in modern households (and office buildings) [15], [16], the representative of LED lamp was selected for the experiment. Its data are listed in the Appendix together with data of other nonlinear examined load devices.

All load devices with switch mode power supply are named switch mode power supply (SMPS) type of load [17]. The representatives of this type of nonlinear load are: personal computers, monitors, DVD/CD players/recorders, televisions, etc. The participation of SMPS loads in total energy consumption of modern household increases as concluded in [18] on the bases of numerous scenarios. In order to obtain current harmonic-rms voltage dependencies of one representative of SMPS loads typically used in residential load sector, the experiment was performed on a laptop computer.

As a result of climate change, air-conditioners are frequently used in Serbian households during summer months. Therefore, there is the impact of air-conditioner on total energy consumption of residential consumers and consequently on the whole power system, as also noted in many countries (e.g. [19]). In [18] it is found that the ownership of air-conditioning equipment (and personal computers) will grow mostly in urban and rural settlements in the future. Therefore, an air-conditioner was selected for laboratory experiment.

Refrigerators consume noticeable portion of energy in each household, since they operate during the whole year [14]. There are many types of compressor refrigerators, but the refrigerator which is already placed in the laboratory is used for the experiment. In modern households, conventional washing machines are rapidly being replaced with direct drive washing machines that are also nonlinear devices typically used in households. However, an experiment on the washing machine was not performed, since there was not such machine in the laboratory.

3. Description of the Experiments

As mentioned in Introduction, laboratory experiments were performed in order to investigate the influence of rms supply voltage on current harmonics of selected nonlinear load devices. In these experiments devices supply voltage changed by a variable autotransformer which was connected to low voltage laboratory installation. The output voltage of autotransformer was decreased from the higher limit of 110 % U_n according to the standard EN 50160 [20] that relates normal operating conditions in low (and medium) voltage distribution networks, to the voltage of 80 % U_n (that is 10 % bellow EN 50160 lower limit of 90 % U_n) selected to be sufficiently high to ensure that none of the tested devices is damaged. The steps of voltage changes during experiments were 2% U_n, where U_n is the rated phase-to-neutral voltage of low voltage network, i.e.230 V. Thus, the results presented in the paper are the indicators of current harmonic variations during both normal operating conditions and those abnormal conditions in low voltage networks when the voltage reduces down to 10 % bellow EN 50160 lower limit.

The measurements of voltage and current were performed by 4-Channel Power Meter LMG450 [21] after each voltage decrease when the steady-state regime was achieved. The applied meter measures voltage and current according to standard [22], i.e. − performs Discrete Fourier Transform (DFT) in order to obtain the amplitudes and phase angles of voltage and current harmonics. During the experiments, total harmonic distortions of voltage and current, *THDU* and *THDI*, respectively, were calculated by the meter on the basis of voltage and current Fourier series with frequency components whose harmonic order is up to the 99th:

$$THDU = \frac{\sqrt{\sum_{h=2}^{99}(U_h)^2}}{U_1}100\% \ , \ THDI = \frac{\sqrt{\sum_{h=2}^{99}(I_h)^2}}{I_1}100\% \ , \tag{1}$$

where U_h and I_h are voltage and current frequency components, respectively, of h^{th} harmonic order, and U_1 and I_1, are fundamental voltage and current components. Although the meter recorded numerous frequency components including those which frequencies are higher than 2 kHz (high-frequency components), for practical reasons this paper analyses only several current frequency components whose order is up to 9th.

Total and individual harmonic distortions are most frequently used as measures of sine wave harmonic distortion [1], [3]. The latter are also defined for voltage and current,

$$HDU_h = \frac{U_h}{U_1}100\% \, , HDI_h = \frac{I_h}{I_1}100\% \ , \tag{2}$$

and calculated from corresponding voltage and current frequency components.

As mentioned, the autotransformer used in experiments was supplied by public network. Therefore, the voltage waveform was not an ideal sinusoid. The values of *THDU* and U_h were recorded during the experiments on selected nonlinear load devices. Dominant frequency components, U_5 and U_7, are analysed in particular. Other frequency components were less than 1 % of voltage fundamental component during all experiments. For example, odd frequency components, U_3, U_9, U_{11}, U_{13} and U_{15}, were less than 0.14 %, 0.14 %, 0.50 %, 0.35 % and 0.17 %, respectively, at the half of all measuring instants during experiments. Table 1 summarizes the ranges of *THDU*, HDU_3 and HDU_5 obtained by the statistical analysis of data during each experiment of the voltage decrease. The ranges during particular experiment are represented in the form:

$$THDU \in (THDU_{25\%}; THDU_{75\%}) \ , HDU_h \in (HDU_{h,25\%}; HDU_{h,75\%}) \ , \tag{3}$$

where: $THDU_{25\%}$ and $THDU_{75\%}$ are 25th and 75th percentiles of *THDU*, respectively, and $HDU_{h,25\%}$ and $HDU_{h,75\%}$ are 25th and 75th percentiles of HDU_h, respectively. Since, each voltage frequency component is characterized by its angle, φ_{Uh}, that also influences current harmonic emission of nonlinear loads [6], [11]-[13], the ranges of φ_{U5} and φ_{U7} during the experiments are also determined in an analogous way as in (3), and are presented in Table 1.

It is found that the recorded *THDU* ranges that relate to different experiments performed in the same laboratory on various days and day periods, differ from each other, but during each experiment they changed stochastically in narrow ranges. The same conclusion is drawn for particular HDU_h and φ_{Uh} ranges. Therefore, it should be emphasized that the results presented in the paper correspond to specific distortion of supply voltage recorded when the experiments were performed.

Table 1 The ranges of $THDU$, HDU_5, HDU_7, φ_{U5} and φ_{U7} during experiments

Load device	LED lamp	Laptop computer	Air-conditioner (cooling)	Refrigerator
$THDU$ [%]	2.23; 2.31	3.02; 3.06	2.50; 2.62	2.14; 2.19
HDU_5 [%]	1.73; 2.40	2.02; 2.09	2.29; 2.41	1.57; 1.64
HDU_7 [%]	1.44; 1.86	1.65; 1.67	0.76; 0.81	1.25; 1.36
φ_{U5} [°]	169.2; 172.6	171.2; 173.3	178.7; 181.3	178.8; 180.9
φ_{U7} [°]	51.1; 53.1	53.0; 54.3	59.9; 63.1	43.6; 45.5

4. Results

4.1. LED lamp

Current harmonics of one representative of LED lamps are examined on the bases of experiment results. It is found that *THDI* of LED lamp increases negligibly from 39.9 % to 43.4 %, for supply voltage variation of 30 %, i.e. for the voltage decrease from 110 % U_n to 80 % U_n (253 V ÷ 184 V). As mentioned before, the meter records up to 99th frequency component, but this paper analyses only odd current components: 1st (fundamental), 3rd, 5th, 7th and 9th, i.e. I_1, I_3, I_5, I_7 and I_9, respectively, and their angles, φ_{I1}, φ_{I3} , φ_{I5}, φ_{I7} and φ_{I9}, so as not to burden the text and figures. Even harmonics are not analysed, since they are negligible.

Fig. 1a) presents measured values of I_1, I_3, I_5 and I_9 along with corresponding second order polynomial fits. Measured values of I_7 (and corresponding fitting polynomial) are not presented in the figure, since they are almost the same as I_9 measured values. The polynomials whose general form is $y=b_0+b_1\cdot U+b_2\cdot U^2$, are obtained with adjusted coefficient of determination, i.e. adjusted R^2 ($\overline{R}^2$), greater than 0.5 [23]. All polynomial fittings of current harmonics and their angles presented in the paper are obtained with such, relatively large $\overline{R}^2$. This indicates significant relationships between the variables. The parameters of all polynomial fits obtained for LED lamp, laptop computer, air-conditioner and refrigerator are listed in Section 5 (Table 2).

Fig. 1a) depicts that I_1 is significantly greater than other frequency components and that I_1 slightly decreases with voltage decrease of 30 % – for approximately 8.6 % of its value measured at 110 % U_n. On the other hand, I_3, I_5, I_9 (and I_7), are small: I_3 is less than one third, I_5 is about fifteen percent, and I_7 and I_9 are about ten percent, of I_1. Third current harmonic is almost constant during voltage decrease, while the fifth, seventh and ninth current harmonic increases for about 7 %, 15 % and 3 %, respectively, for 30 % voltage decrease.

For the considered voltage decrease, current harmonic angle of I_1 and I_7 of examined LED lamp decrease from 28.7° to 22.4°, and from 28.8° to about 10°, respectively, the angle of I_5, increases from −21.0° to −11.7°, while the angles of other frequency components are almost constant (Fig. 1b). The angles are also fitted by second order polynomials, whose parameters are denoted by $b_{0\varphi}$, $b_{1\varphi}$ and $b_{2\varphi}$ (Table 2).

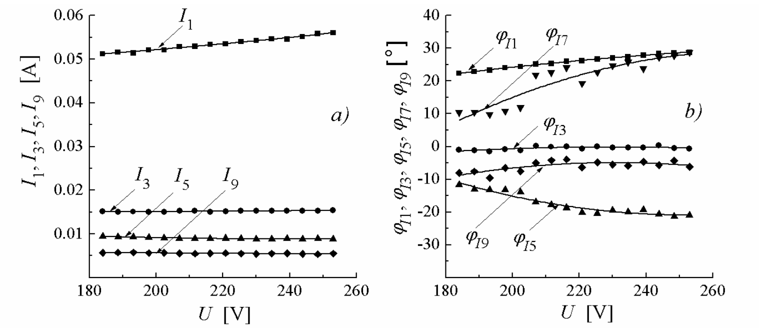

Fig. 1 Measured values and corresponding fitting curves of: a) amplitudes of I_1, I_3, I_5 and I_9, and b) angles of I_1, I_3, I_5, I_7, and I_9, of LED lamp

4.2. Laptop computer

Laptop computers are commonly used in modern households. However, their currents are very distorted. For example, *THDI* of examined laptop computer varies in the range from 203.7 % to 198.5 % for the voltage change from 110 % U_n to 80 % U_n, i.e. it is very high and slightly decreases with mentioned voltage decrease.

Measured values of the amplitudes of I_1, I_3, I_5 and I_9 for different supply voltages, as well as corresponding fitting polynomials, are presented in Fig. 2a). The values of I_7 amplitudes are omitted from this figure, since they are almost equal to the measured I_5 values. Laptop computer characterizes large amplitudes of current frequency components. Thus, analysed frequency components are between 70 % and 90 % of current fundamental component. Furthermore, all of the components, I_1, I_3, I_5, I_7 and I_9, increase with considered 30 % voltage decrease: for about 23 %, 29 %, 40 %, 32 % and 31 %, respectively.

The recorded angles of current frequency components are presented in Fig. 2b) together with corresponding second order polynomial fittings. It is found that the angle of I_1 decreases with the voltage decrease from 39.2° to 21°, while the angles of other analysed components generally slightly increase with voltage decrease. The angles of I_3, I_5, I_7 and I_9 increase: from 158.4° to 167.3°, from –40.8° to –24.6°, from 130.7° to 149.3°, and from –66.2° to –40.3°, respectively, for 30 % supply voltage decrease.

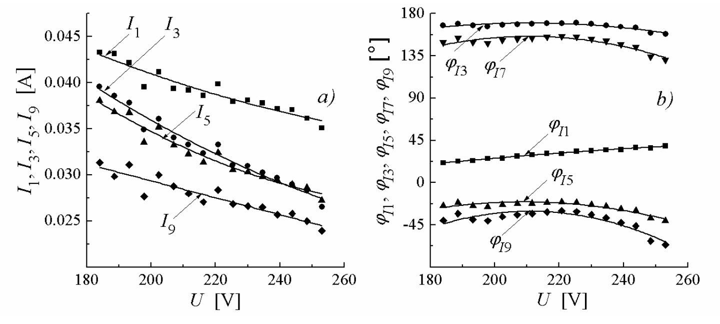

Fig. 2 Measured values and corresponding fitting curves of: a) amplitudes of I_1, I_3, I_5 and I_9, and b) angles of I_1, I_3, I_5, I_7, and I_9, of laptop computer

4.3. Air-conditioner

As mentioned, air-conditioners are commonly used for cooling in households in Serbia. Therefore, the experiments were performed when the selected air-conditioner operated in cooling mode. In this mode, *THDI* changed from 38.9 % to 28.2 %, for the voltage variation from 253 V to 184 V, i.e. it decreases significantly, for even 27.5 % of *THDI* obtained at 110 % U_n. This trend of *THDI* change is different than in the cases of LED lamp and laptop computer.

According to Fig. 3a), amplitudes of fundamental component and current frequency components, slightly change with 30 % voltage decrease, and these changes can be also represented by second order polynomials presented in the same figure. The amplitudes of I_7 during experiments are almost the same as I_9 amplitudes, and are not presented in Fig. 3a). The amplitude of I_1 changes negligibly with 30 % voltage decrease (for about 2%), while final values of I_3, I_5, I_7 and I_9 are for even 19.6 %, 55.5 %, 83.2 % and 31.8 %, respectively, less than their values obtained at 110 % U_n.

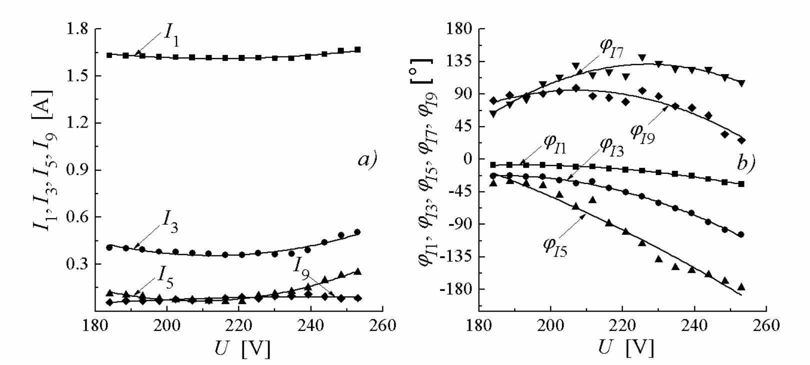

Fig. 3 Measured values and corresponding fitting curves of: a) amplitudes of I_1, I_3, I_5 and I_9, and b) angles of I_1, I_3, I_5, I_7, and I_9, of air-conditioner

On the other hand, there is an increase of the angles of I_1, I_3, I_5 and I_9 with 30 % voltage decrease: from –34.6° to –8°, from –104.5° to –23.3°, from –177° to –33.5°, and from 26.4° to 81.1°, respectively. The angle of I_7 increases from 106.5° to 141.9° with the voltage decrease to 225.4°V, and then decreases to 63.8° which is measured at 184°V.

4.4. Refrigerator

Differently from other nonlinear load devices, *THDI* of the examined refrigerator is relatively small. It changes in the range from 5.7 % to 9.6 % for supply voltage variation from 253 V to 184 V. It increases significantly (about 67 % of its initial value) with 30 % voltage decrease and this is quite a different trend of change than trends of *THDI* changes of other examined load devices.

Amplitudes of I_1, I_3 and I_5 of refrigerator, as well as corresponding polynomial fittings, are depicted in Fig. 4a). The amplitudes of I_7 and I_9 are omitted, because they are very small and almost the same as amplitudes of I_5. Fundamental current component decreases for 13.3 % with 30 % voltage decrease, while the trends of I_3 and I_5 are opposite –

they increase for even about 49 % and 149 % of their small initial values measured at 253 V. For the same, 30 % voltage decrease, the angles of I_1, I_3 and I_7 increase: from −51.7° to −35.5°, from 107.3° to 117.6°, and from −35.5° to −24.9°, respectively, I_9 increases significantly from 105.4° to 220.7°, while the angle of I_5 is almost constant.

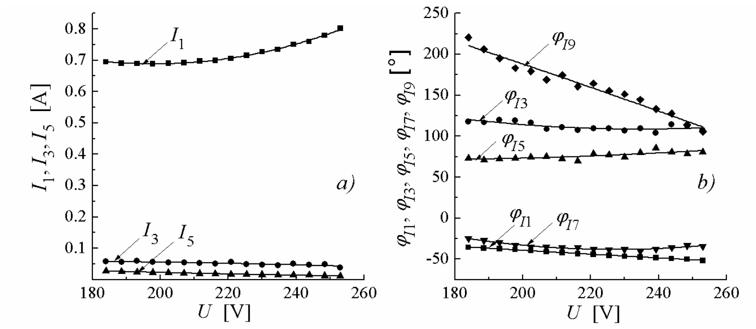

Fig. 4 Measured values and corresponding fitting curves of: a) amplitudes of I_1, I_3 and I_5, and b) angles of I_1, I_3, I_5, I_7, and I_9, of refrigerator

5. Summary of Current Harmonic Dependencies on Rms Supply Voltage

As discussed in Section 4, *THDIs* of LED lamp, laptop computer, air-conditioner and refrigerator change quite different with rms supply voltage decrease from 110 % U_n to 80 % U_n. The reason is different variation of current frequency components of different devices with the voltage change. Also, current frequency components of a device have different trends of change with the same voltage variation. These trends are presented by polynomial fittings with acceptable accuracy. For better insight, the parameters of these fittings, of both amplitudes and angles of I_1, I_3, I_5, I_7 and I_9, are summarized in Table 2 for all examined load devices. Listed parameters correspond to particular devices operating under conditions of specific harmonic distortion of the supply voltage, as discussed in Section 3. The parameters of similar load devices and other nonlinear devices used in different load sectors can be obtained using experiments analogous to those presented in this paper. For comprehensive research regarding parameter determination at different harmonic distortion of supply voltage expensive programmable source is needed.

Polynomial functions of both amplitudes and angles of current frequency components of various load devices, obtained under different supply voltage pollution conditions, can be used as input data for harmonic load flow analysis in low voltage installations, or the base for determination of harmonic model of aggregate load. Obtained dependencies on rms supply voltage can be used as the part of load and/or harmonic management system in future smart homes and smart buildings, since the regulation of supply voltage can decrease current harmonics and eliminate existing or potential problems caused by harmonic emission.

Table 2 Parameters of polynomial fits of I_h amplitudes and angles, of different nonlinear load devices

Load device	I_h	Parameters of polynomial fit of I_h amplitudes			Parameters of polynomial fit of I_h angles		
		b_0 [A]	b_1 [10^{-4}·A/V]	b_2 [10^{-6}·A/V^2]	$b_{0\varphi}$ [°]	$b_{1\varphi}$ [°/V]	$b_{2\varphi}$ [°/V^2]
LED lamp	I_1	0.04617	–0.03683	0.16840	–14.2008	0.27478	–0.00041
	I_3	0.01668	–0.17859	0.04997	–31.7018	0.27437	–0.00060
	I_5	0.01922	–0.86482	0.18041	113.517	–1.06471	0.00211
	I_7	0.01505	–0.79088	0.15743	–174.346	1.4987	–0.00276
	I_9	0.00873	–0.24801	0.04654	–98.1075	0.80731	–0.00175
Laptop computer	I_1	0.08447	–3.13475	0.48013	–76.1786	0.72586	–0.00108
	I_3	0.10307	–4.74304	0.69349	–86.9708	2.43972	–0.00579
	I_5	0.10933	–5.67059	0.96997	–432.505	3.94086	–0.00943
	I_7	0.07309	–2.6096	0.33821	–405.194	5.32206	–0.01263
	I_9	0.04765	–0.91079	–0.00171	–845.348	7.72459	–0.01831
Air-conditioner	I_1	3.08103	–137.600	32.1795	–267.487	2.70608	–0.00706
	I_3	4.17088	–358.800	84.3613	–674.884	7.00444	–0.01881
	I_5	4.28898	–405.200	97.1605	62.3786	1.01267	–0.00791
	I_7	0.1112	–21.9000	9.24923	–1745.01	16.5361	–0.03644
	I_9	–0.52854	51.1000	–10.534	–1217.14	12.6702	–0.03058
Refrigerator	I_1	2.11544	–144.100	36.3634	20.3878	–0.35263	0.00027
	I_3	0.02649	4.48077	–1.51362	363.872	–2.1763	0.00464
	I_5	0.12448	–7.48473	1.20006	109.046	–0.45892	0.0014
	I_7	0.06567	–4.40451	0.90482	335.228	–3.28763	0.00723
	I_9	–0.0322	3.22985	–0.76027	444.094	–1.14503	–0.00067

6. CONCLUSIONS

The research based on laboratory experiments, reveals that current harmonic distortion of the examined typical nonlinear load devices changes in different ways with variation of rms supply voltage. The dependences of the amplitudes and angles of fundamental and frequency components of the current are obtained in the form of second order polynomials for the considered load devices. It is revealed that corresponding dependencies of the devices are significantly different. Also, the dependencies, of both amplitudes and angles, for particular device are often with the opposite trends of change with rms voltage variation. Therefore, the dependencies on rms supply voltage should be taken into account for proper harmonic models of nonlinear load devices. Future research should include experiments on numerous load devices under different harmonic distortion conditions of supply voltage by using programmable source, when investment in such equipment is possible, as well as implementation of their results into voltage control procedures for load and harmonic control in low voltage installations and distribution networks.

Acknowledgement: *The paper is a part of the research done within the projects III44004 and III44006 supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia. The authors would like to thank prof. Milutin P. Petronijević for the help during setting up the experiments.*

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APPENDIX

Examined load devices:

- LED lamp with rated power of 11 W: General Electric dimmable lamp, A60, 810 lm, 2700K.
- Intel pentium quad core laptop computer with charger input 100-240 V~; 1,4 A; 50-60 Hz; and charger output 19,5 V DC; 2,31 A DC: HP 250 G3.
- Window type air-conditioner with rated power of 1500 W: Frozzini, KFR 35 GW/A.
- Classic refrigerator with rated power of 72 W: Obod, HL-145 ecolux.