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Experimentally evaluated impact of nonlinear loads on the energy transmission losses and distortion of voltage waveforms

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Abstract. This paper evaluates the impact of nonlinear loads on the losses related with energy transmission and distortion of voltage waveforms. When the field tests are performed in an electric network, it is impossible to assure that the voltage total harmonic distortion is caused exclusively by the observed nonlinear load. On the contrary, in this paper the evaluation is performed under controlled conditions. A controlled voltage source is applied. It is able to generate sinusoidal terminal voltage with the total harmonic distortion under 0.1 percents regardless on nonlinear behaviour of the load and waveform of the load current. The loads are connected to the voltage source by a four-wire cable. The impact of the nonlinear load on the total harmonic distortion and losses related with the energy transmission losses is evaluated using measured line currents and voltages measured at the terminals of the voltage source and load.

Key words

Nonlinear loads, power quality, power transmission losses, measurements, controlled voltage source

1. Introduction

Nonlinear and time-variant loads can be treated as sources of higher order harmonic currents in an electric network. The network itself provides paths, where these currents can flow and cause voltage drops on impedances of network elements. In this way, on the one hand the higher order nonlinear load generated currents distort the voltage waveforms in individual network nodes, while on the other hand they do not contribute to the active power and increase losses related with the energy transmission.

Different kinds of orthogonal current decompositions in the time and frequency domain [1]-[4] can be used as a very powerful tool for analysis of energy transmission and losses related with it, especially in the cases, when the current and voltage waveforms are distorted due to the impact of nonlinear loads. Some of these tools are applied in [5], where the impact of nonlinear loads, in the form of compact fluorescent lamps, on the losses related with energy transmission and voltage total harmonic distortion is evaluated. The analysis performed in [5] is based on measured currents and voltages. Since the distribution network was used as a voltage source, the waveforms of the supply voltages were distorted by the other nonlinear loads connected to the network, which were not considered in the analysis.

In this work, the experiments are performed under controlled conditions. This means that the impact of elements not considered in the analysis is eliminated. A controlled voltage source of sinusoidal voltage is applied. The total harmonic distortion (THD) of the sinusoidal voltages on the terminals of the voltage source is under 0.1 percents regardless of the waveform of nonlinear load generated currents. The applied linear and nonlinear loads are connected to the voltage source by a four-wire cable. The impact of the nonlinear loads on losses related with the energy transmission and total harmonic distortion of voltages is evaluated by measurements. Measured are the line currents, the neutral conductor current and the line-to-neutral voltages on terminals of the source and load. As already mentioned, the voltage THD on terminals of the voltage source is under 0.1 percents. In the cases when linear loads are applied, the total harmonic distortion of voltages on the terminals of the load is small. Thus, the increase of the voltage total harmonic distortion on the terminals of the load can be caused exclusively by the nonlinear load. Similarly, the difference of the powers measured on the source and load terminals represents the losses related with the energy transmission. If they are increased in the case when linear load is replaced by the nonlinear one, then this increase of losses is caused exclusively by the nonlinear load.

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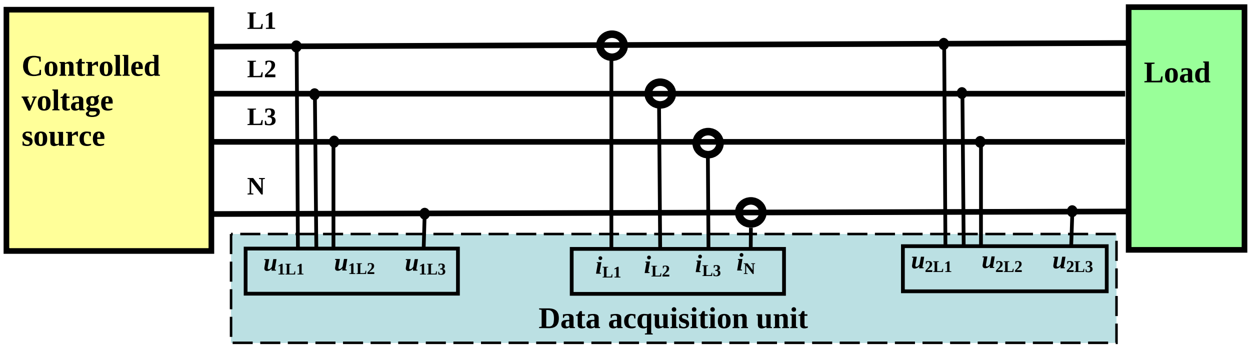


Fig. 1. Experimental setup

2. Experimental setup

The applied experimental setup is schematically presented in Fig.1. It consists of the controlled voltage source, four-wire connection cable, current and voltage measurements chains, data acquisition unit and single- and three-phase linear and nonlinear loads. The linear load is composed of incandescent lamps with the rated power 40 W while the nonlinear load is composed of compact fluorescent lamps with the rated power 20 W. The resistance of the individual wire in the connection cable is 24.7 Ω. All signals are synchronously sampled with the sampling frequency of 5 kHz.

3. Evaluation of the transmission losses and total harmonic distortion

The line-to-neutral voltages u_{1L1}, u_{1L2} and u_{1L3} are measured on the terminals of the controlled voltages source while the line-to-neutral voltages u_{2L1}, u_{2L2} and u_{2L3} are measured on the terminals of the load. They are applied together with the measured line currents i_{L1}, i_{L2}, i_{L3} and neutral conductor current i_N in the evaluation of the losses related with energy transmission and total harmonic distortion of voltages and currents.

The active power on the terminals of the controlled voltages source P_1 is calculated by (1) while the active power on the terminals of the load P_2 is calculated by (2)

$$P_1 = \frac{1}{T}\int_0^T u_{1L1}\, i_{L1} + u_{1L2}\, i_{L2} + u_{1L3}\, i_{L3}\; dt \tag{1}$$

$$P_2 = \frac{1}{T}\int_0^T u_{2L1}\, i_{L1} + u_{2L2}\, i_{L2} + u_{2L3}\, i_{L3}\; dt \tag{2}$$

where T denotes the interval of observation, normally one cycle of the fundamental frequency. The losses related with the energy transmission P_{loss} are calculated by (3).

$$P_{\text{loss}} = P_1 - P_2 \tag{3}$$

The root mean square (RMS) values of voltages and currents are calculated by (4) and (5)

$$U_{Ku} = \sqrt{\frac{1}{T}\int_0^T u_{Ku}\, u_{Ku}\; dt} \tag{4}$$

$$I_{Ki} = \sqrt{\frac{1}{T}\int_0^T i_{Ki}\, i_{Ki}\; dt} \tag{5}$$

where the index K_u (6) is defined for voltages while the index K_i (7) is defined for currents.

$$K_u \in \{1L1,\ 1L2,\ 1L3,\ 2L1,\ 2L2,\ 2L3\} \tag{6}$$

$$K_i \in \{L1,\ L2,\ L3,\ N\} \tag{7}$$

The THDs of individual voltages $\mathrm{THD}u_{Ku}$ and currents $\mathrm{THD}i_{Ki}$ are defined by (8) and (9), respectively.

$$\mathrm{THD}u_{Ku} = \sqrt{\frac{\sum_{h=2}^{40} U_{hKu}^2}{U_{1Ku}^2}} \tag{8}$$

$$\mathrm{THD}i_{Ki} = \sqrt{\frac{\sum_{h=2}^{40} I_{hKi}^2}{I_{1Ki}^2}} \tag{9}$$

The amplitudes of the h-th order harmonic component are denoted by U_{hKu} for voltages and by I_{hKi} for currents. The indices Ku and Ki are defined in (6) and (7), while h=1 stands for the fundamental frequency 50 Hz.

The accuracy of measured results, influenced by the voltage and current measurement chains, is evaluated by calculation of losses related with energy transmission (10)

$$P_{loss} = R\,\frac{1}{T}\int_0^T i_{L1}^2 + i_{L2}^2 + i_{L3}^2\; dt + R_N\,\frac{1}{T}\int_0^T i_N^2\; dt \tag{10}$$

where R is the resistance of the line conductor and R_N is the resistance of the neutral conductor. The results are acceptable when the difference between P_{loss} calculated by (3) and (10) is negligible.

4. Results for single-phase load

This section shows results obtained for the linear single-phase load in the form of an incandescent lamp with the rated power 40 W and results obtained for the nonlinear single-phase loads composed of compact fluorescent lamps with the rated power 20 W connected in parallel.

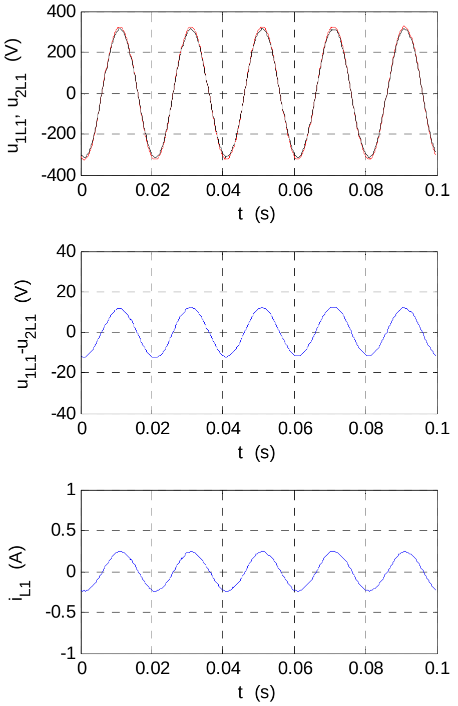


Fig. 2. Voltages u_{1L1} and u_{2L1}, voltage drop u_{1L1}-u_{2L1}, and current i_{L1}, given for the single-phase linear load with rated power 40 W

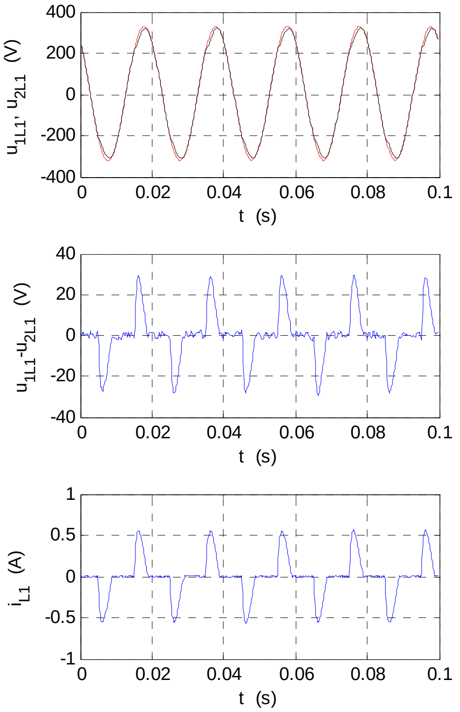


Fig. 3. Voltages u_{1L1} and u_{2L1}, voltage drop u_{1L1}-u_{2L1}, and current i_{L1}, given for the single-phase nonlinear load with rated power 2×20 W

Figs. 2 and 3 show the measured waveforms of supply voltage u_{1L1}, load voltage u_{2L1}, voltage drop on the connection cable u_{1L1}-u_{2L1}, and measured current i_{L1}, all for linear and nonlinear single-phase loads. Figs. 4 and 5 show the amplitude spectra of aforementioned currents and voltages.

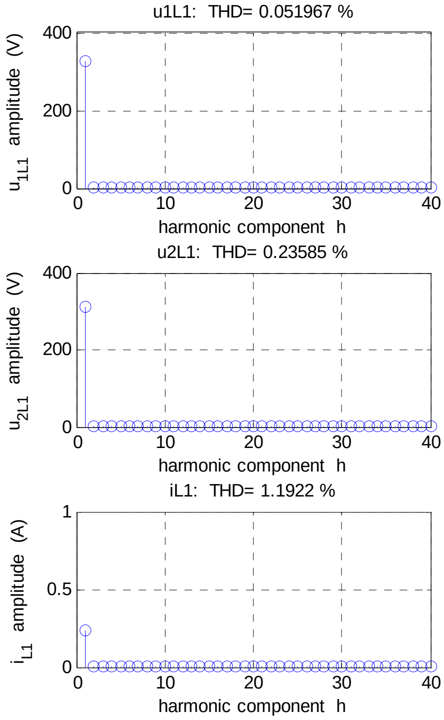


Fig. 4. Amplitude spectra and THDs of supply voltage u_{1L1}, load voltage u_{2L1}, and current i_{L1}, given for the single-phase linear load with rated power 40 W

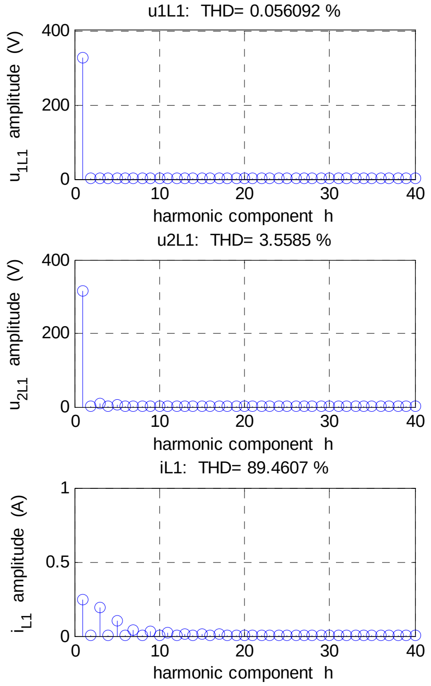


Fig. 5. Amplitude spectra and THDs of supply voltage u_{1L1}, load voltage u_{2L1}, and current i_{L1}, given for the single-phase nonlinear load with rated power 2×20 W

The results of analysis performed for the linear and nonlinear single-phase loads are summarized in Table I. Presented are the active power at the terminals of the voltage source P_1, the active power at the terminals of the load P_2 and the losses caused by the energy transmission $P_{loss}= P_1-P_2$. The RMS values of the source voltage u_{1L1}, load voltage u_{2L1}, and current i_{L1}, are marked with U_{1L1}, U_{2L1}, and I_{L1}, while the values of THDs of u_{1L1}, u_{2L1} and i_{L1} are marked with THDu_{1L1}, THDu_{2L1}, and THDi_{L1}.

Table I: Source power P_1, load power P_2, transmission losses P_{loss}, RMS values of u_{1L1}, u_{2L1}, i_{L1} and their THDs given for linear load and different nonlinear loads

	Load				
	Linear	Nonlinear			
P_1 (W)	39.02	19.08	37.87	58.28	79.42
P_2 (W)	37.57	18.31	35.13	52.37	69.31
P_{loss} (W)	1.45	0.77	2.74	5.91	10.11
U_{1L1} (V)	230.11	230.10	230.13	230.17	230.13
U_{2L1} (V)	221.56	226.00	222.03	217.90	213.46
I_{L1} (A)	0.170	0.126	0.236	0.347	0.453
THDu_{1L1} (%)	0.052	0.060	0.0560	0.055	0.063
THDu_{2L1} (%)	0.236	1.942	3.558	5.103	6.396
THDi_{L1} (%)	1.192	95.611	89.461	82.583	75.901

The results presented in Table I clearly shows that the voltage source in all cases generates sinusoidal supply voltage with RMS values between 230.10 and 230.17 V and THDu_{1L1} under 0.1 %. Since the aforementioned parameters of the supply voltage can be treated as constant, different losses related with the energy transmission as well as different THDs of the voltage u_{2L1} and current i_{L1} are caused exclusively by the load. The results given for the linear load P_2=37.57 W and nonlinear load P_2=35.13 W show, that the losses related with the energy transmission P_{loss} are almost doubled in the case of nonlinear load. The THDu_{2L1} increases from 0.236 % for the linear load to 3.558 % for the nonlinear load, while the THDi_{L1} increases form 1.192% for the linear load to 89.461 % for the nonlinear load. With the increasing power of the nonlinear load the load voltage THDu_{2L1} increases while the current THDi_{L1} decreases.

5. Results for balanced three-phase load

This section deals with the results obtained for the wye connected balanced three-phase linear and nonlinear loads. The linear load is composed of incandescent lamps with the rated power 40 W, the nonlinear load is composed of compact fluorescent lamps with the rated power 20 W, while in the case of combined load both aforementioned loads are connected in parallel.

Figs. 6 and 7 show the measured waveforms of supply voltages u_{1L1}, u_{1L2}, u_{1L3}, voltage drops $\Delta u_{L1}=u_{1L1}-u_{2L1}$, $\Delta u_{L2}=u_{1L2}-u_{2L2}$, $\Delta u_{L3}=u_{1L3}-u_{2L3}$, line currents i_{L1}, i_{L2}, i_{L3}, neutral conductor current i_N, and amplitude spectra of i_{L1}, i_{L2}, i_{L3}. Fig. 6 shows the results for the linear load while Fig. 7 shows the results for the nonlinear load.

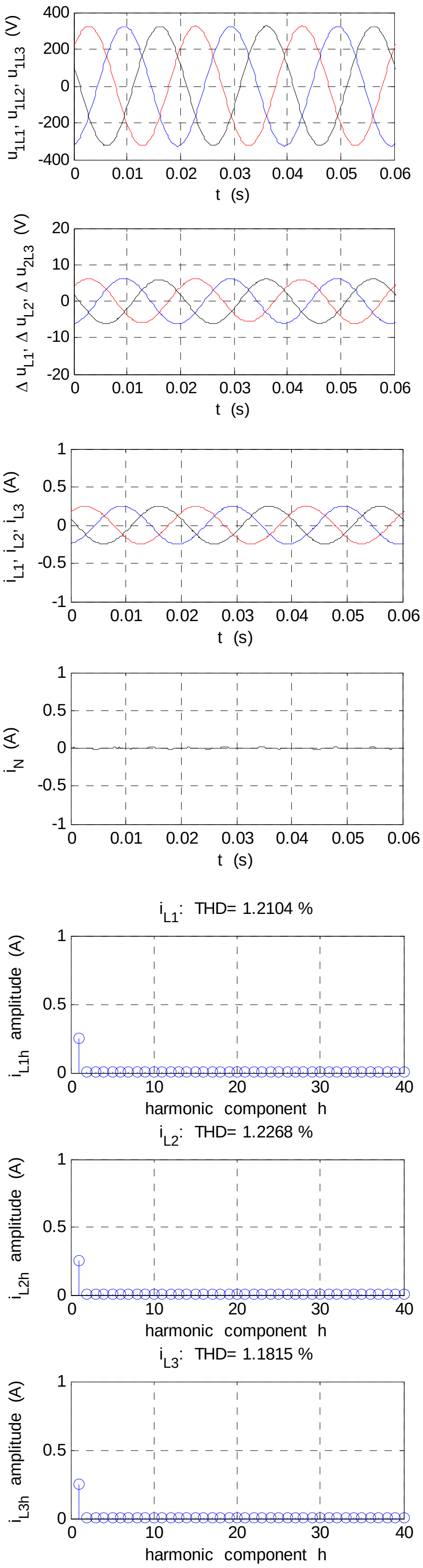
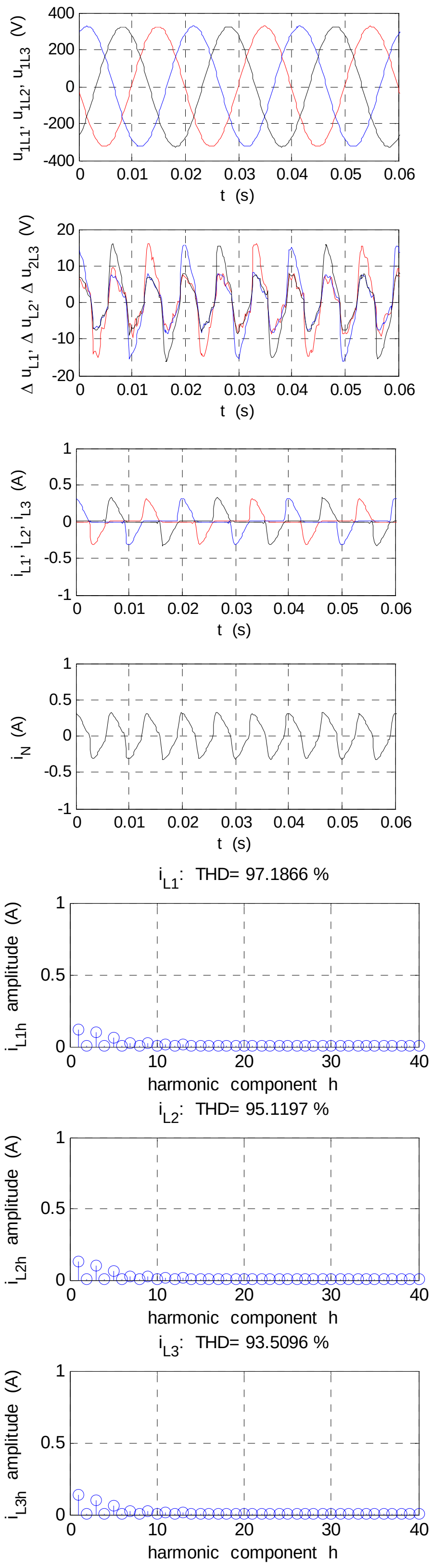


Fig. 6. Supply voltages u_{1L1}, u_{1L2}, u_{1L3}, voltage drops $\Delta u_{L1}=u_{1L1}-u_{2L1}$, $\Delta u_{L2}=u_{1L2}-u_{2L2}$, $\Delta u_{L3}=u_{1L3}-u_{2L3}$, line currents i_{L1}, i_{L2}, i_{L3}, neutral conductor current i_N, and amplitude spectra of i_{L1}, i_{L2}, i_{L3}, given for the wye connected balanced three-phase linear load with rated power 3×40 W



i_{L1}: THD= 97.1866 %

i_{L2}: THD= 95.1197 %

i_{L3}: THD= 93.5096 %

Fig. 7. Supply voltages u_{1L1}, u_{1L2}, u_{1L3}, voltage drops $\Delta u_{L1}=u_{1L1}-u_{2L1}$, $\Delta u_{L2}=u_{1L2}-u_{2L2}$, $\Delta u_{L3}=u_{1L3}-u_{2L3}$, line currents i_{L1}, i_{L2}, i_{L3}, neutral conductor current i_N, and amplitude spectra of i_{L1}, i_{L2}, i_{L3}, given for the wye connected balanced three-phase nonlinear load with rated power 3×20 W

Table II summarizes the results of analysis performed for the linear three-phase load, nonlinear three-phase load and combined three-phase load. Presented are the active power at the terminals of the voltage source P_1(1), active power at the terminals of the load P_2 (2), losses caused by the energy transmission P_{loss} (3), RMS values of voltages (4) at the voltage source terminals U_{1L1}, U_{1L2}, U_{1L3} and at the load terminals U_{2L1}, U_{2L2}, U_{2L3}, RMS values of currents I_{L1}, I_{L2}, I_{L3}, I_N (5), and values of THDs of all aforementioned voltages and currents determined by (6) to (9).

Table II: Source power P_1, load power P_2, transmission losses P_{loss}, RMS values of voltage source voltages U_{1L1}, U_{1L2}, U_{1L3}, RMS values of load voltages U_{2L1}, U_{2L2}, U_{2L3}, RMS values of currents I_{L1}, I_{L2}, I_{L3}, I_N, and THDs of all currents and voltages, given for the three-phase linear load 3×40 W, three-phase nonlinear load 3×20 W, and combination of both loads

	Load		
	Linear	Nonlinear	Combination
P_1 (W)	121.00	57.28	177.49
P_2 (W)	118.73	55.06	171.01
P_{loss} (W)	2.2675	2.22	6.48
U_{1L1} (V)	230.07	230.11	230.11
U_{1L2} (V)	230.08	230.12	230.10
U_{1L3} (V)	230.10	230.10	230.08
U_{2L1} (V)	225.81	228.46	224.03
U_{2L2} (V)	225.69	228.04	223.68
U_{2L3} (V)	225.83	228.11	223.84
I_{L1} (A)	0.175	0.121	0.270
I_{L2} (A)	0.176	0.121	0.273
I_{L3} (A)	0.176	0.129	0.274
I_N (A)	0.006	0.213	0.203
THDu_{1L1} (%)	0.052	0.077	0.054
THDu_{1L2} (%)	0.061	0.070	0.073
THDu_{1L3} (%)	0.067	0.0714	0.069
THDu_{2L1} (%)	0.241	3.103	3.057
THDu_{2L2} (%)	0.117	3.132	3.046
THDu_{2L3} (%)	0.107	3.147	3.060
THDi_{L1} (%)	1.210	97.187	31.843
THDi_{L2} (%)	1.226	95.120	31.685
THDi_{L3} (%)	1.181	93.510	31.957
THDi_N (%)	514.67	3193.20	5106.10

The results presented in Table II show that the changes in RMS values and THDs of supply voltages are small. Therefore, they can be treated as constant for all loads. Since the parameters of supply voltages are constant, the losses related with the energy transmission and the THDs of load voltages and currents can be influenced only by the load.

The losses related with the energy transmission P_{loss} reach almost the same value of 2.2 W for the linear load P_2=118.73 W and for the nonlinear load P_2=55.06 W. Since the RMS values of the line currents are lower in the case of nonlinear load, the neutral conductor current, whose RMS value is negligible in the case of linear load, substantially contributes to the P_{loss} (10) in the case of nonlinear load. In the case of load combined of linear and nonlinear load, with P_2=171.01 W, the losses related with the energy transmission are increased substantially to P_{loss}=6.48 W.

The comparison of voltage THD values at the load terminals shows, that they are under 0.3 % in the case of linear load, they reach over 3.1 % in the case of nonlinear load, while they reach values around 3.05 % in the case of combined load. Thus, the values of the voltage THDs at the load terminals are determined predominantly by the nonlinear load.

The values of line current THDs are under 2 %in the case of linear load, they are higher as 90 % in the case of nonlinear load, while they decrease below 32 % in the case of combined load.

6. Conclusion

The paper evaluates the impact of nonlinear loads on the losses related with the energy transmission and total harmonic distortion of voltages and currents. The analysis is based on currents and voltages measured during experiments performed under controlled conditions. A controlled voltage source of sinusoidal voltage is applied. It provides sinusoidal voltages with constant RMS values and THDs under 0.1 % in all operating conditions discussed in paper. Since the supply voltage is constant in all tests, the losses related with the energy transmission and the values of current THDs and load voltage THDs change exclusively due to the load properties.

In the cases of single-phase load, the losses related with the energy transmission are almost doubled when the linear load is replaced with the nonlinear load with the same active power. If the power of nonlinear load increases linearly, the losses related with the energy transmission increase faster than with the square. The value of the load voltage THD increases with the increasing power of nonlinear load, while the value of the current THD decreases with the increasing power of nonlinear load.

In the cases of wye connected balanced three-phase loads, the nonlinear load and the linear load with doubled power of nonlinear load cause similar losses related with the energy transmission. The neural conductor current contributes substantial share to the total losses related with the energy transmission in the case of nonlinear load. In the cases, when the load is composed of the linear and nonlinear load, the losses related with the energy transmission increase substantially. The impact of nonlinear load on the values of the load voltage and current THDs is dominant in the cases of combined loads.

The increasing share of nonlinear loads in electricity distribution networks could substantially increase losses related with the energy transmission and total harmonic distortion of currents and voltages. Thus, the appropriate measures, for minimizing the impact of nonlinear loads on distribution networks, are required.

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