Krzysztof Ludwinek[*]**, Arkadiusz Siedlarz**[**]
[*]**Kielce University of Technology, Kielce**
[**]**Pilkington Automotive Poland Sp. z o.o., Sandomierz**

HARMONIC DISTORTION ANALYSIS IN ARMATURE CURRENTS OF SYNCHRONOUS MACHINE DURING CO-OPERATION WITH THE POWER SYSTEM

Abstract: In the article an analysis of harmonic distortion in armature currents in synchronous machine during co-operation with electric power system is presented. The analysis is carried out thanks to the computer applications designed in LabVIEW - graphical programming environment. The applications allow to carry out the analysis of the influence of voltage unbalance and harmonic distortion on the power quality and to display on screen the non-sine waveforms of the voltages and currents taken by electrical equipment. Moreover, the programs display the RMS values of active, reactive and apparent power as well as power of distortion and coefficients: THD, PHD, IHD, power factor and voltage unbalance. In addition, the applications allow to record the signals from A/C measuring devices or oscilloscopes and save them to file for further analysis.

1. Introduction

Due to the fact that power supply market in Poland has gradually been freed from government regulations, producers and consumers of electrical energy pay more attention to its quality and reliability of power system. Bad power quality increases its total loss during transmission, could be a reason of serious machine failures leading to reduction of the production volume or to down-time increase. Moreover, it contributes to shortening of total lifetime of the electrical machines. The problem of bad power quality concerns not only industrial consumers but also individual people. Flickering of light, often computers failures and data loss, improper interruption of the circuits by fuses, circuit breakers or RCDs, or electrical and electronic device overheating are only a few example of how big the impact of bad power quality on the life of ordinary people is. Thus, Polish work market needs engineers qualified to deal with this issue. However, Universities in Poland do not spare much time for teaching young engineers about this matter. Therefore, Chair of Electrical Machines and Mechatronic Systems (KMEiSM) of Kielce University of Technology created lab stations to start educating students in the field of power quality. The lab stations make possible for the students to analyse the parameters of electrical energy, to display the momentary waveforms of the current, voltage, and momentary power and to carry out some simulations of the influence of asymmetrical currents and voltage on the quality of energy and machines' work.

2. Computer measurement set for the analysis of higher harmonics in currents and voltages

Computer measurement set enables to carry out an analysis of higher harmonics in currents and voltages supplying 1-, 2-, or 3-phase electrical machines or electrical equipment. The computer measurement set consists of both: measurement set and computer applications in LabVIEW 8.2 (simulation and analysis). These applications allow to carry out the real-time analysis (to calculate the coefficients THD, PHD, IHD, power factor, unsymmetrical factor, powers: active P, reactive, Q, apparent S, modulus apparent $|S|$ and distortion T) or to record the waveforms of currents and voltages for later analysis. The measurement set consists of 8 measuring transducers, designed and made in Chair of Electrical Machines and Mechatronic Systems, for recording the currents and voltage waveforms (in phase and interfacial configuration).

2.1. Applications in LabVIEW - Simulator

The simulator allows to generate arbitrary signals by an appropriate set up of the amplitudes and initials phases of particular harmonics current and voltages. Students can do that by taping the values directly from the keyboard or by changing position of sliders on the screen. Following analysis can be carried out:

1) Analysis of voltage unbalance and higher harmonics distortion in current and voltage and their the influence on the power quality in

accordance with Polish Norms PN-EN 50160 and PN-EN 61000.

2) Simulation of the amplitudes and phases influence of particular higher harmonics on the resultant waveforms of currents, voltages and powers.

3) Depending on the set values of the voltages and currents in particular phases some calculations can be done including Apparent Power (S), Real Power (P), Reactive Power (Q), Power of Distortion (D) and the Power Factor. Block Diagram of the simulator.vi application (for one phase analysis) made in LabView is shown in Fig. 1. It consists of several subprograms:

generacja.vi – generates non-sine momentary waveforms;

obliczenia.vi – carries out the calculations of Apparent Power (S), Real Power (P), Reactive Power (Q), Power of Distortion (D) and the Power Factor and coefficients THD, EHD, IHD etc;

analiza prądowa.vi, analiza napięciowa.vi - calculates the level of current and voltage harmonics distortion by displaying the amplitude of fundamental and higher harmonics (up to 25th). It also indicates if the any of the higher harmonics exceeds acceptable values by lighting green LEDs diode on the screen;

selektor.vi – enables to choose which harmonics are to be included to the waveform;

prostopadłościan mocy.vi – enables to present in 3D the relations between Powers; Apparent (S), Real (P), Reactive (Q), Distortion (T);

zapis przebiegów.vi, zapis do pliku.vi – enables to save the waveform and calculation to file to which the path can be chosen.
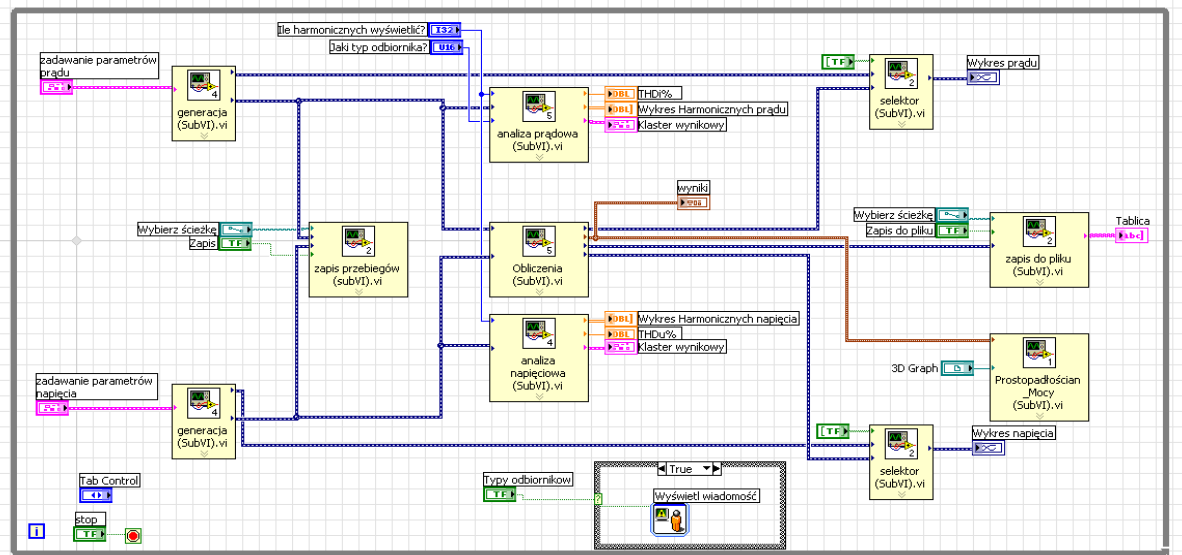

Fig. 1. Block Diagram of the simulator.vi application for one phase analysis made in LabView

A Front Panel of the simulator.vi (Fig. 1) is shown in Fig. 2, where fundamental and harmonics 3 and 5 are set giving resultant non-sine waveform.
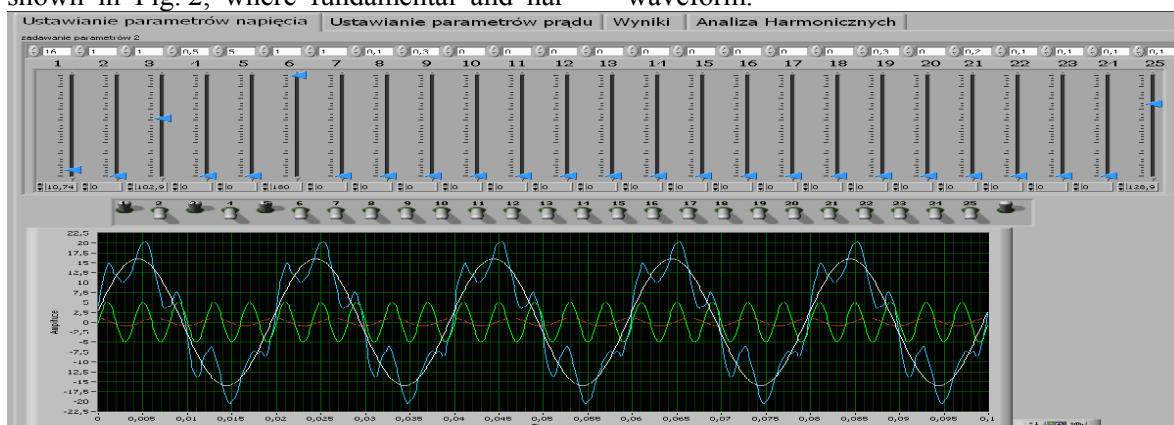

Fig. 2. Front Panel of the simulator.vi

The Front Panel has got four windows. First two of them (*Ustawianie parametrów napięcia* and *Ustawianie paramentrów prądu*) can be used for setting parameters of arbitrary non-sine signals by changing amplitudes and phases of particular harmonics. If we assume that one of the signals is current and the other is voltage, some calculations can be done. The results of the calculations are presented in window 3 – *Wyniki,* where RMS values of current and voltage as well as powers: apparent (S), active (P), reactive (Q) and distortion (T) and Power Factor are displayed. Calculations are done according to following formulas:

From definition of real power of fundamental harmonic, the real power of *n* harmonic can be expressed by:

$$P_n = U_n I_n \cos\varphi_n \tag{1}$$

and the total active power as a sum of individual harmonic products of voltage and current *n*:

$$P = A_{0i}A_{0u} + \sum_{n=1}^{k} U_n I_n \cos\varphi_n = P_0 + \sum_{n=1}^{50} U_n \cdot I_n \cdot \cos\varphi_n \tag{2}$$

where: U_n, I_n – RMS voltage and current harmonics, A_{0i}, A_{0u} – voltage and current constant component.

For a given $\cos\varphi_n$ the value of $\sin\varphi_n$ can be calculated as well as the reactive powers for harmonics *n*:

$$Q_n = U_n I_n \sin\varphi_n \tag{3}$$

and the total reactive power as a sum of individual harmonic products of voltage and current *n*:

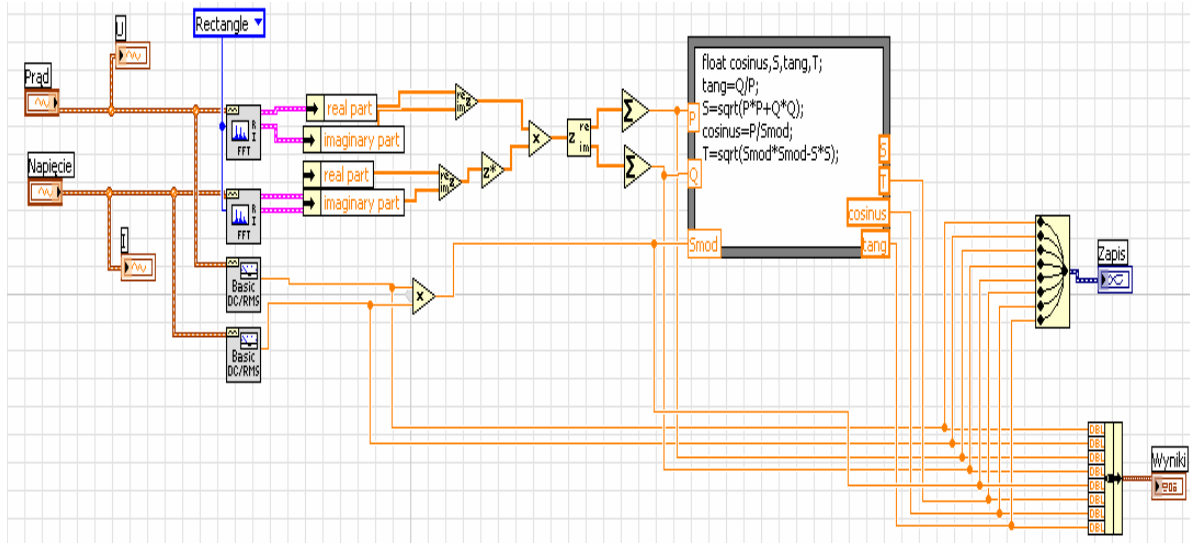$$Q = \sum_{n=1}^{50} U_n I_n \sin\varphi_n \tag{4}$$

Modulus apparent power as indicated in [6] is described as:

$$S = U \cdot I = \left(\sum_{n=0}^{50} U_n^2 \sum_{n=0}^{50} I_n^2\right)^{\frac{1}{2}} \tag{5}$$

and apparent power is described as:

$$|S|^2 = P^2 + Q^2 \tag{6}$$

Powers in equation (5) and (6) are not equal. According to the theory of Budenau the difference between them can be explained by so called power of distortion (T). The relations between the powers can be expressed by:

$$S^* = \sqrt{P^2 + Q^2 + T^2} \tag{7}$$

As stated in [6] the above formula is controversial. Thus, in the paper in LabView applications the real and reactive powers for all harmonics are calculated separately on the basis of the RMS values of current and voltage of particular harmonics, as well as $\cos\varphi_n$ and $\sin\varphi$.
Power factor can be described as:

$$PF = \frac{P}{S} = \frac{\sum_{n=1}^{50} U_n \cdot I_n \cdot \cos\varphi_n}{U \cdot I} \tag{8}$$

All values are displayed on screen. It is also possible to save the calculation to the txt file.
All the calculations are carried out by the subprograms in LabView and have been showed in separated windows Front Panel.

Fig. 3. Block Diagram **Obliczenia.vi**

Fig. 3 shows elaborated Block Diagram **Obli-czenia.vi** of the LabView system.

In window four *Analiza harmonicznych*, harmonic spectrum of simulated signals is displayed.

By turning on green LED diodes, the application can also indicate if threshold values of particular harmonics are exceeded. The threshold signaling of set point permissible harmonic values of voltages and currents are defined in PN-EN 50160 (which concerns limits for power supply voltage emissions) and in PN-EN 61000-3-2 (which concerns limits for harmonic current emissions in depends on equipment classis) [3, 4].

2.2. Applications in LabVIEW - Analyser

The application *Analizator jakości.vi* allows to carry out the analysis of voltage unsymetrical and harmonic distortion and their influence on the power quality and to display the non-sine waveforms of the voltages and currents. The application shown in Fig. 4 consists of 17 subprograms, with some of them being described in previous chapter. The functions of others are:

DAQ Assistant – allows to read the signals from the A/C measurement device;

Kalibrator.vi – allows to calibrate the signals from current and voltage transducers;

Średnia.vi – allows to calculate RMS values of the current and voltages in each of three phases as well as power factor, apparent power, real power, reactive power consumed by arbitrary electrical equipment;

Asymetria.vi – allows to calculate the coefficients of the voltage and current unbalance for 3-phase supply system according to the formulas:

$$\varepsilon_u = \frac{U_2}{U_1} \cdot 100 \text{ and } \varepsilon_i = \frac{I_2}{I_1} \cdot 100 \qquad (9)$$

where U_1, U_2 – positive- and negative-sequence of voltage I_1, I_2 – positive- and negative-sequence of current;

DAQ Assistant – makes possible reading of voltages and currents signals from 12B multifunction DAQ device.

Fig. 4 shows the application of the *Analizator jakości.vi* block diagram in LabView.
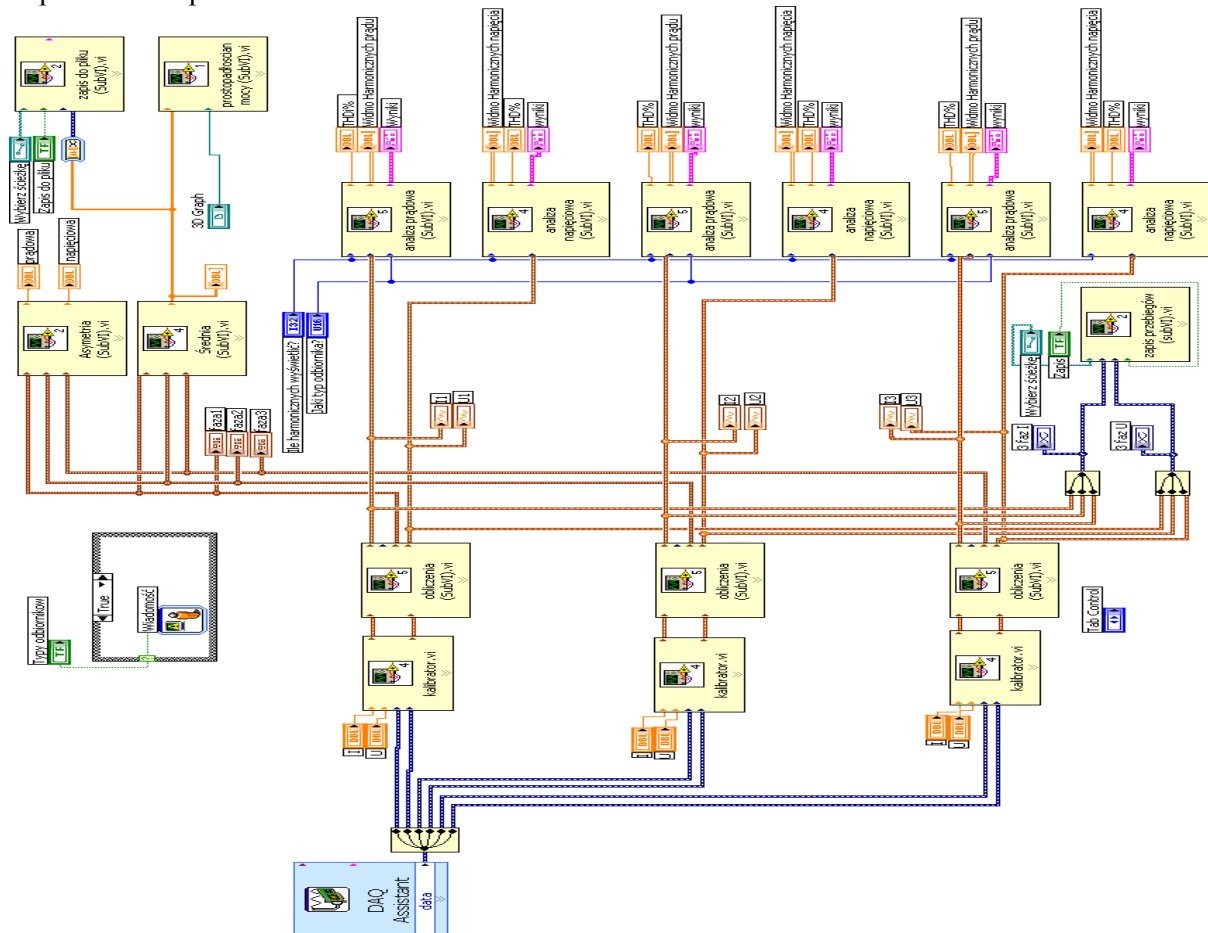

*Fig. 4. Block Diagram of the **Analizator jakości.vi***

3. Analysis of harmonic distortion in currents and voltages of synchronous machine

An analysis of the contents of higher harmonics in currents and voltages of 3-phase synchronous machine (P_N = 8,5 kW, U_N = 380 V, $cos\phi_N$ = 0,85, n_N = 3000 rpm) in case of the co-operation with the electric power system in the chapter is presented. The analysis has been done with active power of the synchronous generator equal to P = 1,1 kW (const.) and different values of reactive power Q from the state of underexcitation Q = -5,2 kVAr to the state of overexcitation Q = 3,8 kVAr.

Fig. 5 shows a diagram of the measurement set for the simulation, analysis and investigations of the synchronous generator during co-operation with electric power system.
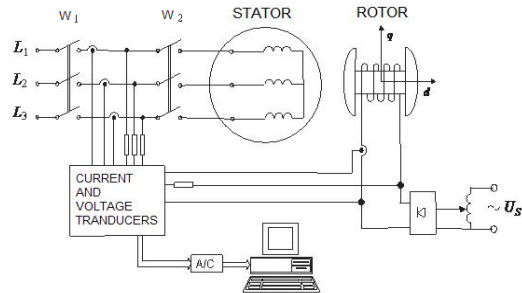

Fig 5. Diagram of the measurement set

The measuring set consists of: synchronous generator rated P_N = 8,5 kW, U_N = 380 V, $cos\phi_N$ = 0,85, n_N = 3000 rpm, eight transducers with Hall-effect sensors to measure the momentary values of voltages and current, two independent circuit breakers W1 and W2, PC with NI-6009 A/C measurement device and Lab-VIEW software.

Registration of steady–state armature current waveforms ($\omega = \omega_l$ = const*)* for the investigated synchronous generator in case of co-operation between the synchronous generator and the distorted electric power system taking into account the real rotor structure (damping cage, solid iron and field winding) has been carried out. The field winding was supplied by means of full-wave rectifier and autotransformer to adjust value of the field current from underexcitation (*P* = 1,1 kW and *Q* = -5,2kVAr, *Q* = -2,3 kVAr, *Q* = -0,5 kVAr) to overexcitation (*P* = 1,1 kW and *Q* = 0,7 kVAr, *Q* = 3,8 kVAr). The waveforms of the registered 3-phase voltages and armature currents are presented in the Fig. 6 – Fig. 7.

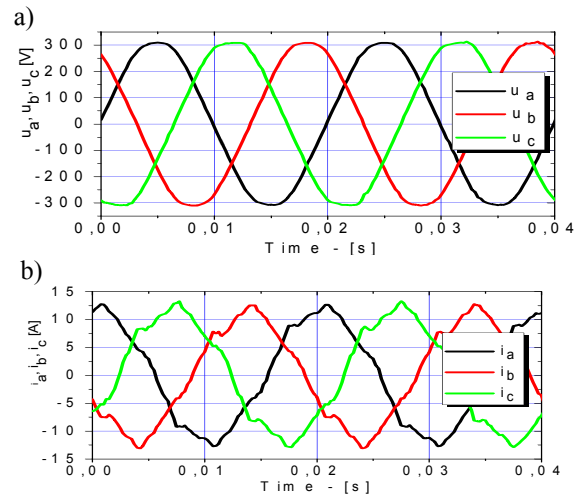*Fig. 6. Waveforms of a) voltages and b) armature currents P = 1,1 kW and Q = -5,2 kVAr*

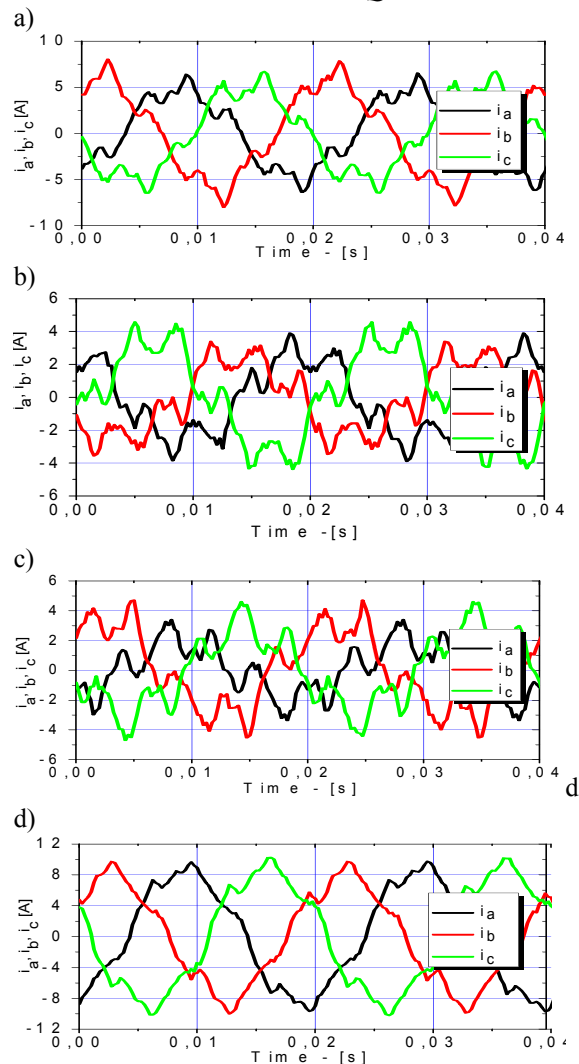*Fig. 7. Armature currents waveforms P = 1,1 kW and a) Q = -2,3 kVAr b) Q = -0,5 kVAr, c) Q = 0,7kVAr and d) Q = 3,8 kVAr*

In Fig. 8 are shown a percentage participation of all voltage harmonics (IHD$_{U\%}$ up to 40th)

which were recorded during measurements and a percentage participation of all armature current harmonics ($IHD_{i\%}$ up to 40th) in relation to fundamental harmonic and in relation to nominal fundamental harmonic. Fundamental harmonics of current ant voltage is not shown).
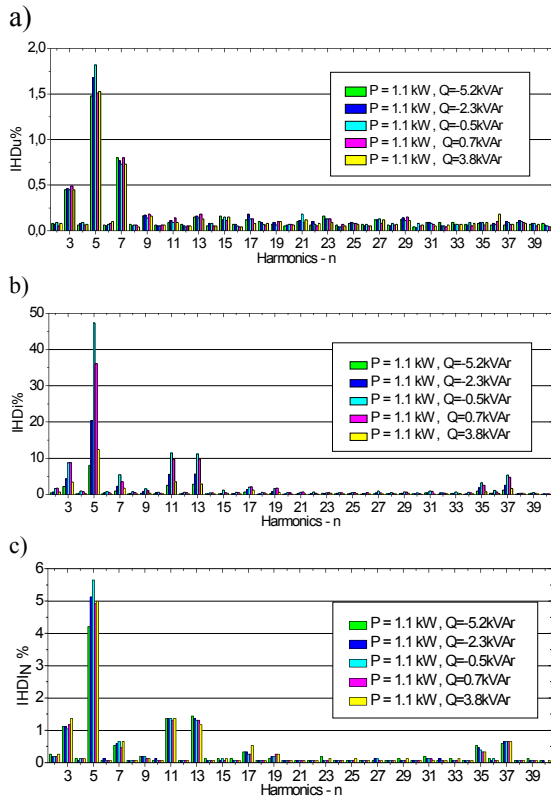
a)

b)

c)

Fig. 8. Percentage participation of a) voltage harmonics and armature current harmonics in relation to b) fundamental harmonic and c) nominal fundamental harmonic

Analyzing the compilation presented in Fig. 8 it can be noticed that the harmonics in the voltage of supplying system have got nearly constant values. Small variation ($< 0.5\% U_{(1)}$) can be observed only for harmonic 5. Analyzing the statements presented in Fig. 8 it can be noticed that the harmonics of armature current have got nearly constant values. Small variations ($< 0,2$ A) of harmonic 5 results from the variations of the same harmonic in the supplying voltage during carrying out the measurements [7, 8]. However, in case of comparison the harmonics content not in relation to nominal fundamental harmonic of armature current but in relation to fundamental harmonic, then for example $IHD_{I\%}$ for the 5 harmonics result differs even about forty percentage – Table 1.

Fig. 8 shows a comparison of the harmonics content not only in reference to fundamental harmonic of armature current, as often found in literature but in relation to value of fundamental harmonic of nominal current as imposed in PN-EN 61000-3-12 for equipment with nominal current > 16 A and < 75 A.

Setting-up of individual harmonic distortion (IHD) and Total harmonic distortion (THD) coefficient for presented harmonic voltages and armature currents in Fig. 9a and Fig. 9b are given in the Table 1.

Table 1. Setting-up of IHD and THD up to 40th harmonics

Harm. n	P = 1,1 kW Q = -5,2 kVAr				P = 1,1 kW Q = -2,3 kVAr				P = 1,1 kW Q = -0,5 kVAr				P = 1,1 kW Q = 0,7 kVAr				P = 1,1 kW Q = 3,8 kVAr			
	IHDi	I	IHDu	U	IHDi	I	IHDu	U	IHDi	I	IHDu	U	IHDi	I	IHDu	U	IHDi	I	IHDu	U
	[%]	[A]	[%]	[V]	[%]	[A]	[%]	[V]	[%]	[A]	[%]	[V]	[%]	[A]	[%]	[V]	[%]	[A]	[%]	[V]
1	100,0	7,99	100,0	219,5	100,0	3,84	100,0	222,2	100,0	1,90	100,0	222,0	100,0	2,10	100,0	222,9	100,0	6,10	100,0	222,8
3	2,17	0,17	0,45	0,99	4,33	0,17	0,46	1,02	8,70	0,16	0,45	1,00	8,81	0,18	0,49	1,10	3,42	0,21	0,45	0,99
5	8,07	0,64	1,48	3,25	20,44	0,78	1,68	3,73	47,29	0,86	1,82	4,03	36,14	0,75	1,51	3,37	12,44	0,76	1,53	3,41
7	0,99	0,08	0,80	1,76	2,32	0,09	0,77	1,70	5,43	0,10	0,73	1,63	3,50	0,07	0,80	1,78	1,74	0,10	0,73	1,62
9	0,39	0,03	0,16	0,36	0,83	0,03	0,17	0,37	1,56	0,03	0,14	0,32	1,08	0,02	0,18	0,40	0,34	0,02	0,16	0,35
11	2,59	0,21	0,09	0,19	5,55	0,21	0,11	0,23	11,44	0,21	0,09	0,20	9,71	0,20	0,14	0,31	3,52	0,21	0,09	0,19
13	2,80	0,22	0,15	0,33	5,62	0,21	0,16	0,36	11,21	0,20	0,14	0,31	9,74	0,20	0,18	0,39	2,91	0,18	0,13	0,29
15	0,20	0,02	0,16	0,35	0,27	0,01	0,12	0,26	1,21	0,02	0,15	0,32	0,56	0,01	0,11	0,24	0,35	0,02	0,15	0,33
17	0,68	0,05	0,12	0,27	1,33	0,05	0,18	0,40	2,04	0,04	0,13	0,30	2,13	0,04	0,13	0,29	1,26	0,08	0,08	0,18
19	0,30	0,02	0,07	0,14	0,77	0,03	0,09	0,19	1,66	0,03	0,06	0,13	1,78	0,04	0,10	0,22	0,59	0,04	0,10	0,23
35	0,94	0,08	0,08	0,19	1,85	0,07	0,09	0,21	3,23	0,06	0,09	0,21	2,55	0,05	0,06	0,13	0,78	0,05	0,09	0,21
37	1,18	0,09	0,06	0,13	2,54	0,10	0,10	0,22	5,34	0,10	0,09	0,19	4,80	0,10	0,07	0,15	1,70	0,10	0,07	0,16
THD %	9,51		1,84		22,88		2,00		51,71		2,1		40,49		1,87		14,41		1,82	

4. Conclusions

In the article, the analysis of higher harmonic contents in currents and voltages of synchronous machine armature during co-operation with the electric supply system has been presented. The analysis of higher harmonic contents has been carried out in applications made in LabView graphical programming environment. The designed graphical applications allow to display the waveforms of voltages and

currents taken by arbitrary electrical equipment. Additionally, the applications can carry out calculations of RMS values of Apparent Power (S), Real Power (P), Reactive Power (Q), Power of Distortion (D) as well as Power Factor and coefficients THD, PHD, IHD, and voltage unbalance. Application *Analizator jakości.vi* allows also to carry out an analysis of previously recorded waveforms of current and voltages. Analysing the harmonic spectrum of armature currents in synchronous machine during co-operation with supply system, it can be noticed that the content of harmonics 3, 5 and 7 is the most significant. So called slot harmonics, in our case No 11, 13 and 35, 37, come from the design of the machine itself, which has got 12 aluminium bars (squirrel-cage) in the rotor and 36 slots in the stator.

The synchronous generator meets specified requirements in the standard PN-EN 61000-3-2 regarding harmonic distortion. This norm, depending on the equipment characteristic, determines the limits for particular harmonics. However, it is not clearly stated to what value, RMS of fundamental harmonic of current or RMS of nominal fundamental harmonic current of the machine (as determined in PN-EN 61000-3-12) for particular harmonics should be referenced. In case of individual co-operation of the electrical machine with electrical power system commonly used $THD_{I\%}$ and $IHD_{I\%}$ coefficients do not give unequivocal answer to the content of higher harmonics in the armature currents. The analysis of the individual work of synchronous machine during co-operation with power system proved that $THD_{I\%}$ and $IHD_{I\%}$ coefficients have different values depending on how the machine is loaded (Fig. 6 – Fig. 7 and Table 1). RMS values of the voltage harmonics basically almost do not change. If synchronous generator is loaded with $P = 1,1$ kW and $Q = -5,2$ kVAr (reactive power taken from the system) the $THD_{i\%}$ coefficient is equaled to 9,5%. If generator is loaded with $P = 1,1$ kW and $Q = -0,5$ kVAr the $THD_{i\%}$ is equaled to 51,7%. However, RMS values of the current harmonics remained at similar level in the whole range and small changes came from the fact of harmonic variations in the supplying voltage [6, 7]. Similar variations of $THD_{I\%}$ and $IHD_{I\%}$ coefficients could be noticed when the synchronous machine have been in the state of overexcitation. Comparison of individual contents of harmo-

nics in armature currents registered in measurement set and in relation to nominal fundamental component are presented in Fig. 8. Comparison of harmonic contents in armature currents unambiguously results, that in case of individual co-operation electric machine with electric power system in wide range of load variations more reliable information about THD and individual harmonic contents is in relation to nominal fundamental component then to fundamental component.

5. Bibliography

[1] Z. Kowalski: *The Quality of Electrical Energy.* Monograph. Technical University of Lodz, Łódź 2007, Poland (in Polish)
[2] A. Siedlarz: *Analysis and visualization of influence unsymmetrical and distortion of power supply system voltages and currents on the quality of electrical energy in LabView.* Master's thesis. Kielce University of Technology. Kielce 2008, Poland (in Polish)
[3] PN-EN 50160: *Voltage characteristics of electricity supplied by public distribution systems.* PKN, Warszawa 2008, Poland (in Polish)
[4] PN-EN 61000-3-2: *Electromagnetic compatibility (EMC) Part 3-2: Limits - Limits for harmonic current emmissions (equipment input current ≤16A per phase)* PKN, Warszawa 2007, Poland (in Polish)
[5] PN - EN 61000-3-12: *Electromagnetic compatibility (EMC) Part 3-12: Limits - Limits for harmonic current produced by equipment connected to public low-voltage systems with input current >16A and ≤75A per phase.* PKN, Warszawa 2005, Poland (in Polish)
[6] Czarnecki L. S.: *Moc bierna i deformacji według definicji Budenau i przyczyny bezużyteczności tych wielkości w elektrotechnice.* ZNPŚl, Elektryka 107, Gliwice 1989, pp. 41-51
[7] S. Wiak, R. Nadolski, K. Ludwinek, J. Staszak: *Influence of the Synchronous Cylindrical Machine Damping Cage on Content of Higher Harmonics in Armature Currents During Co-Operation with the Distorted and Asymmetrical Electric Power System Computer Engineering in Applied Electromagnetism*, IOS Press, 2006, pp. 520-527
[8] K. Ludwinek: *Nonsinusoidal and unsymmetrical influence of electric power system on armature currents waveforms in synchronous machine*, Zeszyty Naukowe Politechniki Świętokrzyskiej – Elektryka 42, Kielce 2005, pp. 251-266, Poland (in Polish)

Authors

DSc. Krzysztof Ludwinek,
e–mail: k.ludwinek@tu.kielce.pl
Kielce University of Technology,
Al. Tysiąclecia PP. 7, 25–314 Kielce, Poland,
MSc. Arkadiusz Siedlarz,
e–mail: arkadiusz.siedlarz@gmail.com
Pilkington Automotive Poland Sp. z o.o.
ul. Portowa 24, 27-600 Sandomierz, Poland