Anna KOZIOROWSKA, Jacek BARTMAN
Uniwersytet Rzeszowski, Instytut Techniki

The influence of reactive power compensation on the content of higher harmonics in the voltage and current waveforms

Abstract *The paper presents the results of measurement tests carried out in the mine aggregate for various states of operation of electrical equipment installed in the plant, for cases with and without compensation of reactive power compensation. Development of drawings illustrating waveforms enrich the state by working with the load, the load is decreased, the state shut down the equipment in the plant, commissioning of individual machines and re-load status. Included in the individual states and the compensating capacitor banks excluded. We analyzed the current and voltage signals in the context of the harmonic content, set the value of THD_i and THD_u factors.*

Streszczenie *W pracy przedstawiono wyniki badań pomiarowych przeprowadzonych w kopalni kruszywa dla różnych stanów pracy urządzeń elektrycznych zainstalowanych w zakładzie, dla przypadków z kompensacją i bez kompensacji mocy biernej. Opracowanie wzbogacają rysunki obrazujące przebiegi mocy dla stanu pracy z obciążeniem, po zmniejszeniu obciążenia, dla stanu wyłączenia urządzeń w zakładzie, rozruchu poszczególnych maszyn oraz ponownie stanu pracy pod obciążeniem. W poszczególnych stanach dołączano oraz wyłączano baterie kondensatorów kompensacyjnych. Analizie poddano sygnały prądu oraz napięcia w kontekście zawartości wyższych harmonicznych, wyznaczono wartość współczynników THD_i oraz THD_u.* ***Wpływ kompensacji mocy biernej na zawartość harmonicznych na przykładzie urządzeń kopalnianych***

Keywords: Reactive Power Compensation, Voltage and Current Distortion, Higher Harmonics, Frequency Converter.
Słowa kluczowe: kompensacja mocy biernej, odkształcenie napięcia i prądu, wyższe harmoniczne, przemiennik częstotliwości.

doi:10.12915/pe.2014.01.32

Introduction

Electrical equipment users aim to minimize the costs of operation, for this purpose, among others. There are used reactive power compensation and power electronic drives for adjusting the electrical power to the current request.

Most of electric energy receivers take active and reactive power and energy. Active energy is converted into useful work and heat energy (representing mostly losses), and the reactive energy pulses between the power supply and the receiver, not performing any work. This occurs because the majority of electric energy receivers has the reluctance induction character (eg, asynchronous motors, power transformers, induction furnaces, etc.). The measure of the use of electricity is power factor (cos φ), defined as the ratio of active power to apparent power (which is the geometrical sum of active and reactive power) of the system. If the power factor has the higher value, than there is the higher share of the active power, which means that less reactive power is taken by the fed system. In order to improve the power factor there is used the compensation. Most often for reactive power compensation there are used the capacitor batteries which are connected in parallel with the receivers of electric energy.

In the last years there has been a very dynamic increase of using of alternating current induction motors with controlled - by changing the frequency - speed. This type of modern power systems - which use power electronic circuits - have many advantages compared to the traditional systems. However they have a serious disadvantage - they cause distortion of the supply voltage[1], which is the effect of non-sinusoidal current consumption by frequency converter. They generate higher harmonics significantly deforming the current and voltage waveforms. The cause of distortion are usually 3,5,7,11 and 13 harmonics [2].

The question is whether the reactive power compensation in systems with variable speed frequency brings the same results as in classical systems? The paper presents the results of a measurement study carried out in the stone mine.

The plant chosen for the measurement tests is an example of the place, where there are mostly used asynchronous squirrel-cage motors, which implies necessary to use the system for reactive power compensation (Fig.1.). In addition, there are used in the plant - for motor control - integrated converters introducing non-linearity of the electrical circuits.

Fig. 1 A view of the compensation system with the energy capacitors (own photo)

Characteristics of the tested object

The measurements were performed in stones mine located in the province of Subcarpathian. The mine was supplied by a dedicated transformer, 15/0, 4 kV (Fig. 2). Measurements were performed for different operating conditions of the plant included and excluded batteries compensation capacitors.

The mine where the measurements were made was subjected to modernization, which included in particular an electric power section of the plant. Drives used in the mine use cage induction motors, fed directly from the transformer. Power supply of the devices is carried out in a radial arrangement (Fig. 3). The modernization of the plant was based on an upgrade of the drive system of the mine cutting excavator (indicated in figure 3 with the letter K) and adjust the compensation capacitor to new working conditions of the mine. The frequency converter with vector inverter replaced the star-delta starter used before. Such exchanges allow to adjust the motor speed and thus power control of the excavator.

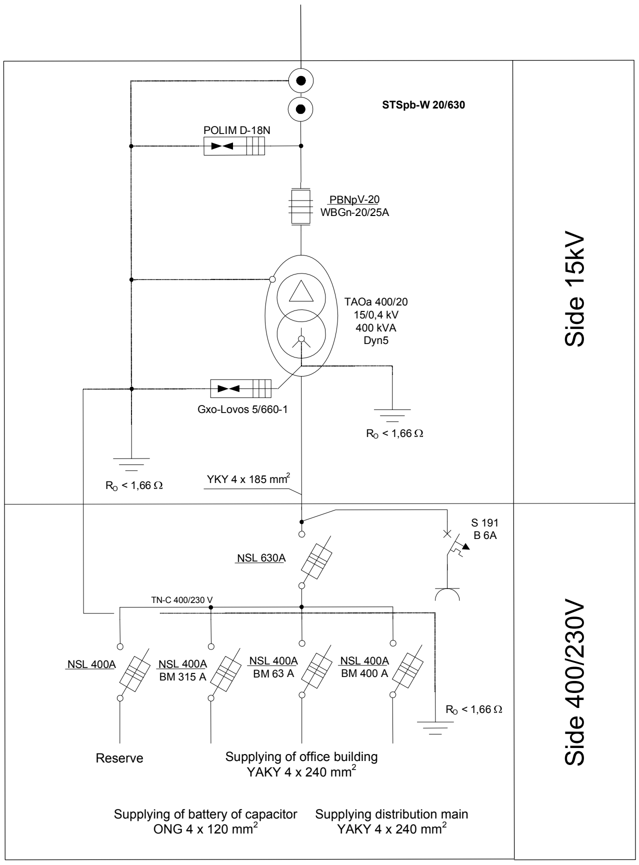

Fig. 2 The diagram of mine's supplying system [3]

The plant currently operates four power units with frequency inverters - three of inverters with vector control and one with scalar control. There are used input noise filter from Schaffner for each unit to meet EMC requirements.

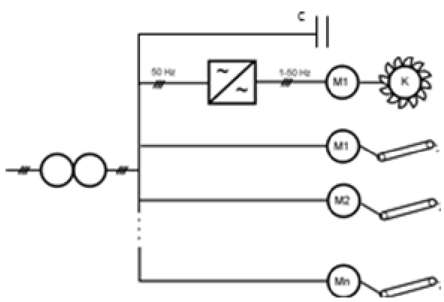

Fig. 3 Schematic layout of devices in the stone mine

Reactive power compensation

Reactive power management including aspects of power quality has been an important problem to solve in the modernization of power units at the stone mine Attaching appropriate capacitive loads to supply network fed receivers taking passive induction energy causes reactive power compensation. The active component, the reactive and harmonic components can be distinguished in the load current:

$$i_0(t) = A_1 \sin\omega t + B_1 \cos\omega t + \sum_{n=2}^{\infty} A_n \sin(n\omega t) + \sum_{n=2}^{\infty} B_n \cos(n\omega t) \quad (1)$$

The component $A_1 \sin\omega t$ of the above formula is the active component, $B_1 \cos\omega t$ is the passive component, the other components are the harmonic components of the load current.

Limitation of the last three components constituted a task which solution can reduce the negative impact of non-linear devices and compensate the reactive power. Compensating devices used in modern industrial systems can be divided into the following groups:

- compensating devices with energetic capacitors;
- integrated power electronic compensators;
- systems of hybryd compensating units capacitor – power electronics;
- synchronous machines.

In the analyzed stone mine for reactive power compensation there was used the battery of power capacitor.

Higher harmonics in voltage and current waveforms

On the power quality affects the harmonic content of the voltage and current signals. Failure to comply with specified in the standards levels of harmonics in the electricity delivered to customers may cause interference in receivers work and cause serious damages. For current and voltage waveforms which were registered in the stone mine, there was determined the harmonic spectrum in order to analyze the content of these harmonics in the signals.

Harmonics can be defined as a component of the waveform at the frequency of integer multiple of the fundamental frequency. There are standards for the percentage content of the individual harmonic in waveforms [5, 6].

In order to determine the content of harmonics in voltage waveform there is defined the factor THD_u (Total Harmonic Distortion) as the ratio of the square root of the sum of the squares of the effective higher harmonics of voltage signal to the rms value of the fundamental voltage:

$$THD_u = \frac{\sqrt{\sum_{k=2}^{n} U_k^2}}{U_1} 100\% \quad (2)$$

where: U_1 - effective value of the fundamental voltage signal, U_k - effective value of the voltage signal of k-th harmonic, n – number of harmonics taken into account; according to the standard PN-EN 50160 n=40. There is similary defined the factor of harmonics in current waveform - THD_i:

$$THD_i = \frac{\sqrt{\sum_{k=2}^{n} I_k^2}}{I_1} 100\% \quad (3)$$

where: I_1 - effective value of the current signal of the fundamental component, I_k - the effective value of the signal of k-th harmonic of current [4, 5, 6].

The measuring device

Measurements of electrical values were performed using microprocessor recorder for power quality analysis - Skaylab. The device allows the measurement of voltages and currents in each phase with frequency of 6400 Hz (128 samples over 20 ms). It allows for the measurement of most electrical signals in single and three phase systems. Device speed enables the realization of on-line harmonic analysis for the three voltages and three currents at intervals from 1 second to 15 minutes – it allows to control all the parameters of the power supply in accordance with the international standard EN 50160.

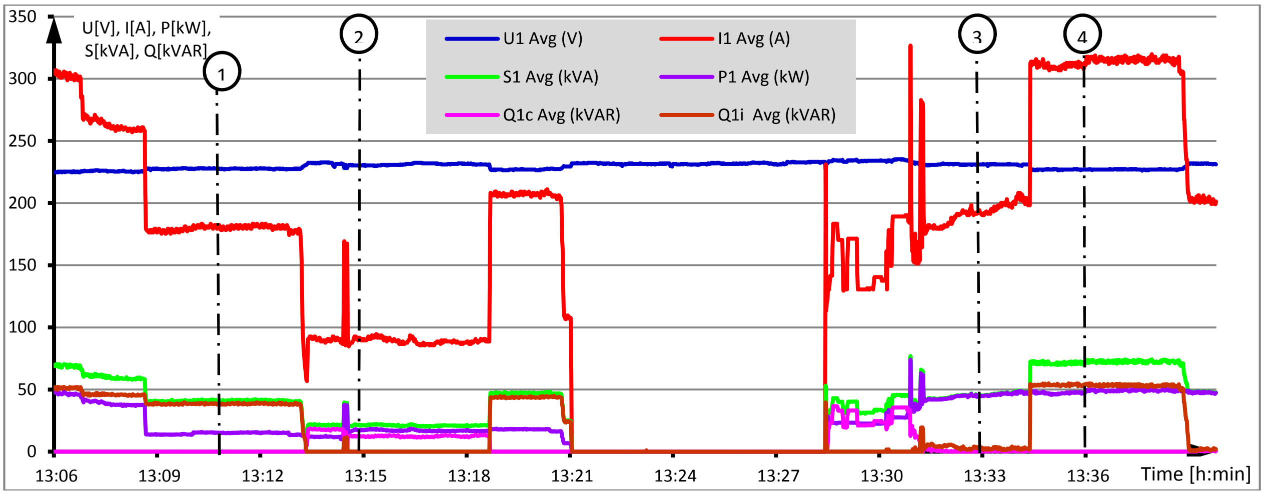

Fig. 4. Waveforms of average values of voltage, current and power as a function of time. Vertical dotted lines indicate the measurement points where signals were analyzed.

Measuring tests in the stone mine

The tests were carried out during the operation of the stone mine for different working conditions and for the case of compensation, and without reactive power compensation. There are presented the measurement results for particular operating conditions below. In the first of the analyzed cases there is shown the distribution of harmonic voltages and currents in all phases (Fig. 6, Fig. 7). However, in order to facilitate the assessment of the impact of compensation and work states on the value of THD there is shown the distributions of harmonics of voltage of phase L1 for all analyzed cases in figure 9. and the corresponding distributions for the current in figure 10.

Idle state with turned off capacitors

The measurements reported in this section were taken at idle state of the plant (operating electrical machines were unloaded) at the disconnected capacitor battery – in figure 4 the moment of the measurement is indicated by line 1. The analysis of power waveforms (apparent, active and passive) shown in figure 4 demonstrate that the plant gets mostly inductive reactive power, share of active power is more than twice lower.

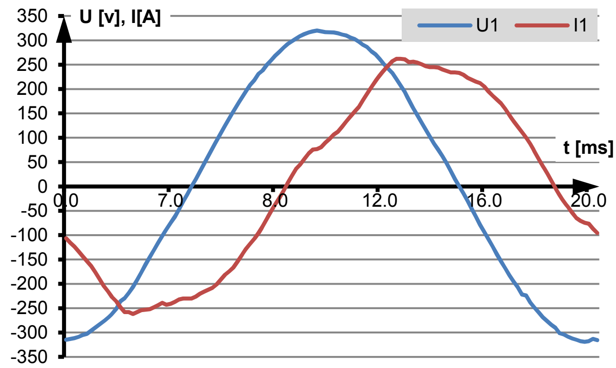

Fig. 5 Voltage and current waveforms for the first phase for idle state and the battery of capacitors turned off

The voltage and current waveforms shown in figure 5 confirm that current taken from the supply network is inductive and has low distortion (involving higher harmonics). Presented in figure 6 the spectrum of voltage harmonics shows slight voltage distortion, the THD factors are respectively in phase L1 - 1.24% for L2 - 1.11%, and L3 - 1.24%. Slightly larger distortion occur in the waveforms of the current, where the THD factors are respectively (Fig. 6): for L1 - 6.34% for L2 - 6.56%, and L3 - 6.46%. The harmonics 3, 5, 7, 11 and 25 (Tables 1 and 2) have the highest share, the dominant role (espe-cially in the current waveforms) has the 7-th component.

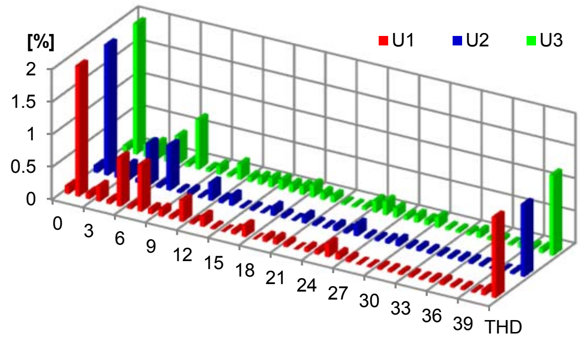

Fig. 6. The voltage harmonics at the idle state with the capacitor battery turned off.

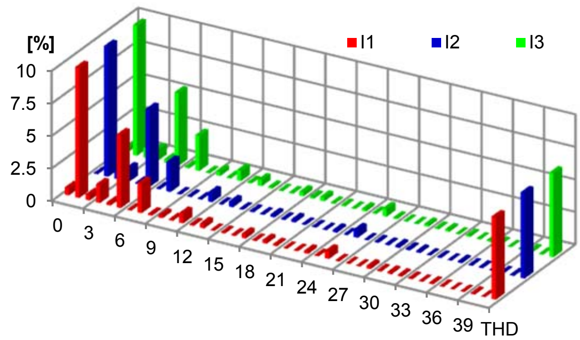

Fig. 7. The current harmonics at the idle state with the capacitor battery turned off.

Idle state with turned on capacitors

Subsequent measurements were performed after switching on battery of compensation capacitors, while machines in the plant remained unloaded (idle state) – in Figure 4 the moment of the measurement is indicated by line 2. Analyzing waveforms shown in figure 4 there can be seen that the inductive reactive power decreased to zero, and that capacitive reactive power appeared. This means that at idle state the plant is overcompensated, the proportion of reactive power to apparent power has significantly diminished. Figure 8 shows the waveforms of current and voltage of the first phase of input current and indicate that the current character became minimally capacitive. In addition, significantly decreased the current value and appeared a very strong share of higher harmonics in the current waveform. Although there can not be observed significant changes in the voltage waveform. The analysis of harmonic spectrum of voltage indicates a slight increase in distortion factors THD, now they are respectively for phase L1 - 2.24% (Fig, 9, red), for L2 - 2.08%, and L3 - 2.33%. Higher voltage distortion is caused by a very strong distortion of input current, THD factores for particular phases increased to values: for L1 - 37.14% (Fig. 10. red), for L2 - 44.13%, and L3 - 39.25%. The largest share have harmonics 3, 5, 7 and 11 (Tables 1 and 2).

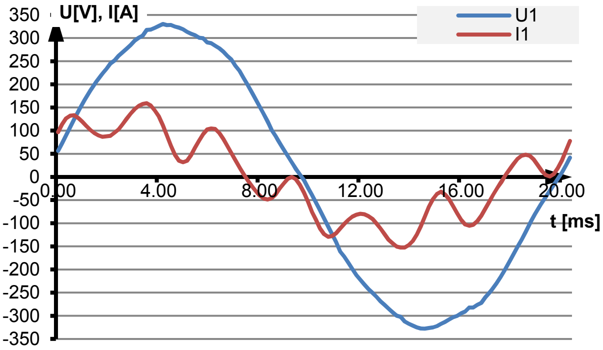

Fig. 8 Voltage and current waveforms of the first phase for idle state and turned on the battery of capacitors

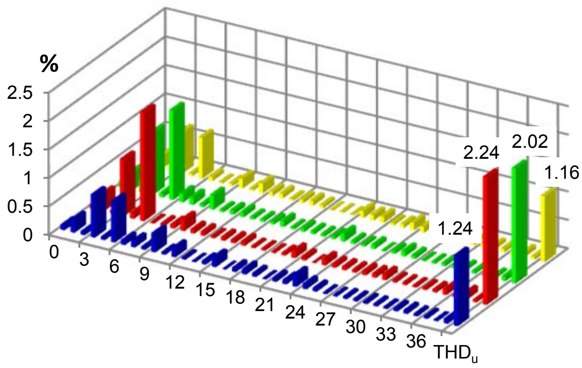

Fig. 9 Harmonic spectrum of voltage of phase L1 for each of the analyzed cases.

- Idle state with turned off capacitors
- Idle state with turned on capacitors
- Working with the load with capacitors turned off
- Working with the load with capacitors turned on

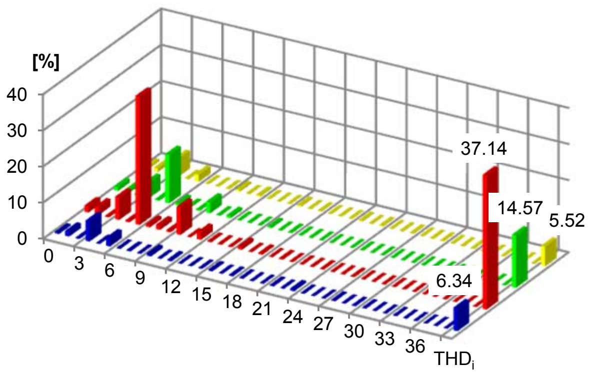

Fig. 10 Harmonic spectrum of currents of phase L1 for each of the analyzed cases.

- Idle state with turned off capacitors
- Idle state with turned on capacitors
- Working with the load with capacitors turned off
- Working with the load with capacitors turned on

Analysis of the data presented in Table 1 demonstrate that the switching on of compensation capacitor battery at idle state of plant operation resulted in a slight increase in harmonic content in voltage waveforms. There is the highest increase of component 7 - by 165% for L1 and L2, and by 179% for phase 3, while the share of the 25th component decreased.

Tab.1. Statement of most powerfully affecting harmonic on voltage distortion at idle state.

Harmonic	Without compensation			With compensation		
	U_1	U_2	U_3	U_1	U_2	U_3
3	0,23	0,23	0,24	0,30	0,24	0,17
5	0,75	0,64	0,43	1,00	0,86	0,75
7	0,72	0,69	0,76	1,91	1,83	2,12
11	0,33	0,27	0,24	0,20	0,27	0,22
25	0,21	0,18	0,21	0,10	0,04	0,14
THD	**1,24**	**1,11**	**1,25**	**2,24**	**2,08**	**2,33**

Summarized in Table 2 percentage of the share of individual harmonic of current with respect to the fundamental harmonic show a large increase in harmonic content after switching on the battery of compensation capacitors. Particularly strongly have increased harmonic 7 (for phase L1 of 1468%, 1752% for L2 and L3 of the 1304%) and harmonic 11 (respectively 927% for L1, 1422% for L2 and 840% for L3). The contetnt of 25th harmonic declined. Consequently, the factor THD of current have increased from 6 to 7 times.

Tab.2. Statement of most powerfully affecting harmonic on current distortion at idle state.

Harmonic	Without compensation			With compensation		
	I_1	I_2	I_3	I_1	I_2	I_3
3	1,38	0,97	0,83	2,11	2,11	1,75
5	5,61	5,94	5,60	6,25	6,65	5,94
7	2,27	2,27	2,70	35,60	42,05	37,91
11	0,74	0,70	0,80	7,60	10,66	7,52
25	0,58	0,60	0,59	0,11	0,33	0,07
THD	**6,34**	**6,56**	**6,46**	**37,14**	**44,13**	**39,25**

The increase in the harmonic content may be the result of incorrectly selected capacitances of compensation capacitors.

Working with the load with capacitors turned off

After loading machines working in the factory, there were made further measurements. During the time of measurements the conveyors transported aggregate and bucket excavator collected excavated material.

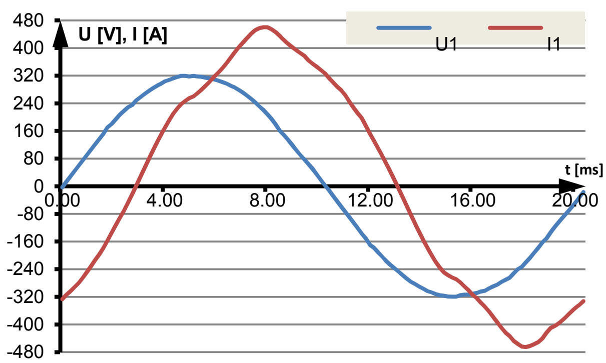

Fig.11. Voltage and current waveforms of the first phase. Working with the load with the capacitor battery turned off.

The following measurements were taken at the time 4 (Fig. 4), with turned off compensation capacitor battery.

Figure 11 shows the waveforms of the current and voltage. There is clear, but not significant distortion of current waveform and phase shift between current and voltage indicating the inductive nature of the load.

The largest share in the voltage waveform distortion have harmonics 3, 5, 7, 11 and 13. The coefficients of distortion for the various phases are: for L1 - 1.16% (Fig. 9. yellow), for L2 - 0.97% for L3 - 1.15%. In harmonic spectrum of current there can be observed that the highest values have harmonics 3, 5 and 7, while explicitly dominates harmonic 5. THD are respectively for L1 - 5.52% (Fig. 10. yellow), for L2 - 5.33% for L3 - 5.09%.

Working with the load with capacitors turned on

Measurements taken at the time indicated line number 3 in figure 4 apply where electrical equipment was loaded and the battery of compensating capacitors was turn on. In figure 12 showing the waveform of voltage and current of the first phase there can be seen that the current taken by the system clearly lost its inductive nature, while there can be seen its higher deformation. This is confirmed by shown in figure 10 (green) harmonics spectrum - distortion rates have increased to a value appropriate for phase L1 - 14.57%, for L2 - 15.74%, and L3 - 15.92%. The largest impact on the current deformation have harmonics 5, 7 and 11. The increase in the current waveform distortion has little effect on the voltage waveform - THD are for L1 - 2.02% (Fig. 9, green), for L2 - 1.84%, and for L3 - 1.92%.

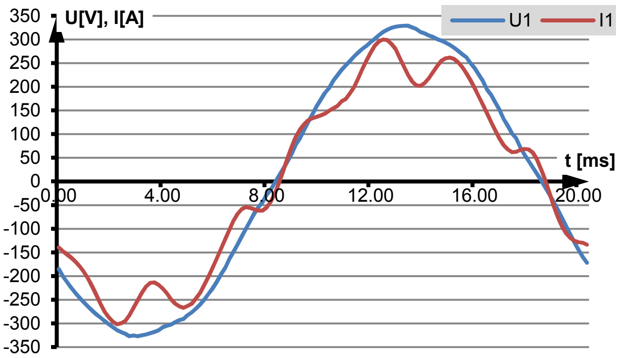

Fig.12. Voltage and current waveforms of the first phase. Working with the load with the capacitor battery turned on.

Table 3. Statement of harmonic most powerfully affecting voltage distortion at the load state.

Harmonic	Without compensation			With compensation		
	U_1	U_2	U_3	U_1	U_2	U_3
3	0,22	0,19	0,14	0,32	0,27	0,26
5	0,72	0,60	0,55	1,09	1,00	0,71
7	0,72	0,56	0,80	1,57	1,47	1,66
11	0,17	0,21	0,22	0,25	0,19	0.12
THD	**1,16**	**0,97**	**1,15**	**2,24**	**2,08**	**2,33**

Table 4. Statement of harmonic most powerfully affecting current distortion at the load state.

Harmonic	Without compensation			With compensation		
	I_1	I_2	I_3	I_1	I_2	I_3
3	0,98	0,45	0,66	0,75	0,65	0,86
5	4,98	4,77	4,43	4,34	4,36	4,26
7	1,96	1,99	2,13	13,46	14,57	14,96
11	0,46	0,46	0,56	3,05	3,43	2,98
THD	**5,52**	**5,33**	**5,09**	**14,57**	**15,74**	**15,92**

In Tables 3 and 4 there are collected relative values of harmonic which have the most powerfully influence on the voltage and current waveforms distortion. As in the idle state after switching on of compensation distortion of signals has increased, although in operation state, this increase is much smaller than at idle state.

Summary

The aim of this study was to examine whether reactive power compensation in systems with variable speed frequency brings the same results as in classical systems? The measurements were made in the company of a specified structure, equipment, using concrete electrical equipment, etc. Therefore, it is difficult to just put them under general thesis, however analysis of measurements empowers us to make a number of statements which are given below.

Reactive power compensation in systems with frequency speed control leads to a reduction in energy consumption - namely its reactive component (Fig. 4). As a result, the power factor is improved.

In the present case after switching on capacitor battery there was an increase of distortion of current and voltage signals, the compensation had a negative impact on the quality of energy - this is especially true during operation at idle state. Most likely, the increase of signals distortion was a result of inappropriate choice of compensating devices [7]. Reactive power compensation can affect the quality of energy.

REFERENCES

[1] Bartman, J. Koziorowska, A. Kuryło, K. Malska, W., Analiza rzeczywistych parametrów sygnałów elektrycznych zasilających układy napędowe pomp wodociągowych, *Przegląd elektrotechniczny,* (2011), nr 8, 8-11

[2] Koziorowska A., Kuryło K., Bartman J., Harmoniczne napięcia i prądu generowane przez nowoczesne napędy stosowane w kopalniach kruszywa, *Przegląd Elektrotechniczny,* (2010), nr 6, 279-284

[3] Dokumentacja techniczna kopalni kruszywa

[4] Piróg, S., Kompensacja zmiennych obciążeń biernych i filtracja wyższych harmonicznych prądu w sieciach przemysłowych, *Wiadomości Elektrotechniczne*, (2000), n. 4, 183-189

[5] Pasko M., Maciążek M., Buła D., Wprowadzenie do zagadnień analizy jakości energii elektrycznej, *Wiadomości elektrotechniczne*, (2007), nr 4, 4-9

[6] Henzelka Z., Jakość energii elektrycznej, *www.twelvee.com.pl*

[7] Matyjasek K., Urządzenia do kompensacji mocy biernej w środowisku napięć i prądów odkształconych, *www.elma-energia.pl*

[8] PN EN 50160 „Parametry napięcia zasilającego w publicznych sieciach rozdzielczych" PKN 1998

[9] Rozporządzenie Ministra Gospodarki z 4 maja 2007 r. w sprawie szczegółowych warunków funkcjonowania systemu elektroenergetycznego [DzU nr 93 z 2007 r., poz. 623]

***Authors**:*
dr inż. Anna Koziorowska, e-mail: akozioro@ur.edu.pl;
dr inż. Jacek Bartman, e-mail: jbartman@ur.edu.pl;
Uniwersytet Rzeszowski,
Instytut Techniki,
al. Rejtana 16c, 35-959 Rzeszów,