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INFLUENCE OF A PASSIVE CONTROLLED L-C FILTER ON HIGHER VOLTAGE AND CURRENT HARMONICS IN THE POWER SUPPLY NETWORK FOR ELECTRIC ARC DEVICES

WPŁYW STEROWANEGO FILTRA PASYWNEGO NA WYŻSZE HARMONICZNE NAPIĘCIA I PRĄDU W SIECIACH ZASILAJĄCYCH URZĄDZENIA ŁUKOWE

A b s t r a c t

Electrical machines, such as welding arc devices, negatively affect the quality of electric power in a supply network, which in turn affects the operation of loads connected in parallel. The aim of this paper is to present the results of research confirming the positive effect of a passive L-C filter dedicated for welding devices. The paper demonstrates the effectiveness of the filter, which not only helps to reduce the total voltage distortion, but the reactive power compensation as well. The results confirm that installing a passive controlled L-C filter significantly reduces power losses in elements of the power supply network. The conducted research leads the authors to recommend using such filters in electrical arc devices.

Keywords: voltage distortion, current distortion, welding arc devices, passive controlled L-C filter, higher harmonics

S t r e s z c z e n i e

Urządzenia elektryczne, takie jak spawalnicze urządzenia łukowe, negatywnie oddziałują na jakość energii elektrycznej w sieci zasilającej, co wpływa na pracę równolegle podłączonych odbiorników. Celem artykułu jest przedstawienie wyników badań, które potwierdzają pozytywny wpływ pasywnego filtra sterowanego przeznaczonego do urządzeń spawalniczych. Pokazano efektywność działania filtra, który nie tylko wpływa na obniżenie całkowitego współczynnika zniekształcenia przebiegu napięcia, ale i również kompensacje mocy biernej. Wyniki potwierdzają, że instalacja pasywnego filtra sterowanego pozwala na istotne obniżenie strat mocy w elementach sieci zasilającej. Na podstawie otrzymanych wyników autorzy rekomendują stosowanie takich filtrów do urządzeń łukowych.

Słowa kluczowe: odkształcenie napięcia, odkształcenie prądu, spawalnicze urządzenia łukowe, pasywny filtr sterowany, wyższe harmoniczne

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1. Introduction

Many branches of industry use welding arc devices, which negatively affect the power supply network in terms of voltage fluctuations and the generation of higher harmonics. Loads connected in parallel, such as digital circuits and microprocessors, are vulnerable to distortions generated by active arc devices within the same network. One of the effects of arc devices is an unstable operation of power inverters. A majority of arc devices are powered with a low-voltage (0.4 kV) network and connected directly to it, with the electric arc constituting the source of process heat and a non-linear element of the electric circuit. The negative effect of these devices on the supply network depends on the parameters of the network and the device itself as well as on the short-circuit impedance of the electric power system [1, 5].

Numerous studies investigating the operation of arc devices in networks with different parameters showed that these devices are the sources of both even and uneven harmonics. During arc burning, however, the amplitude values of even harmonics depend on the material that the electrodes are made from and the welded material, while uneven harmonics depend on the voltage and current characteristics of the arc. Thus, it is extremely important to analyze the effect of arc devices on the power supply network and develop a method for limiting this effect [3, 6–8, 11–15].

2. Effect of arc devices on current and voltage waveforms in the power supply network

Welding arc devices using a jacketed fusible metal electrode (manual arc welding, MMA) are most commonly employed for minor welding works. They usually operate in objects with a connected load of 6 kW for a single-phase connection point and 16 kW for a three-phase connection point. The generated distortions and a low power factor of arc devices affect the distribution transformer located in a substation, leading to a pre-magnetization of the transformer, which in turn leads to increased voltage distortion, increased load of the transformer and, ultimately, to increased power losses [1, 7, 8, 11–15].

The waveform of the registered voltage (Fig. 2) in the power supply line during the operation of the analyzed arc device is asymmetrical about the *time*-axis and not

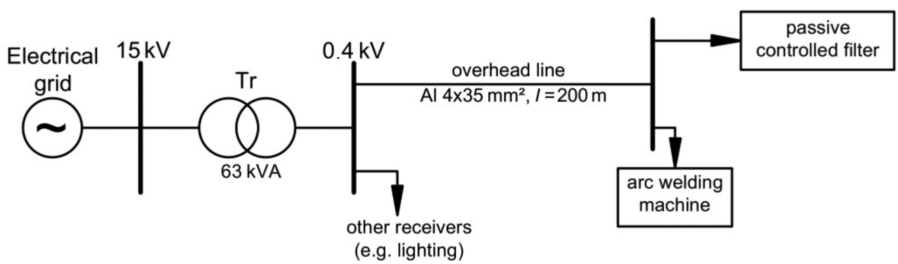

Fig. 1. Concept diagram of the power supply system

sinusoidal. This negative effect indicates the presence of a constant component in the frequency spectrum of voltage harmonics. This constant component causes undesirable pre-magnetization in the core of the transformer, which leads to increased distortion. The asymmetry results from differences in the characteristics of electron emissions between the metal and the electrode in the welded material. The analyzed arc device draws reactive power from the supply network, as indicated by the phase shift between the current and voltage waveforms.

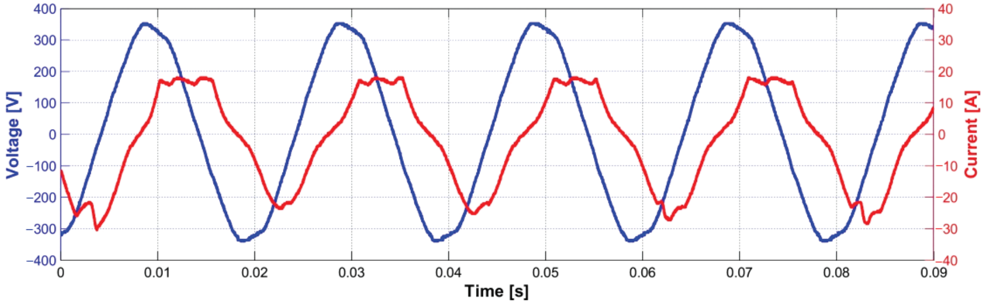

Fig. 2. Waveforms of voltage and current in the power supply line

The low value of the power factor (0.39) resulted in high reactive power consumption, which is highly undesirable from the viewpoint of an electric network, as it leads to increased values of operational currents, which in turn lead to increased power losses and voltage drops at individual elements of the transmission network and an increased temperature of the wires. On the other hand, from the viewpoint of the technological process and electric arc stability, the same state is beneficial and, indeed, necessary [1, 3, 9, 10].

The results in Fig. 3 and 4 are not presented in the discrete form, because not only multiples of the fundamental harmonic are existent. The total harmonic distortion of the voltage (THD_U), calculated based on the obtained spectrum of higher voltage harmonics, amounted to 13.08% (Fig. 3). According to the Polish Standard No. [9], THD_U should not exceed 8%, which means that the obtained result exceeds the allowable level by over 5% and is thus unacceptable [9, 10].

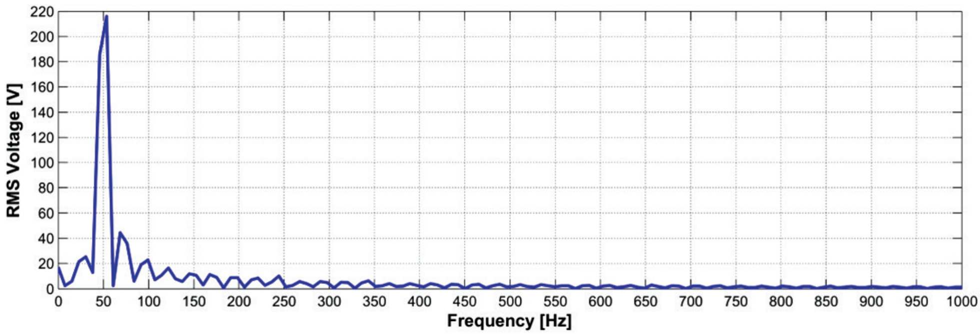

Fig. 3. Harmonic voltage spectrum

Even though [9] does not specify the allowable levels of current distortion, the total harmonic distortion of the current THD_I was calculated. THD_I amounted to 25.22%. The obtained frequency spectrum of higher current harmonics (Fig. 4) constitutes a reference point and will enable the assessment of the effect of a passive controlled L-C filter on reactive power compensation [9, 10].

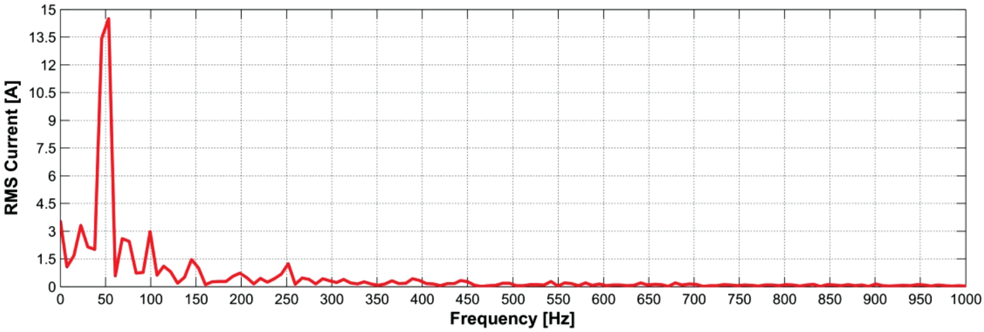

Fig. 4. Harmonic current spectrum

Passive resonant filters are usually used to reduce voltage distortion. However, due to changes in the amplitudes of harmonics over time and the occurrence of signals that are not whole-numbered multiples of the fundamental harmonic, filters with constant parameters can hardly improve the situation. A solution to these limitations may involve a passive controlled L-C filter, shown in Fig. 5.

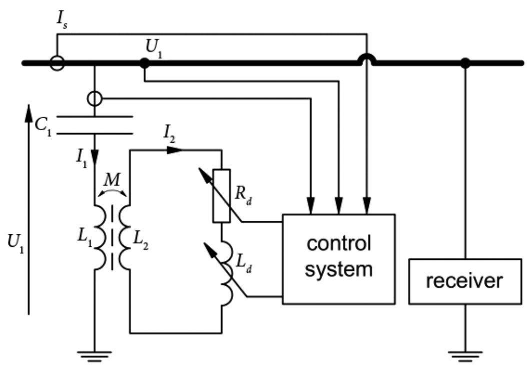

Fig. 5. Passive controlled L-C filter

The benefit of a passive controlled L-C filter is that its parameters can be adjusted during operation, i.e., without the need to detach the filter system from the supply voltage. The possibility to adjust the damping band and resonance frequency enables better filtration than in the case of ordinary passive filters with constant parameters. The filter is equipped in a solid-state relays (SSR) to changing values of the elements R_d and L_d. Systems of this type cause losses in active power. This, however, is acceptable in view of the benefits provided by the filter [2, 6, 15].

The filter system has capacitor properties for the frequency of the fundamental harmonic. This means that reactive power is generated, i.e., the system enables reactive power compensation. As the frequency increases, the system begins to function as a band-stop filter. The individual parts of the passive controlled L-C filter are selected to ensure that the total reactance for the resonance frequency between the connection points is equal to zero [2, 6, 15].

The System of Equations (1) was written based on the equivalent circuit shown in Fig. 5 to determine the values of resistance and inductance entering the main circuit of the filter [4].

$$\begin{cases} R_1\underline{I}_1 + j\omega L_1\underline{I}_1 + j\omega M\underline{I}_2 = U_1 \\ R_2\underline{I}_2 + j\omega L_2\underline{I}_2 + R_d\underline{I}_2 + j\omega L_d\underline{I}_2 + j\omega M\underline{I}_1 = 0 \end{cases} \quad (1)$$

After transformation it is obtained:

$$\underline{I}_1 = \frac{U_1}{R_1 + R_{w1} + j\omega\left(L_1 - L_{w1}\right)} \quad (2)$$

where:

$$R_f = R_1 + R_{w1} \quad (3)$$

$$L_f = L_1 - L_{w1} \quad (4)$$

$$R_{w1} = \frac{(\omega M)^2 \left(R_2 + R_d\right)}{\left(R_2 + R_d\right)^2 + \left(\omega L_2 + \omega L_d\right)^2} \quad (5)$$

$$L_{w1} = -\frac{(\omega M)^2 \left(L_2 + L_d\right)}{\left(R_2 + R_d\right)^2 + \left(\omega L_2 + \omega L_d\right)^2} \quad (6)$$

$$M = k\sqrt{L_1 L_2} \quad (7)$$

f – frequency,
k – coil coupling coefficient,
L_1, L_2 – choke coil inductance,
R_1, R_2 – choke coil resistance,
R_{w1}, L_{w1} – resistance and inductance introduced into the primary circuit of the filter,
R_d, L_d – resistance and inductance connected to the secondary coil of the choke,
$U_1, \underline{I}_1, \underline{I}_2$ – have been explained in the Fig. 5.

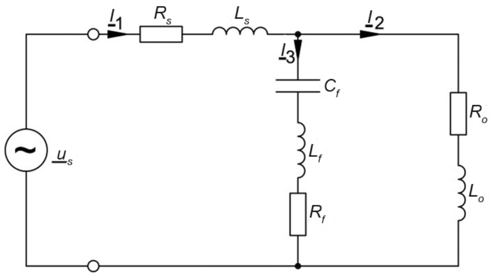

Fig. 6. Simplified diagram used for system analysis

To enable a more detailed analysis of the passive L-C filter and its effect on the power supply network, the impedance characteristics of the system shown in Fig. 6 were established. This analysis helps to determine the frequencies for which an undesirable parallel resonance can occur. The calculated equivalent impedance is given by Equation (8) [4].

$$\underline{Z}_z(j\omega) = R_s + j\omega L_s + \frac{(R_o + j\omega L_o)\left(R_f + j\omega L_f - j\dfrac{1}{\omega C_f}\right)}{R_o + j\omega L_o + R_f + j\omega L_f - j\dfrac{1}{\omega C_f}} \tag{8}$$

where:

R_s, L_s – resistance and inductance of the power supply network,
R_f – resistance representing losses in the filter,
C_f, L_f – capacitance of the capacitor and inductance of the choke in the L-C filter,
R_o, L_o – resistance and inductance of the load – measured for quasi steady-state.

Waveforms were established for the following parameters:

$$R_o = 240\ \text{m}\Omega, L_o = 0.120\,\text{mH},$$

$$R_f = 110\ \text{m}\Omega, C_f = 100\ \mu\text{F}$$

$$R_f = 110\ \text{m}\Omega, C_f = 100\ \mu\text{F},$$

For the resonance frequency, the impedance of the filter should be lower than the impedance of the power supply network to ensure appropriate damping of the filtered harmonic. The impedance characteristics presented in Fig. 7 show that, for certain frequencies, an undesirable resonance with the power supply network may occur, which strengthens the current harmonics and may thus lead to distortions in the waveform of the current flowing through the load and the network.

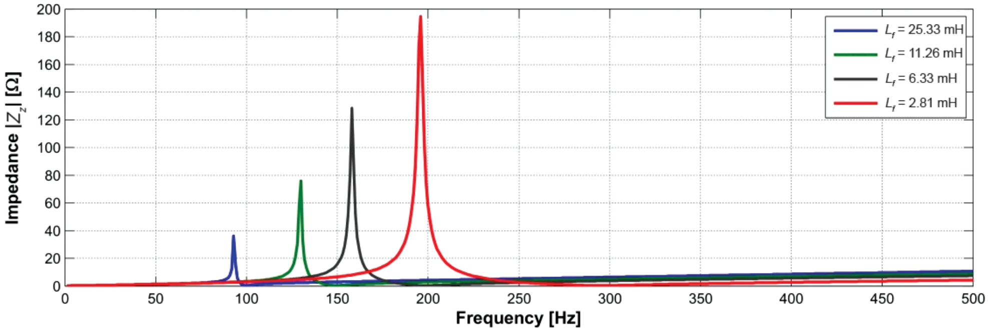

Fig. 7. Impedance characteristic of system

The phase characteristics shown in Fig. 8 indicate that changes to the inductance of the choke, with other elements of the filter remaining at constant values, correlate with a decrease in the Q factor of the system. As a result, the damping band increases.

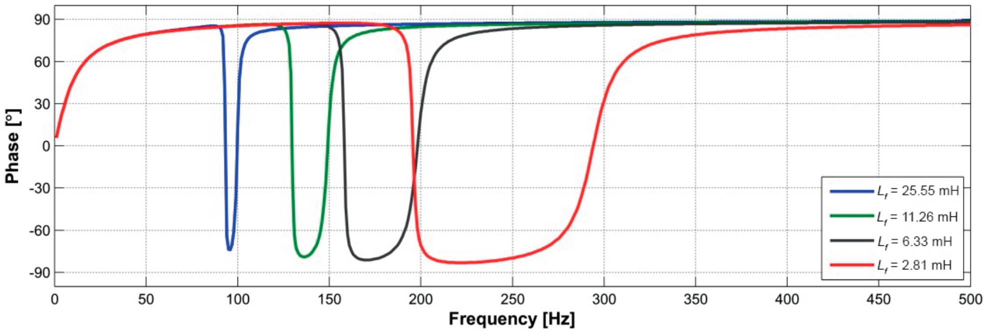

Fig. 8. Phase characteristic of system

When appropriate elements are added to the secondary circuit of the choke, a change in the parameters of the passive L-C filter allows the width of the damping band and the resonance frequency to be adjusted. Thus, filters of this type can extent their damping band over a large range of frequencies, eliminating not only the harmonics, but other constituents that are not whole-numbered multiples of the fundamental harmonic as well.

3. Effect of passive controlled filter on the quality of electric power

Connecting the passive L-C filter to the analyzed load in parallel helped to improve the waveform of the voltage in the power line, decreasing distortion to 4.57%. Fig. 9 shows the voltage waveform for the arc device with the filter introduced to the input. The applied filtration method also allowed the phase shift angle between current and voltage waveforms to be reduced, which indicates that the reactive power taken by the load from the supply network was compensated for. This means that the power factor cosα has been improved, which led to the decrease in the current flowing in the power line and to the decrease in power losses.

The advantage provided by L-C filters, i.e., the ability to adjust the parameters of the system by introducing appropriately selected elements into the secondary coils of the filter

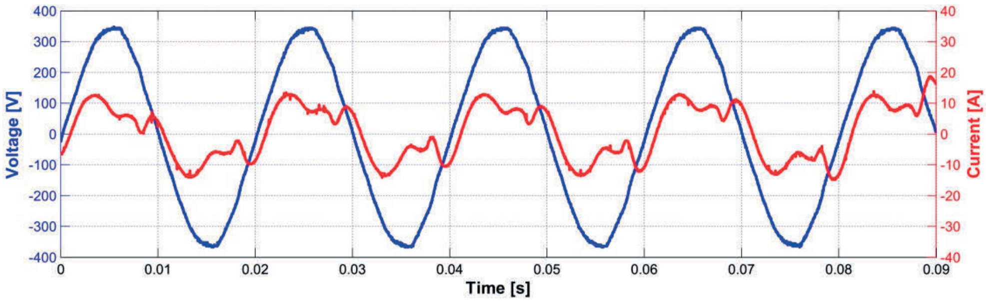

Fig. 9. Waveform of current and voltage in the power supply line (filter on)

choke, helped to improve the voltage waveform in the power supply line. The registered waveform was subjected to FFT. Fig. 10 shows the full range of obtained spectra of higher harmonics.

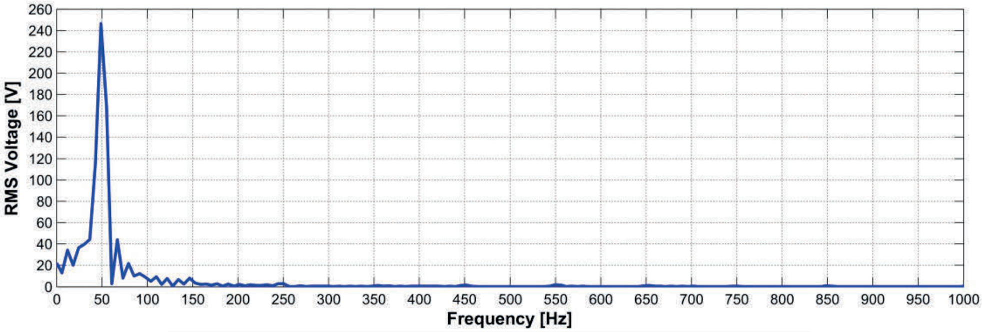

Fig. 10. Harmonic voltage spectrum (filter on)

A comparison between the spectra of higher voltage harmonics for two cases, i.e., a filter-less load and a load with a passive L-C filter introduced to the input, indicates a decrease in the amplitudes of higher harmonics for a certain range of frequencies. The voltage distortion coefficient has been decreased by over 10%. The new value falls within the allowable range stipulated by the Standard [9].

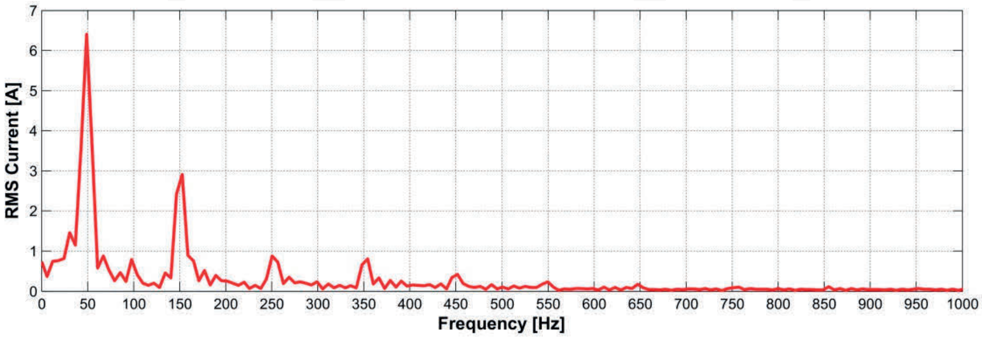

Fig. 11. Harmonic current spectrum (filter on)

The current distortion coefficient has been doubled. This was caused by the fact that the amplitude of the fundamental harmonic of the current has been decreased 2 times. In addition, the amplitudes of higher harmonics also has been decreased: the second harmonic has been decreased by approx. 23.5%, and the fifth by 52.3%. On the other hand, the value of the third harmonic increased, but because the required value of THD_U (stipulated by the [9] Standard) had been reached, the damping band of the filter was not raised. The current flowing through the power line decreased due to reactive power compensation. Consequently, the power factor increased from 0.39 to 0.96.

Important parameters related to the quality of electric power are the true mean square of voltage in the power supply network, the true mean square of current flowing in the power supply network, the reactive power, and the power factor cosα (all measurements were taken using True RMS gauges). Table 1 shows the values of these parameters for a load with a filter and without one.

Table 1

Measured parameters

	filter off		**filter on**	
Parameter	**Value**	**Unit**	**Value**	**Unit**
Voltage U	242.6	[V]	247.38	[V]
Current I	15.0	[A]	8.7	[A]
Active power *P*	1419.2	[W]	2074.1	[W]
Reactive power *Q*	3350.8	[VAr]	574.4	[VAr]
Apparent power *S*	3639.0	[VA]	2152.2	[VA]
cosα	0.39	[–]	0.96	[–]
THD_U	13.08	[%]	4.57	[%]
THD_I	25.22	[%]	51.76	[%]

The obtained results indicate that the passive controlled L-C filter not only helps to decrease voltage distortions, but can also be used to compensate reactive power. Furthermore, installing the filter helped to reduce the current flowing in the power supply line, leading to decreased power losses. The previous observations confirm these arguments.

4. Summary

The analysis of literature and research results concerning arc loads allowed to determine the negative effect of these devices on the power supply network. This negative effect involves a dynamic process of changes to the arc discharge, which affects the current and voltage waveforms of the devices.

Using a passive controlled L-C filter helped to eliminate the disadvantage of passive filters adjusted to a single frequency, i.e., the risk of detuning due to changes in the frequency of the supply voltage and allowed the damping band to extend to constituents that were not whole-numbered multiples of the fundamental harmonic.

The obtained results indicate that the installed passive L-C filter operated correctly, as indicated by the decrease in THD_U by over 8% to 4.13%, which fell within the standard [9].

Arc loads have a low power factor. The power factor in the analyzed device amounts to 0.39, which negatively affects the power supply network. Thanks to the application of the passive controlled L-C filter, not only did the voltage waveform improve, but reactive power compensation also dropped from 3350.8 VAr to 574.4 VAr, improving the power factor to 0.96.

References

[1] Dobaj E., *Maszyny i urządzenia spawalnicze*, WNT, Warszawa 1998, 52–60.
[2] *Zagadnienia energetyczne wybranych urządzeń elektrycznych systemów stalowniczych*, pod red. Antoniego Sawickiego, Wydawnictwo Politechniki Częstochowskiej, Częstochowa 2010, 98–101.
[3] Žeželenko I.V., *Vysšie garmoniki v sistemah elektroposnabženiâ prompredpriâtij*, 4-e izd., M: Energoatomizdat, 2000.
[4] Bolkowski S., *Teoria obwodów elektrycznych*, WNT, Warszawa 2008, 187–194.
[5] Dugan R.C., McGranaghan M.F., Satoso S., Wayne Beaty H., *Electrical Power Systems Quality*, McGraw-Hill Companies, 2004.
[6] Gudim V.I., T*ehnični zasobi znižennâ garmonik v elektropostačalnih sistemah*, Tehn. Elektrodinamika, No 3/1996, 67–72.
[7] Hanzelka Z., *Rozważania o jakości energii elektrycznej (IV)*, Elektroinstalator, No. 2/2001, 10–17.
[8] Hanzelka Z., *Rozważania o jakości energii elektrycznej (V)*, Elektroinstalator, No1/2002, 26–31.
[9] PN-EN 50160: Parametry napięcia zasilającego w publicznych sieciach elektroenergetycznych.
[10] Rozporządzenie Ministra Gospodarki z dnia 4 maja 2007 r. w sprawie szczegółowych warunków funkcjonowania systemu elektroenergetycznego (Dz.U. Nr 93 z 2007 r., poz. 623).
[11] Kusko A., *Power Quality in Electrical Systems*, McGraw-Hill Professional, 2007.
[12] Vedam R. Sastry, Sarma M.S., *Power Quality: VAR Compensation in Power Systems*, CRC Press, 2008.
[13] *Power Quality*, Edited by A. Eberhard, InTech, 2011.
[14] Chattioadhyah S., Mitra M., Sengupta S., *Electric Power Quality*, Springer, 2011.
[15] Fuchs E., Masoum M.A.S., *Power Quality in Power Systems and Electrical Machines*, AcademicPress, 2015.