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The concept for enhancing mitigation of the line current harmonics for the twelve-pulse diode bridge rectifier with the active interphase reactor

Koncepcja dodatkowego ograniczenia harmonicznych prądów liniowych dla dwunastopulsowego prostownika diodowego z aktywnym dławikiem kojarzącym

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Abstract: The paper discusses the application of the auxiliary controlled current source connected in parallel to the load of the twelve-pulse diode bridge rectifier operating with the active interphase reactor. The proposed solution allows additional mitigation of the rectification system line current harmonics. The concept is supported by the space vector analysis conducted for the studied rectification system. The simulation studies on the rectification system operation carried out in Matlab/Simulink confirm the usefulness of the presented method for the line current THD reduction.

Keywords: diode bridge rectifiers, total harmonic distortion, power conversion harmonics, harmonic mitigation

Streszczenie: W artykule omówiono zastosowanie pomocniczego sterowanego źródła prądowego podłączonego równolegle do obciążenia dwunastopulsowego mostka prostowniczego diodowego z aktywnym dławikiem kojarzącym. Rozwiązanie to zapewnia dodatkowe ograniczenie harmonicznych prądów liniowych układu prostowniczego. Koncepcja została poparta analizą badanego układu prostowniczego przeprowadzoną z zastosowaniem teorii wektora przestrzennego. Przydatność prezentowanej metody redukcji THD prądów liniowych potwierdzono badaniami symulacyjnymi wykonanymi z wykorzystaniem oprogramowania Matlab/Simulink.

Słowa kluczowe: prostowniki diodowe, współczynnik zniekształceń harmonicznych, harmoniczne układów konwersji energii, ograniczanie harmonicznych

Introduction

Three-phase diode bridge rectifiers are commonly used in many industrial applications, traction and power transmission/distribution systems where AC to DC conversion is required. This is due to their inherent simplicity, robustness and satisfactory overall performance. However, the use of the diode bridge rectification systems causes harmonic distortion in the electric power network line currents, and so, affects the quality of electric power.

The literature presents various methods for reduction of the line current total harmonic distortion (THD) introduced by the three-phase diode rectification systems. Two approaches can be distinguished. The first one relays on using the passive, active or hybrid power filters which are connected in series or in parallel to the electric power network at the AC side of the diode bridge rectifiers [1]. The second one is based on shaping the line current waveforms per power supply cycle through augmenting the secondary winding phase number of a phase-shifting transformer and incorporating another diode bridge rectifiers in the rectification system or by expanding the rectifier DC circuit on auxiliary circuits [2].

An increase in the number of the output phases of the multi-winding phase-shifting transformers leads to the increase in the step number in the line current waveforms per power supply cycle. The conventional twelve-pulse diode bridge rectifier can serve as an example of the system employing this technology. The twelve-step line current waveforms are achieved with the three-winding transformer which ensures the adequate phase shift of the line-to-line voltages powering two six-pulse diode bridge rectifiers connected in series or in parallel. In that case, the line current THD is reduced two fold, theoretically to about 15 %, when compared to the six-step line current waveform THD of the six-pulse rectification system. The further augmenting of the output phase number of the multi-winding phase-shifting transformer draws the line current waveforms more to the pure-sine waveforms [3]. However, this technology requires the adequate arrangements for the secondary windings of the multi-winding phase-shifting isolated transformer or autotransformer [2, 3] which causes difficulties in their production.

The mitigation of the line current harmonics can be also achieved by the use of the conventional twelve-pulse diode bridge rectifier with parallel connected six-pulse diode bridge rectifiers where the rectifier DC circuit is expanded on auxiliary circuits. These auxiliary circuits are generally connected to the interphase reactor (IPR) additional tapping points or windings [4 – 16].

In [10] and then in [11 – 13] the active PWM current source was incorporated to the IPR additional (secondary) winding. This configuration is usually referred in the literature to as the active interphase reactor (AIPR). It is clear that the ability of the twelve-pulse diode bridge rectifier with the AIPR to mitigate line current harmonics depends directly on the auxiliary circuit current waveform and its parameters (i.e., amplitude, frequency and phase) [12]. The researchers in [10 – 12] assumed a triangle waveform with a frequency of six times the power supply frequency and the amplitude adequately related to the load current for the auxiliary circuit current. The experimental investigations indicated that such an auxiliary circuit

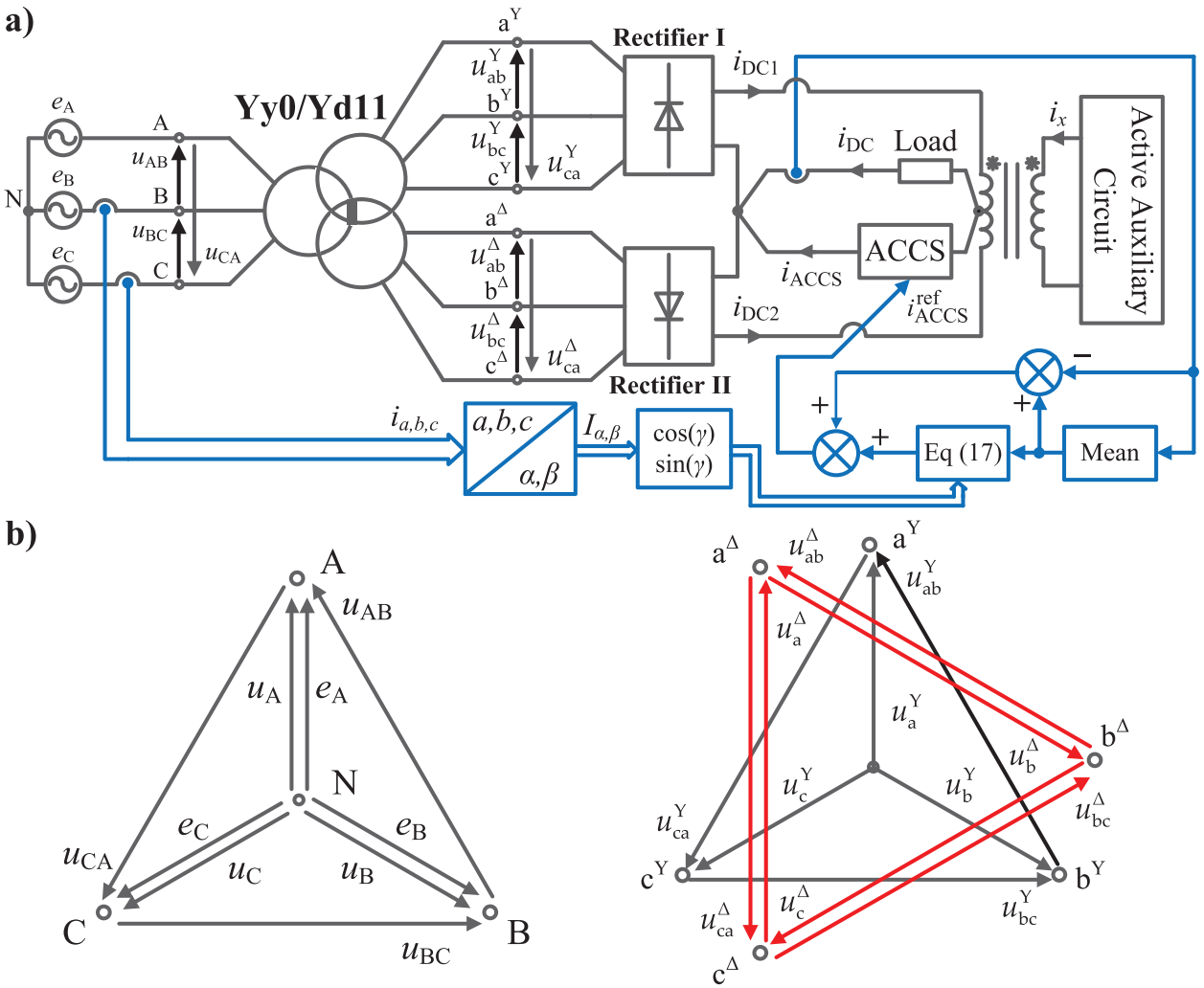

Fig. 1. The twelve-pulse diode bridge rectifier powered by the wye-wye-delta transformer: a) the schematic diagram together with the algorithm for the ACCS current reference determination (blue paths); b) voltage phasor diagrams

current provided operation of the twelve-pulse diode bridge rectifier with the AIPR at the line current THD of about 1%. In [14] the formula was devised which explicitly defines the auxiliary circuit current waveform that guarantees the lowest line current THD that the twelve-pulse diode rectification system with the AIPR is capable to reach, however, it still remains at the level of 1%.

The concept for enhancing mitigation of the line current harmonics of the twelve-pulse diode bridge rectifier with the AIPR was presented in [15]. This concept involves the auxiliary controlled current source (ACCS) coupled with the rectification system load. The ACCS is responsible for load current tracking and adequate additional loading of the rectification system to assure the lowest possible line current THD. This concept was then employed in [13, 16], however, the algorithm for the ACCS reference current was determined empirically without giving the theoretical background.

This paper discusses the concept of the ACCS application based on the space vector analysis conducted for the twelve-pulse diode bridge rectifier with the AIPR. The equation for the ACCS reference current is devised for the idealised constant load current. Subsequently, the algorithm for the ACCS reference current is developed for a resistive-inductive load. The operation of the twelve-pulse diode bridge rectifier with the AIPR and ACCS is tested through simulations conducted with Matlab/Simulink.

Theoretical basis for the ACCS application

The theoretical studies presented in this chapter are conducted assuming that the rectification system load ensures the constant load current without an AC component. The schematic diagram of the studied twelve-pulse rectification system is presented in Figure 1 a). It is composed of the two parallel connected six-pulse diode bridge rectifiers whose independent operation ensures the IPR. The required phase shift between the rectifier line-to-line voltages is provided by the isolated three-winding transformer with the unity rated voltage ratio wye-wye (Y-Y) and wye-delta (Y-Δ) connected windings. Figure 1 b) presents the voltage phasor diagrams resulted from the windings connections of the isolated transformer. The rectifier line-to-line voltages determine their switching functions which are then used to calculate the line current waveforms of the considered rectification systems. In order to visualize the theoretical study results, the discrete calculations of this line currents waveforms were conducted with the sampling period of 2 μs. Thus, the line current amplitude spectrum, which is also presented in this chapter, includes the frequency components which are related to the current commutation process. In addition, all the current waveforms presented in this paper are related to the load current and expressed in percentage units (p.u.).

The rectifier input currents can be expressed in terms of the rectifier switching functions and output currents:

$$(1)\qquad \begin{bmatrix} i_{a1} \\ i_{b1} \\ i_{c1} \end{bmatrix} = \begin{bmatrix} S_{a1} \\ S_{b1} \\ S_{c1} \end{bmatrix} i_{DC1} \text{ and } \begin{bmatrix} i_{a2} \\ i_{b2} \\ i_{c2} \end{bmatrix} = \begin{bmatrix} S_{a2} \\ S_{b2} \\ S_{c2} \end{bmatrix} i_{DC2}$$

where:

i_{a1}, i_{b1}, i_{c1}, i_{DC1} and i_{a2}, i_{b2}, i_{c2}, i_{DC2} – the input and output currents of Rectifier I and Rectifier II, respectively,

S_{a1}, S_{b1}, S_{c1} and S_{a2}, S_{b2}, S_{c2} – the switching functions of Rectifier I and Rectifier II, respectively.

The line currents of the six-pulse diode bridge rectifiers powered by the wye-wye and wye-delta unity rated voltage ratio transformers are defined by Equations (2) and (3), respectively:

$$(2)\qquad i_A^{(Y-Y)} = i_{a1},\ i_B^{(Y-Y)} = i_{b1},\ i_C^{(Y-Y)} = i_{c1}$$

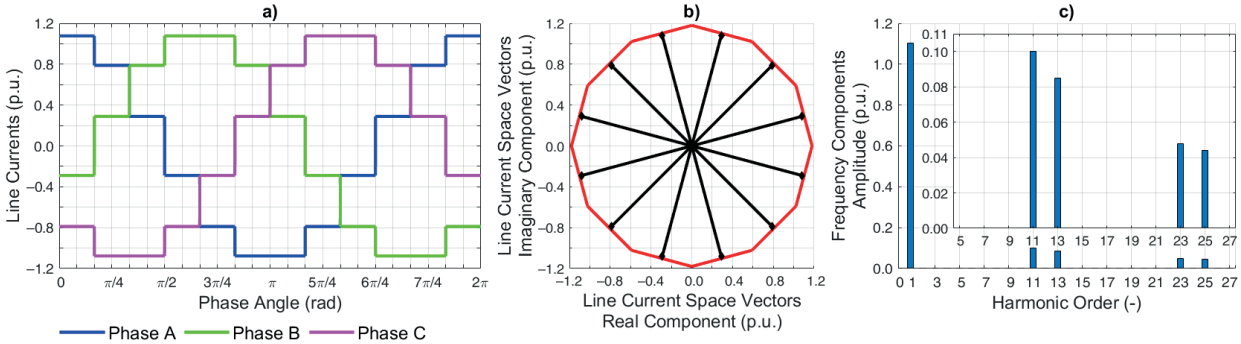

Fig. 2. The line currents per power supply cycle of the twelve-pulse diode bridge rectifier: a) the line current waveforms; b) the line current space vectors; c) the line current frequency components

$$(3)\quad i_{\mathrm{A}}^{(\mathrm{Y}-\Delta)}=\frac{1}{\sqrt{3}}\left(i_{\mathrm{a2}}-i_{\mathrm{c2}}\right),\ i_{\mathrm{B}}^{(\mathrm{Y}-\Delta)}=\frac{1}{\sqrt{3}}\left(i_{\mathrm{b2}}-i_{\mathrm{a2}}\right),\ i_{\mathrm{C}}^{(\mathrm{Y}-\Delta)}=\frac{1}{\sqrt{3}}\left(i_{\mathrm{c2}}-i_{\mathrm{b2}}\right)$$

Now, the line currents of the twelve-pulse diode bridge rectifier can be expressed as the sum of the line currents (2) and (3) of the six-pulse diode bridge rectifiers.

The line currents of the six-pulse and twelve-pulse rectification systems can be expressed in the space vector form employing the well-known Clarke transformation. For the case of the balanced loadings of the six-pulse diode bridge rectifiers:

$$(4)\quad i_{\mathrm{DC1}}=i_{\mathrm{DC2}}=0.5i_{\mathrm{DC}}$$

the space vectors can be described as follows:

- for the six-pulse diode bridge rectifier fed by the wye-wye transformer:

$$(5)\quad \underline{I}^{(\mathrm{Y}-\mathrm{Y})}=\left|\underline{I}^{(\mathrm{Y}-\mathrm{Y})}\right|\mathrm{e}^{\mathrm{j}\left(\frac{(1+2k)\pi}{6}\right)}$$

- for the six-pulse diode bridge rectifier fed by the wye-delta transformer:

$$(6)\quad \underline{I}^{(\mathrm{Y}-\Delta)}=\left|\underline{I}^{(\mathrm{Y}-\Delta)}\right|\mathrm{e}^{\mathrm{j}\left(\frac{2k\pi}{6}\right)}$$

- for the twelve-pulse diode bridge rectifiers fed by the wye-wye-delta transformer:

$$(7)\quad \underline{I}^{\left(\frac{\mathrm{Y}-\mathrm{Y}}{\mathrm{Y}-\Delta}\right)}=\left|\underline{I}^{\left(\frac{\mathrm{Y}-\mathrm{Y}}{\mathrm{Y}-\Delta}\right)}\right|\mathrm{e}^{\mathrm{j}\left(\frac{(1+2k)\pi}{12}\right)}$$

where:

i_{DC} – the load current,

k – the sector number which takes the value of $k=0, 1, \ldots, q-1$,

q – the DC output voltage waveform pulse number per power supply cycle.

Figure 2 presents the line currents and their space vector placement on the stationary complex plane for the twelve-pulse diode bridge rectifier (with disconnected active auxiliary circuit and ACCS). This Figure also includes the line current frequency components. The THD of the line current presented in Figure 2 a) is about 15.219 %.

The line current space vectors of the six-pulse and twelve-pulse diode bridge rectifiers form the six-pointed and twelve-pointed stars per power supply cycle, respectively [14]. The relationship for the line current space vectors of the six-pulse and twelve-pulse diode bridge rectifiers within the first sector is depicted in Figure 3. The sectors are determined by the placement of the six-pulse rectifiers current space vectors on the complex plane as depicted in Figure 3 by the red dashed lines.

The space vector amplitudes of the six-pulse diode bridge rectifiers fed by the wye-wye and wye-delta transformers can be related to the rectifier output currents:

$$(8)\quad i_{\mathrm{DC1}}=K_{\mathrm{RS}}\left|\underline{I}^{(\mathrm{Y}-\mathrm{Y})}\right|\ \text{ and }\ i_{\mathrm{DC2}}=K_{\mathrm{RS}}\left|\underline{I}^{(\mathrm{Y}-\Delta)}\right|$$

where: K_{RS} – the rectification system current ratio which is equal to $\sqrt{3}/2$ for the tested rectifiers fed by the unity rated voltage ratio wye-wye-delta transformer.

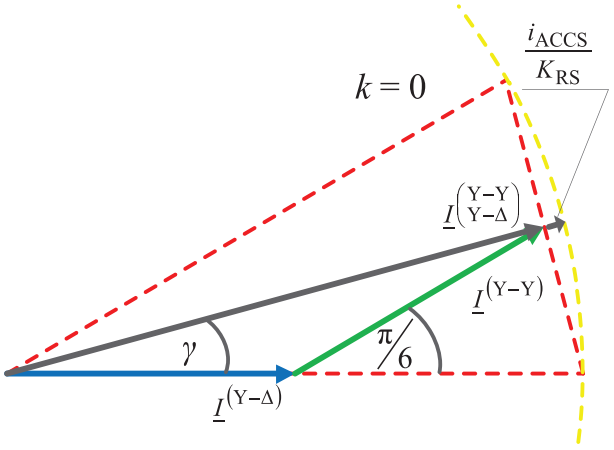

Fig. 3. The relationship of the line current space vectors of the six-pulse and twelve-pulse diode bridge rectifiers within the first sector

Now, it is straightforward from Figure 3 and Equation (8) that the amplitude and phase angle of the twelve-pulse diode bridge rectifier space vector can be controlled through shaping the output currents of the six-pulse diode bridge rectifiers [14]. This can be realized employing the AIPR [10 – 16].

The current reference for the active auxiliary circuit can be determined on the law of sines for the placement of the space vectors presented in Figure 3:

$$(9)\quad \frac{\left|\underline{I}^{\left(\frac{\mathrm{Y}-\mathrm{Y}}{\mathrm{Y}-\Delta}\right)}\right|}{\sin\left(\frac{5\pi}{6}\right)}=\frac{\left|\underline{I}^{(\mathrm{Y}-\mathrm{D})}\right|}{\sin\left(\frac{\pi}{6}-\gamma\right)}=\frac{\left|\underline{I}^{(\mathrm{Y}-\mathrm{Y})}\right|}{\sin(\gamma)}$$

where: γ – the phase angle of the twelve-pulse rectification system space vector which varies in the range $0\le\gamma\le\pi/6$.

Equation (9) relates the space vector amplitudes of the six-pulse and twelve-pulse diode bridge rectifiers with the phase angle of the twelve pulse rectification system line current space vector. Then, using Equations (8) and (9), taking into account the Kirchhoff's

current law relationship between the rectifier output currents and load current (10) and the magnetomotive force relationship for the AIPR (11):

$$i_{DC1} + i_{DC2} = i_{DC} \tag{10}$$

$$N_p(i_{DC2} - i_{DC1}) = N_s i_x \tag{11}$$

the relationships between the auxiliary circuit current, the phase angle of the rectification system line current space vector and the load current are expressed by Equations (12) and (13) for the odd and even sectors, respectively [14]:

$$i_x = \frac{N_p}{N_s}\left(\frac{\sin\left(\frac{\pi}{6}-\gamma\right)}{\sin\left(\frac{\pi}{12}\right)\cos\left(\frac{\pi}{12}-\gamma\right)}-1\right)i_{DC} \tag{12}$$

$$i_x = \frac{N_p}{N_s}\left(\frac{\sin(\gamma)}{\sin\left(\frac{\pi}{12}\right)\cos\left(\frac{\pi}{12}-\gamma\right)}-1\right)i_{DC} \tag{13}$$

where:

N_p – the turn number of the AIPR primary winding sections being a half of the total turn number of the AIPR primary winding,

N_s – the turn number of the AIPR secondary windings,

i_x – the auxiliary circuit current.

For the continuous phase angle changes of the line current space vector, the near-triangular waveform with the frequency of six times power supply frequency and the amplitude adequately related to the load current is obtained for the active auxiliary circuit current [14]. This current waveform provides the output currents of the six-pulse diode bridge rectifiers alternating continuously whilst their sum is constant and equals the load current [14]. Then, the space vector of the twelve-pulse rectification system with the AIPR shifts around continuously along the dodecagon as presented in Figure 4 b). This results in the twelve-section near-sine line current waveforms per power supply cycle (Fig. 4 a), i.e., the waveforms of the lowest THD that can be achieved under operation of the twelve-pulse diode bridge rectifiers with the AIPR. Figure 4 c) presents the frequency components of the line current waveforms included in Figure 4 a). Their THD is about 1.034 %.

The line current space vector amplitude of the twelve-pulse rectification system with the AIPR varies while this space vector shifts around along the dodecagon (Fig. 4 b). The circular trajectory of the line current space vector, and consequently the pure-sine line current waveforms can be achieved when the constant space vector amplitude per power supply cycle is ensured. The concept for such an operation of the twelve-pulse rectification system with the AIPR can be devised on the law of sines for the placement of the space vectors presented in Figure 3.

The relationships described by Equations (14) are derived from Equation (9). Then, making use of Equations (8) and (10), the relation associating the line current space vector amplitude of the twelve-pulse rectification system with this space vector phase angle and the rectification system load current can be established by Equation (15). Equation (15) precisely defines the line current space vector amplitude variations according to the space vector placement in the first sector, however, this solution can be adjusted to other sectors.

$$\begin{aligned}\left|\underline{I}^{(Y-Y)}\right| &= \left|\underline{I}^{\binom{Y-Y}{Y-\Delta}}\right|\frac{\sin(\gamma)}{\sin\left(\frac{5\pi}{6}\right)}\\ \left|\underline{I}^{(Y-D)}\right| &= \left|\underline{I}^{\binom{Y-Y}{Y-\Delta}}\right|\frac{\sin\left(\frac{\pi}{6}-\gamma\right)}{\sin\left(\frac{5\pi}{6}\right)}\end{aligned} \tag{14}$$

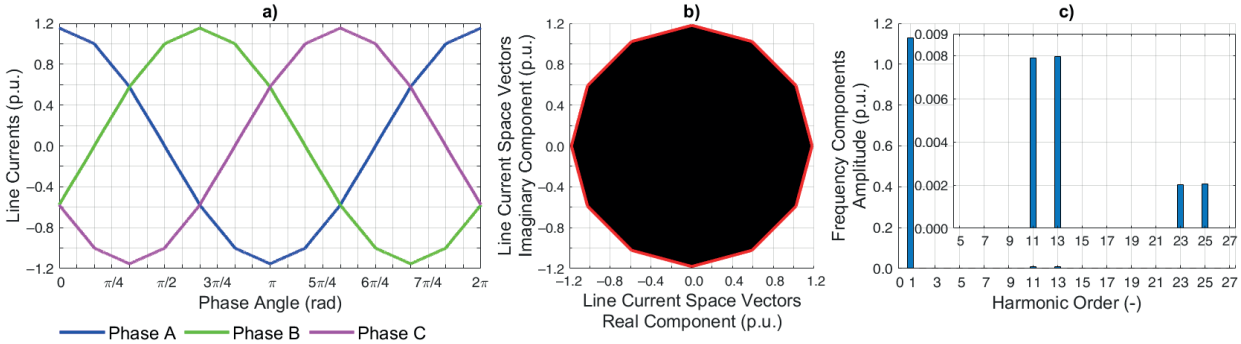

Fig. 4. The line currents per power supply cycle of the twelve-pulse diode bridge rectifier with the AIPR: a) the line current waveforms; b) the line current space vectors; c) the line current frequency components

$$K_{RS}\left|\underline{I}\begin{pmatrix}Y-Y\\Y-\Delta\end{pmatrix}\right| = i_{DC}\frac{\cos\left(\frac{\pi}{12}\right)}{\cos\left(\frac{\pi}{12}-\gamma\right)} \tag{15}$$

The constant amplitude of the line current space vector, and thus, its circular trajectory (yellow dashed line in Fig. 3) can be provided by adequate additional loading of the twelve-pulse rectification system with the AIPR. This can be realised by the ACCS connected in parallel to the rectification system load (Fig. 1). It is illustrated in Figure 3 where the amplitude of the line current space vector is increased by the component proportional to the ACCS current. In that case, Equation (15) can be converted to:

$$K_{RS}\left|\underline{I}\begin{pmatrix}Y-Y\\Y-\Delta\end{pmatrix}\right| = i_{DC}\frac{\cos\left(\frac{\pi}{12}\right)}{\cos\left(\frac{\pi}{12}-\gamma\right)} + i_{ACCS} = \text{const} \tag{16}$$

For the constant amplitude of the line current space vector of the twelve-pulse rectification system with the AIPR and ACCS, the nonlinear γ-dependent multiplier occurring on the right of the equal sign in Equation (16) have to be eliminated with the use of the ACCS current. Based on this argument, equation for the ACCS current is defined:

$$i_{ACCS} = i_{DC}\left(1-\frac{\cos\left(\frac{\pi}{12}\right)}{\cos\left(\frac{\pi}{12}-\gamma\right)}\right) \tag{17}$$

The waveform of the ACCS current per power supply cycle for the continuous phase angle changes of the line current space vector is shown in Figure 5. It is a periodic signal with a frequency of twelve times the power supply frequency and the amplitude adequately related to the load current.

Figure 6 presents the line currents and their space vector placement on the stationary complex plane per power supply cycle for the twelve-pulse diode bridge rectifier operated with the AIPR and ACCS. Figure 6 includes also the line current frequency components. The line current THD is about 0.246 %. The 11-th,13-th, 23-th and 25-th frequency components can be seen in the line current amplitude spectrum (Fig. 6 c). The presence of these frequency components is related to the current commutation process since the line current waveforms were calculated with the use of the twelve-pulse rectification system switching functions. With this argumentation, it is clear that the developed Equation (17) for the ACCS current ensures the pure-sine line current waveforms for the twelve-pulse diode bridge rectifier with the AIPR and ACCS.

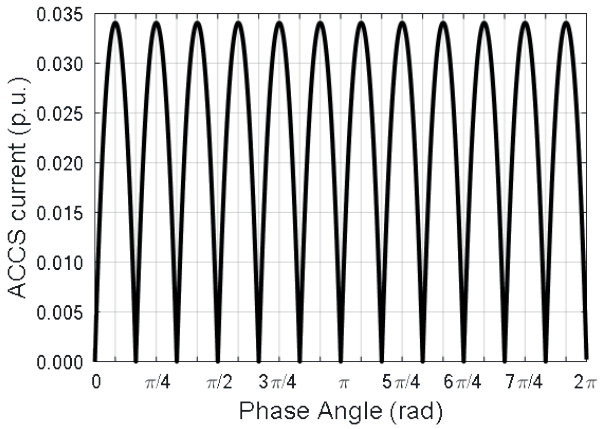

Fig. 5. The ACCS current waveform per power supply cycle

Simulation studies of the twelve-pulse diode bridge rectifier with the AIPR and ACCS

The Equation (17) for the ACCS current was devised for the idealised constant load current of the rectification system. The algorithm expanding the use of this equation for the typical resistive-inductive loads is pre-

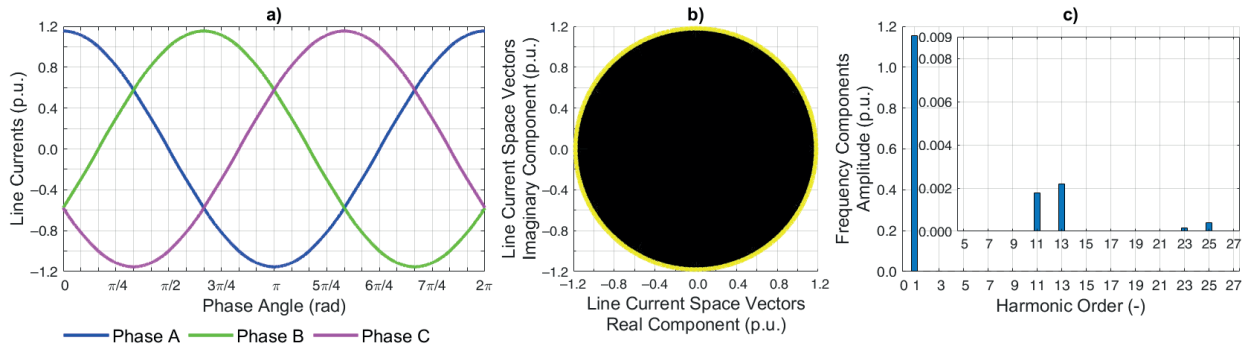

Fig. 6. The line currents per power supply cycle of the twelve-pulse diode bridge rectifier with the AIPR and ACCS: a) the line current waveforms; b) the line current space vectors; c) the line current frequency components

sented in Figure 1 by the blue paths. The algorithm requires the measurements of the rectification system line and load currents. The α, β components of the line current space vector determine the trigonometric functions of the space vector phase angle for the use of Equation (17). This phase angle together with the arithmetic mean value of the rectifier load current form through Equation (17) the ACCS current which approximately corresponds to the one occurring with the idealised constant load current. Then, this current is summed with the difference between the mean and measured rectifier load current to set up the ACCS current reference.

The twelve-pulse rectification system with the AIPR and ACCS which schematic diagram is presented in Figure 1 was implemented in Matlab/Simulink. In the presented studies, the isolated three-winding transformer model did not include a hysteresis phenomenon. Moreover, the active auxiliary circuit and ACCS were implemented as the ideal current sources controlled by the reference currents. Thus, the line current amplitude spectrum of the rectifier model was free from the frequency components related to the transformer no-load and PWM-controlled active current source operations. This, in turn, simplifies the evaluation of the proposed concept capability for the line current harmonic mitigation of the twelve-pulse diode bridge rectifier with the AIPR and ACCS. The operation of such a rectification system was verified at the various resistive-inductive load settings. The inductance was varied in the range from 0.5 H to 50 μH with the constant resistance of 50 Ω. The rectifier line current THD were calculated for each sets of the load inductances.

Figure 7 presents the line currents and their space vector placement on the stationary complex plane per power supply cycle obtained at the load time constant of 5 ms. Figure 7 c) presents the frequency components of the line current waveforms included in Figure 7 a). Their THD is about 0.392 %. The presence of the 5-th and 7-th frequency components, which did not occur in the line current amplitude spectrum determined for the theoretical studies (Fig. 6 c), can be argued by the asymmetry in operation of the six-pulse diode bridge rectifiers which is related to the simulation finite sampling period.

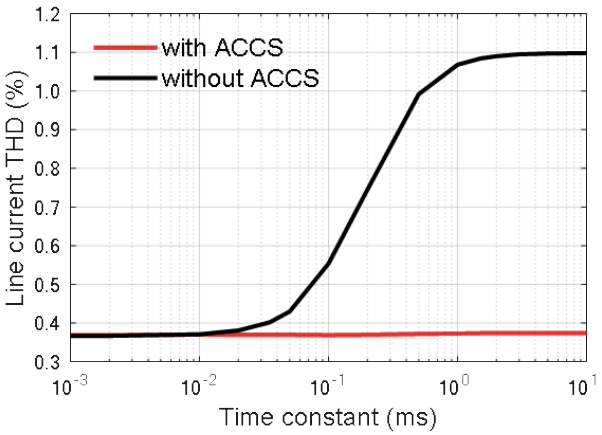

Fig. 8. The line current THD in the function of the resistive-inductive load time constant

Figure 8 presents the line current THD versus the load time constant for the studied rectification system with the AIPR and ACCS. For the comparison, this characteristic also includes the line current THD variations for the twelve-pulse diode bridge rectifier with the AIPR operated without the ACCS. The presented results confirm that the elaborated algorithm for the ACCS current reference enables operation of the studied rectification system with the nearly constant line current THD of less than 0.4 % at each load settings.

Conclusions

The paper describes in detail the theoretical background for the ACCS use with the twelve-pulse rectification system with the AIPR which has not been addressed in the literature so far. The mathematical formula for the ACCS current reference is devised which guarantees, in theory, the pure-sine line current waveforms of the studied rectification system.

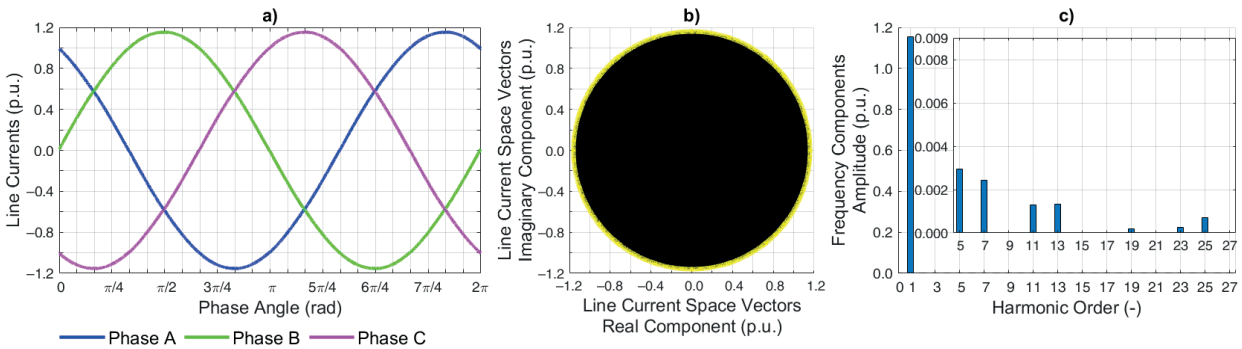

Fig. 7. The line currents per power supply cycle at the rectification system load time constant of 5 ms: a) the line current waveforms; b) the line current space vectors; c) the line current frequency components

The simulation study results indicate that the application of the ACCS ensures the enhanced mitigation of the line current harmonics when compared to the twelve-pulse rectification system with the AIPR operating without the ACCS. The elaborated concept enables operation of the studied rectification system mathematical model with the minimal and nearly constant line current THD at any resistive-inductive load.

A comprehensive description of the power circuits for the ACCS and active auxiliary circuit, their implementation in the experimental rectification system together with the obtained study results will be the subject of the next paper.

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