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Study on determination of an asynchronous motor's reactive power by the current-to-voltage converter

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Abstract. This article presents a method for determining the primary currents, non-sinusoidal and asymmetrical currents flowing through the stator windings of an asynchronous motor based on the signal in the form of the output voltage from the current converter loops placed in each phase between the poles of the asynchronous motor stator and in the arrangement of the stator windings. Differences and characteristics of output signals are researched based on independent, series and opposite (bifilar) connection schemes of asynchronous motor current converter loops of measuring coil. In order to determine the value of the currents generated in each phase of the asynchronous motor stator windings, the output signals of the current converter with independent loop and loops connected in series were mutually analyzed. Measuring non-sinusoidal and asymmetrical currents, according to the opposite (bifilar) connection scheme, the loops of measuring coils are placed in the inter-pole grooves of each phase of the stator in the order corresponding to the three-phase stator windings, the current converter measuring coils each consists of two loops, bifilarly connected to each other. The end of loops of the measuring coils has two exits. Diodes and phase meter-regulators are placed on the first outputs of the loops, and they are oppositely connected to the microprocessor unit for measuring and controlling the asymmetry. The second outputs of the loops are connected directly opposite to the microprocessor unit for measuring and controlling non-sinusoidal currents. This type of current converter is important for determining the non-sinusoidal and asymmetrical currents generated in asynchronous motors, it increases the functional capabilities and accuracy of the current converter, and based on the determined results, it simplifies theoretical calculations, and at the same time, the dynamic and it will be possible to determine the static characteristics through theoretical differential equations. As a result of the research, practical and theoretical results were compared.

1. Introduction

Voltages $u_{out.1}(t), u_{out.2}(t), u_{out.3}(t)$ are obtained at the outputs of the current-measuring measuring coils under the influence of magnetic currents generated by the passage of primary currents i_1, i_2, i_3 through the stator windings of a three-phase asynchronous motor. The voltages at the output of the current converter depend on the location of the measuring coils in the stator groove, the number of windings and the output voltages as follows (Eq. 1) [1-3]:

$$\begin{aligned} u_{out.1}(t) &= -R_{m.1} \cdot i_{out.1}(t) - L_{m.1}\frac{di_{out.1}(t)}{dt} + w_5\frac{d\Phi_2(t)}{dt} + w_6\frac{d\Phi_3(t)}{dt}; \\ u_{out.2}(t) &= -R_{m.2} \cdot i_{out.2}(t) - L_{m.2}\frac{di_{out.2}(t)}{dt} + w_4\frac{d\Phi_1(t)}{dt} + w_6\frac{d\Phi_3(t)}{dt}; \\ u_{out.3}(t) &= -R_{m.3} \cdot i_{out.3}(t) - L_{m.3}\frac{di_{out.3}(t)}{dt} + w_4\frac{d\Phi_1(t)}{dt} + w_5\frac{d\Phi_2(t)}{dt}; \end{aligned} \quad (1)$$

$R_{m.1}, R_{m.2}, R_{m.3}, L_{m.1}, L_{m.2}, L_{m.3}$ – the active resistances and inductors of a three-phase current converter, respectively; $w_{m.4}, w_{m.5}, w_{m.6}$ – the number of packages of measuring elements; $i_{out.1}(t), i_{out.2}(t), i_{out.3}(t)$ – measuring currents.

At the start of the inductance of the stator windings of the asynchronous motor L_1, L_2, L_3 there is an increase in three-phase primary stator currents, and the currents become steady sinusoidal due to the gradual contact of magnetic currents in the stator core [1, 15].

In the research of the characteristics of the current converter, the dependence of magnetic fluxes on the parameters of the asynchronous motor is as follows (Eq. 2):

$$\begin{aligned} \frac{U_{0.1}\sin(\omega t+\alpha_1)}{w_1} &= \frac{d\Phi_1}{dt}+\frac{R_1}{L_1}\Phi_1; \\ \frac{U_{0.2}\sin(\omega t+\alpha_2+120^0)}{w_2} &= \frac{d\Phi_2}{dt}+\frac{R_2}{L_2}\Phi_2; \\ \frac{U_{0.3}\sin(\omega t+\alpha_3-120^0)}{w_3} &= \frac{d\Phi_3}{dt}+\frac{R_3}{L_3}\Phi_3; \end{aligned} \quad (2)$$

where is $\omega = 2\pi f$ the angular frequency of the source; α_1, α_2, α_3 - phase angles, at t = 0; w_1, w_2, w_3 - number of windings of asynchronous motor stator windings; R_1, R_2, R_3 - active resistances of asynchronous motor stator windings; L_1, L_2, L_3 are the inductances of the asynchronous motor stator windings. In order to fully describe the output voltage used as an asynchronous motor three-phase current converter, it is necessary to analyze the transition process in the converter based on the energy currents and currents supplied to the stator windings of the asynchronous motor (Eq. 3):

$$\begin{aligned} U_{out.1} &= K_{\Phi_1 U_{out1}} \begin{pmatrix} \Pi_{\mu_1}\cdot W(F_{111},F_{121})\cdot K_{U_1F_1}\cdot U_1\sin\omega t - \\ -\Pi_{\sigma_1}\cdot W(F_{\sigma111},F_{\sigma121})K_{I_1F_{\sigma1}}\cdot(I_{1np.}\sin\omega t + I_{1anp.}e^{-\frac{t}{T}}) \end{pmatrix}; \\ U_{out.2} &= K_{\Phi_2 U_{out2}} \begin{pmatrix} \Pi_{\mu_2}\cdot W(F_{213},F_{223})\cdot K_{U_2F_2}\cdot U_2\sin(\omega t+120^0) - \\ -\Pi_{\sigma_2}\cdot W(F_{\sigma213},F_{\sigma223})\cdot K_{I_2F_{\sigma2}}\cdot(I_{2np.}\sin(\omega t+120^0) + I_{2anp.}e^{-\frac{t}{T}}) \end{pmatrix}; \\ U_{out.3} &= K_{\Phi_3 U_{out3}} \begin{pmatrix} \Pi_{\mu_3}\cdot W(F_{313},F_{323})\cdot K_{U_3F_3}\cdot U_3\sin(\omega t-120^0) - \\ -\Pi_{\sigma_3}\cdot W(F_{\sigma313},F_{\sigma323})\cdot K_{I_3F_{\sigma3}}\cdot(I_{3np.}\sin(\omega t-120^0) + I_{3anp.}e^{-\frac{t}{T}}) \end{pmatrix} \end{aligned} \quad (3)$$

where is $K_{\Phi_1U_{out1}}, K_{\Phi_2U_{out2}}, K_{\Phi_3U_{out3}}, K_{U_1F_1}, K_{U_2F_2}, K_{U_3F_3}, K_{I_1F_{\sigma1}}, K_{I_2F_{\sigma2}}, K_{I_3F_{\sigma3}}$ – the coefficients of correlation of the magnitudes of the magnetic and electric circuits corresponding to each phase, respectively; $\Pi_{\mu_1}, \Pi_{\mu_2}, \Pi_{\mu_3}$, $\Pi_{\sigma_1}, \Pi_{\sigma_2}, \Pi_{\sigma_3}$ – asynchronous motor magnetic system and magnetic parameters of the stator groove; $I_{1np}, I_{2np}, I_{3np}, I_{1anp}, I_{2anp}, I_{3anp}$ – periodic and non-periodic components of stator current; U_1, U_2, U_3 – voltages applied to the stator windings of an asynchronous motor; $W(F_{111},F_{121}), W(F_{213},F_{223}), W(F_{313},F_{323})$, $W(F_{\sigma111},F_{\sigma121})$, $W(F_{\sigma213},F_{\sigma223}), W(F_{\sigma313},F_{\sigma323})$ – transmission functions of the magnetic transducer.

As a result of the intersection of the main and scattering magnetic currents in the stator part of the sensing element (measuring coil) located in the stator grooves of the asynchronous motor, a signal in the form of a voltage is generated at the output.

Equation (4) is the value of the output voltage depend on the number of windings of the stator winding of the asynchronous motor w_1, the resistance Z_1, the source voltage U_1, the current flowing through the stator winding I_1 and the number of windings of the sensing element w_2 (usually w_2=1 or 2) [13-15].

From the outputs of a three-phase current converter are obtained voltages of equal value and differing in phase by 120^0 degrees.

$$U_{out.1} = \frac{w_4}{w_1} \cdot (U_1 - Z_1 \cdot I_1);$$
$$U_{out.2} = \frac{w_5}{w_2} \cdot (U_2 - Z_2 \cdot I_2); \quad (4)$$
$$U_{out.3} = \frac{w_6}{w_3} \cdot (U_3 - Z_3 \cdot I_3).$$

2. Materials and Methods

An output voltage proportional to the current I_1 of the asynchronous motor is generated from the current converter loops, which are placed in the appropriate order for each phase of the stator windings, in the inter-pole grooves of each phase of the stator. The value of this voltage depends on the active and inductive resistances of the stator windings, the number of coils of the stator windings W_c, the voltage U_1 supplied to the stator windings, and the number of coils of the measuring windings W_m (Eq. 5) [2, 12].

$$U_{out.k} = 4.44 fW_c \frac{I_1 W_m}{R_\mu} \quad (5)$$

Quantitatively similar voltages are generated in the inter-pole loops of measuring coils for each phase. For each phase of the stator winding, voltages with a phase difference of 120^0 degrees are obtained from the outputs of the current converter. The value of the voltage output from asynchronous motor current converter was determined using the Cassylab laboratory device in the 4AA63A4Y3 type asynchronous motor (Figure 1). The number of stator windings of the 4AA63A4Y3 type asynchronous motor is six, that is, two for each phase are placed between the poles, and the number of current converter windings is the same as the stator windings. Three-phase stator coils of the 1st asynchronous motor, the first coil of the 2nd measuring coil placed between the poles, the second coil of the 3rd measuring coil placed between the poles [5].

The resulting voltages in each loop of a three-phase asynchronous motor current converter, in which each phase of the stator is placed between the poles, are determined as follows:

The output voltages of the loops of the measuring winding of phase A, located respectively to the stator winding, are determined as follows (Eq. 6 and 7):

$$U_{a.1} = 4.44 fW_{c.1} \frac{I_A W_{11}}{R_\mu} \quad (6)$$

$$U_{a.2} = 4.44 fW_{c.2} \frac{I_A W_{12}}{R_\mu} \quad (7)$$

The output voltages of the loops of the measuring winding of phase B, located respectively to the stator winding, are determined as follows (Eq. 8 and 9):

$$U_{b.1} = 4.44 fW_{c.3} \frac{I_B W_{21}}{R_\mu} \quad (8)$$

$$U_{b.2} = 4.44 fW_{c.4} \frac{I_B W_{22}}{R_\mu} \quad (9)$$

The output voltages of the loops of the measuring winding of phase C, located respectively to the stator winding, are determined as follows (Eq. 10 and 11):

$$U_{c.1} = 4.44\, fW_{c.5} \frac{I_C W_{31}}{R_\mu} \tag{10}$$

$$U_{c.2} = 4.44\, fW_{c.6} \frac{I_C W_{32}}{R_\mu} \tag{11}$$

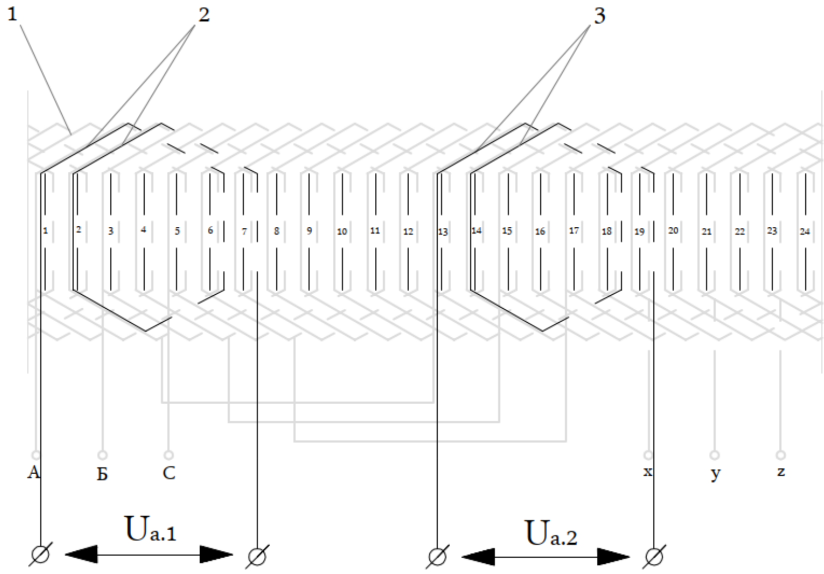

Figure 1. Asynchronous motor current converter with independent loop (for phase A)

The resulting voltages in each loop of a three-phase asynchronous motor current converter, in which each phase of the stator is placed between the poles, are determined as follows:
The output voltages of the loops of the measuring winding of phase A, located respectively to the stator winding, are determined as follows (Eq. 12 and 13):

$$U_{a.1} = 4.44\, fW_{c.1} \frac{I_A W_{11}}{R_\mu} \tag{12}$$

$$U_{a.2} = 4.44\, fW_{c.2} \frac{I_A W_{12}}{R_\mu} \tag{13}$$

The output voltages of the loops of the measuring winding of phase B, located respectively to the stator winding, are determined as follows (Eq. 14 and 15):

$$U_{b.1} = 4.44\, fW_{c.3} \frac{I_B W_{21}}{R_\mu} \tag{14}$$

$$U_{b.2} = 4.44\, fW_{c.4} \frac{I_B W_{22}}{R_\mu} \tag{15}$$

The output voltages of the loops of the measuring winding of phase C, located respectively to the stator winding, are determined as follows (Eq. 16 and 17):

$$U_{c.1} = 4.44\, fW_{c.5} \frac{I_C W_{31}}{R_\mu} \tag{16}$$

$$U_{c.2} = 4.44\, fW_{c.6} \frac{I_C W_{32}}{R_\mu} \tag{17}$$

$U_{a.1}$ – the magnitude of the output voltage of the drive in the primary loop of the measurable circuit of phase A; $U_{a.2}$ – the magnitude of the output voltage of the drive and secondary loop of the measurable circuit of phase A; $U_{b.1}$ – the magnitude of the output voltage of the driving force in the primary loop of the measurable circuit of phase B; $U_{b.2}$ – the magnitude of the output voltage of the drive and secondary loop of the measurable circuit of phase B; $U_{c.1}$ – the magnitude of the output voltage of the driving force in the primary loop of the measurable circuit of phase C; $U_{c.2}$ – the magnitude of the output voltage of the driver and the secondary loop of the measurable circuit of the phase C; I_A – primary current stator phase A; I_B – primary current stator phase B; I_C – primary current stator phase C; W_{11} – the number of windings of the winding of the measuring circuit phase A; W_{12} – the number of windings of the second loop of the measurable area phase A; W_{21} – the number of windings of the winding of the measuring area of phase V; W_{22} – the number of windings of the second loop of the measurable area phase B; W_{31} – the number of coils of the winding of the measuring circuit phase C; W_{32} – the number of coils of the second loop of the measurable area phase C; $W_{c.1}$ – number of coils of the primary winding of the stator phase A; $W_{c.2}$ – the number of coils of the secondary winding of the stator phase A; $W_{c.3}$ – number of coils of the primary winding of the stator phase B; $W_{c.4}$ – number of coils of the secondary winding of the stator phase B; $W_{c.5}$ – number of coils of the primary winding of the stator phase C; $W_{c.6}$ – number of windings of the secondary winding of the stator phase C; f – frequency [1-6].

Connecting the interpolar measuring coil loops, which are suitable for each phase of the current converter, in a series and in a suitable order, leads to an increase in the accuracy of the output signal (Figure 2).

$$\begin{aligned} U_{a.out} &= U_{a.1} + U_{a.2} \\ U_{b.out} &= U_{b.1} + U_{b.2} \\ U_{c.out} &= U_{c.1} + U_{c.2} \end{aligned} \tag{18}$$

Because as a result of the addition of the voltages generated in the coil loops suitable for each phase, the output voltage is twice as large compared to the independent loop, because the voltages coming out of the loops are added (Eq. 18).

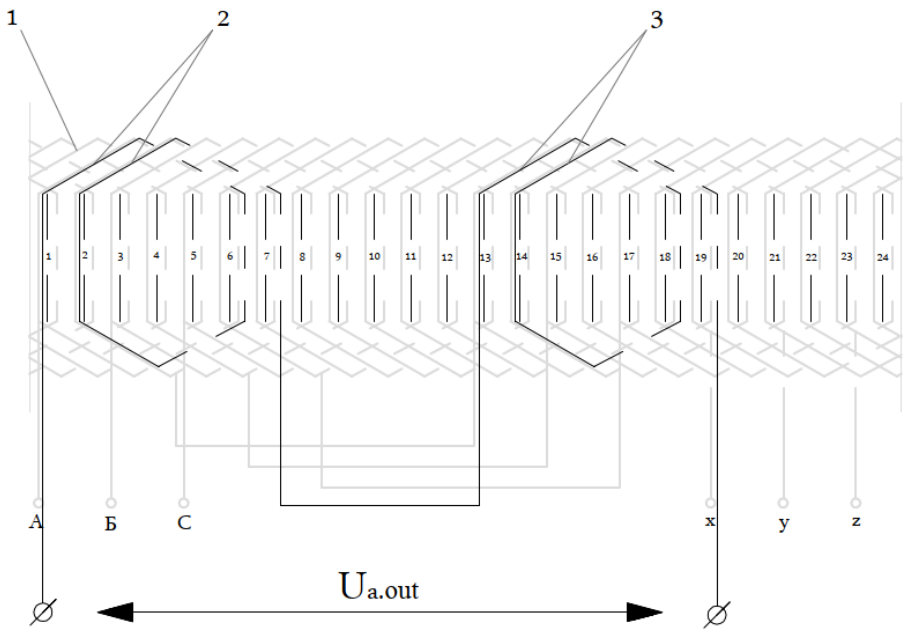

Figure 2. Asynchronous motor current converter with series connected measuring coil loops (for phase A)

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The opposite (bifilar) connection of the measuring coil loops of the asynchronous motor current converter increases its functional capabilities, that is, non-sinusoidal and asymmetrical currents can be determined through the current converter. The ends of the loops belonging to each phase have two outputs, diodes and phase meter-regulators are placed on the first outputs of the loops, and they are oppositely connected to the microprocessor unit for measuring and controlling the asymmetry (Eq. 19, 20). The second outputs of the loops are connected directly opposite to the microprocessor unit for measuring and controlling non-sinusoidal currents [3-7].

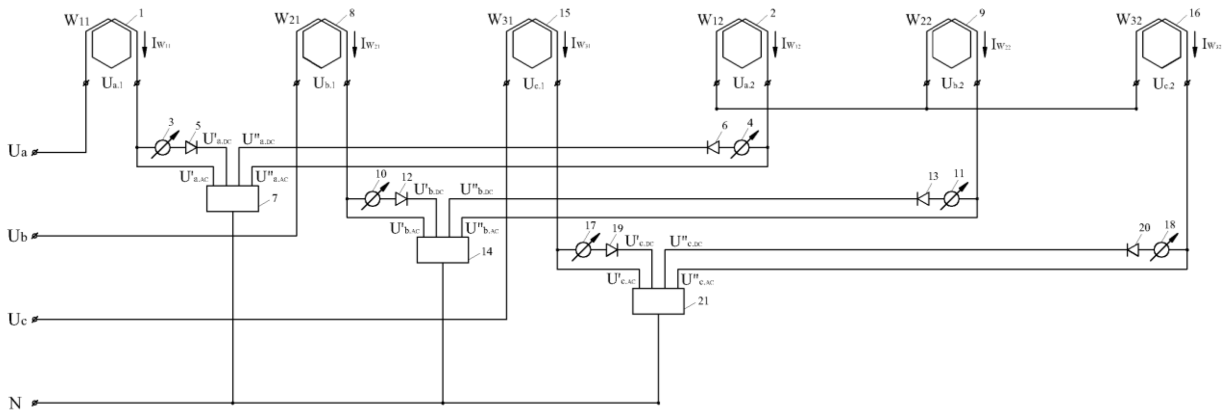

Figure 3. Asynchronous motor current converter with bifilar connected measuring coil loops

The unbalance index as the difference between the output voltages of phase A loops is determined as follows (Eq. 19):

$$U_{out.a} = U'_{a.DC} - U''_{a.DC} \tag{19}$$

The asymmetry indicators for the remaining phases B and C are determined similarly (Eq. 20):

$$U_{out.b} = U'_{b.DC} - U''_{b.DC}$$
$$U_{out.c} = U'_{c.DC} - U''_{c.DC} \tag{20}$$

In the asymmetrical mode of operation of an asynchronous motor, the output voltages supplied to the microprocessor measurement and control unit (Figure 3). Due to rectification with the help of diodes and phase control between the output currents and voltages using the phases meter-regulators, provides a signal in the form of a secondary voltage (15-18) [9, 11]. The value of which is determined as follows way:

When, the output voltages of the loops of the measuring windings are equal, i.e. symmetrical mode of operation of an asynchronous motor (Eq. 21):

$$U_{out.a} = U_{out.b} = U_{out.c} \tag{21}$$

Then the output voltage from the microprocessor blocks of measurement and control (Eq. 22):

$$\sum U_M = U_{out.a} + U_{out.b} + U_{out.c} = 0 \tag{22}$$

If the output voltage of the measuring windings is not equal, i.e. asymmetric operation of an asynchronous motor (Eq. 23):

$$U_{out.a} \neq U_{out.b} \neq U_{out.c} \tag{23}$$

Then the output voltage from the microprocessor measurement and control units differs from zero, i.e. the value in the form of a secondary voltage is provided, which characterizes the controlled mode of asymmetry (Eq. 24):

$$\sum U_M \neq 0 \tag{24}$$

In order to expand the functionality of measuring and monitoring the asymmetry and non-sinusoidal currents of the stator winding of an asynchronous motor in a three-phase current-to-voltage converter (Figure. 1). The outputs of the loops (1) and (2) of the measuring winding of phase A. Each of the loops having two outputs, the ends of the first outputs are connected through the phase meter-regulators (3) and (4) and diodes (5) and (6), providing signals in the form of voltage $U'_{a.DC}$ and $U''_{a.DC}$ to the inputs of the constant signal of the microprocessor unit (7) measurement and control. Providing a signal of asymmetry, by counter-connection and phase equalization (using phase meters-regulators (3) and (4)) and amplitude rectification (using diodes (5) and (6)). The ends of the second outputs providing an alternating signal in the form of voltage $U'_{a.AC}$ and $U''_{a.AC}$ directly to the input of alternating signals of the microprocessor unit (7) for measurement and control, providing a signal about the non-sinusoidality of phase A current.

Similarly, the circuits for connecting the measuring windings of phases B are performed. The leads of the loops (8) and (9) of the measuring winding of phase B. Each of the loops having two leads, the ends of the first leads are connected through the phase meter-regulators (10) and (11) and diodes (12) and (13), providing signals in the form of voltage $U'_{b.DC}$ and $U''_{b.DC}$ to the inputs of the constant signal of the microprocessor unit (14) for measurement and control. Providing a signal of asymmetry, by counter-connection and phase alignment (using phase measuring regulators (10) and (11)) and amplitude rectification (using diodes (12) and (13)). The ends of the second outputs, providing an alternating signal in the form of voltage $U'_{b.AC}$ and $U''_{b\ .AC}$ directly to the input of variable signals of the microprocessor unit (14) for measurement and control. Which provides a signal about the non-sinusoidal current of phase B and phase C - the outputs of the loops (15) and (16) of the measuring winding, each of the loops having two outputs, the ends of the first outputs are connected through a phase meter regulators (17) and (18) and diodes (19) and (20). Providing signals in the form of voltage $U'_{c.DC}$ and $U''_{c.DC}$ to the constant signal inputs of the microprocessor unit (21) for measurement and control, providing a signal of asymmetry, by counter-connection and phase alignment (using phase-measuring regulators (17) and (18)) and amplitude rectification (using diodes (19) and (20). The ends of the second outputs, providing an alternating signal in the form of voltage $U'_{c.AC}$ and $U''_{c.AC}$ directly to the input of variable signals of the microprocessor unit (21) for measurement and control. Which provides a signal about the non-sinusoidality of the phase C current [8-12].

In an asynchronous motor, due to several effects, high harmonics are generated in the stator windings, which in turn has a negative effect on the operation of the asynchronous motor and efficiency. Based on the above schemes, it is possible to determine the high harmonics generated in the stator coils through the output signals. In this case, the high harmonics affecting the asynchronous motor are determined by fast Fourier transform of the value of the voltage coming out of the measurement coil loops (Eq. 25-27) [4-9].

$$A_o = \frac{1}{2\pi}\int_0^{2\pi} f\,(x) \approx \frac{1}{2\pi}\sum_{p=1}^{p=n} f_p\,(x)\Delta X = \frac{1}{2\pi}\sum_{p=1}^{n} f_p(x)\,\frac{2\pi}{n} \tag{25}$$

$$A'_n = \frac{2}{n}\sum_{p=1}^{n} f_p(x)\,sin_p x = \frac{4}{n}\sum_{p=1}^{n/2} f_p(x) sin_p x \tag{26}$$

$$A''_n = \frac{2}{n}\sum_{p=1}^{n} f_p(x)\,cos_p x = \frac{4}{n}\sum_{p=1}^{n/2} f_p(x) cos_p x \tag{27}$$

A_n - is the amplitude of the component of the nth harmonic of the studied variable non-sinusoidal (Eq. 28).

$$A_n = \sqrt{(A'_n)^2 + (A''_n)^2} \tag{28}$$

The non-sinusoidal coefficient is determined by following formula (Eq. 29):

$$K = \sqrt{\sum_{n=2}^{N}\left(\frac{A_n}{A_1}\right)^2} \tag{29}$$

3. Results and Discussion

The characteristics of the 4AA63A4Y3 asynchronous motor with three-phase sensing element changer determined on the basis of theoretical calculations and practical data are given below. Based on the result, the voltages coming out of the independent, serially and oppositely (bifilar) connected measuring coils were determined [7-12, 14].

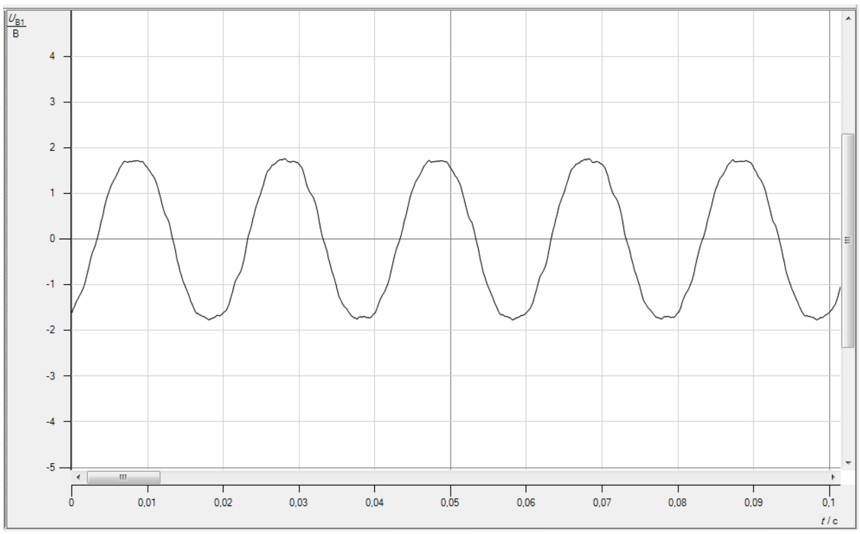

Figure 4. Description of the time dependence of the output signal from the current converter with independent loop

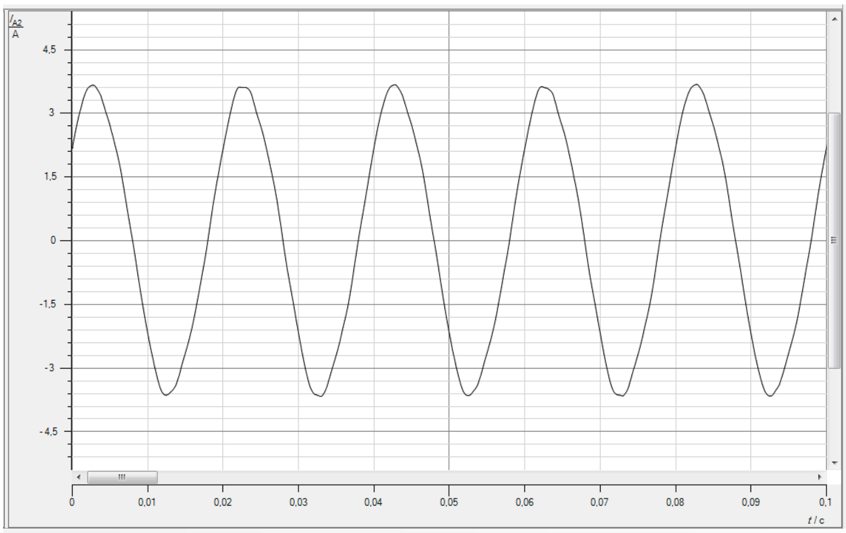

Figure 5. Description of the time dependence of the output signal from the current converter with series connected measuring coil loops

Based on the above results, if we analyze the characteristics of the output voltage signal of the current converter according to the state of connection of the measuring coil loops, the amount of the output signal from the current converter with independent loops is greater than that from the current converter with the loops connected in series. We can see that the amount of the output signal is almost two times smaller than the (12) and according to Figure 4 and Figure 5. Due to the small value of the signal coming out of the current converter with an independent circuit, it is affected by high harmonics, which has a negative effect on the measurement accuracy. The accuracy of the output signal is high in the current converter, which is made up of loops connected in series. However, the accuracy of measuring the value of non-sinusoidal currents and three-phase asymmetrical currents in an asynchronous motor through this connection scheme is low, and it is not possible to determine the asymmetrical currents between the stator windings placed between the poles of each phase [8-11, 13].

The asynchronous motor current converter loops have a wide range of functional options; it can measure in high accuracy, which simultaneously determine the non-sinusoidal currents in the asynchronous motor, the amount of current flowing through the stator windings, and the asymmetrical currents between the stator windings (Figures 6 and 7).

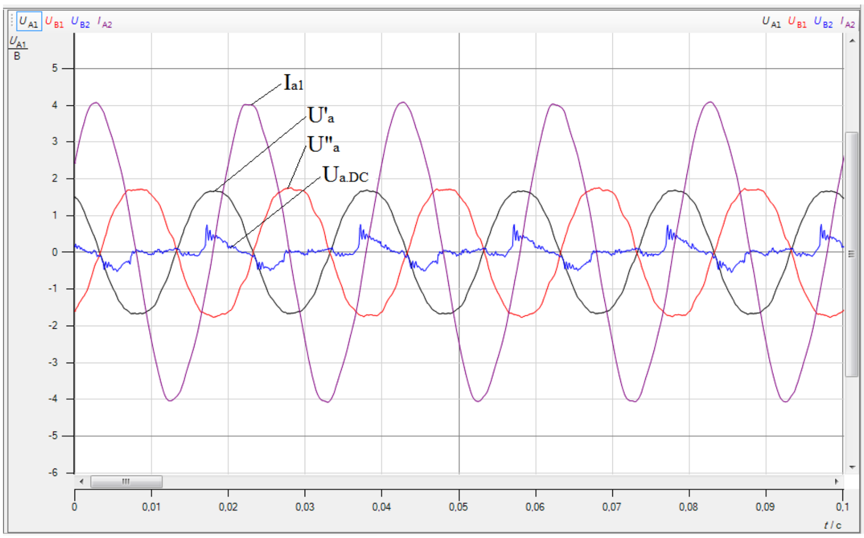

Figure 6. Description of the time dependence of the signal emanating from interpolar loops

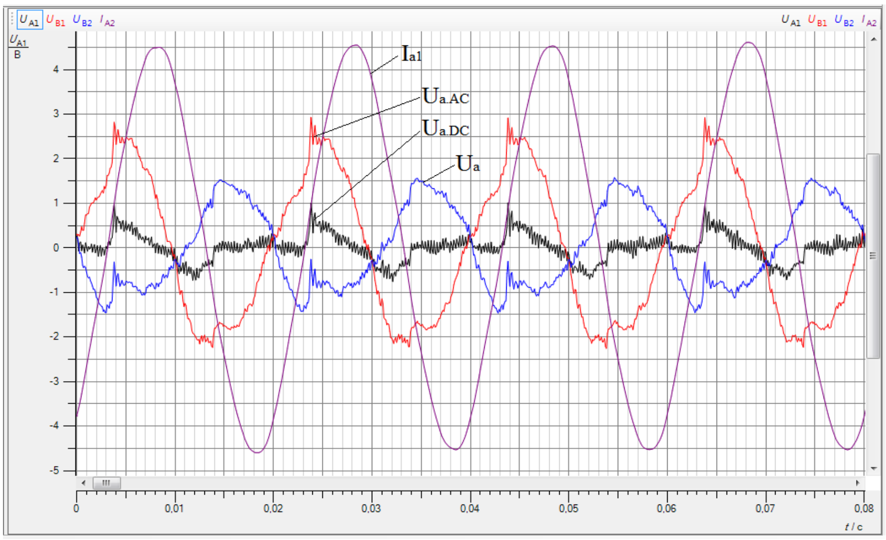

Figure 7. Description of the time dependence of the signals coming out of the current converter with bifilar connected measuring coil loops in the nominal operating mode of the asynchronous motor

From the graphs in Figure 4, it can be seen that the influence of higher harmonics on the output signal of the current converter with independent loop. When we analyzed the output signal based on the fast Fourier transform, the non-sinusoidal coefficient in it was 9.54 %, and the non-sinusoidal coefficient of the output signal from the current converter with the loops connected in series was 6.25 %. The non-sinusoidal coefficient of the non-sinusoidal current generated in the asynchronous motor by the signal coming from the current converter with loops connected bifilar was 14.76 %, the non-symmetry difference between the stator windings belonging to one phase was ΔU=4.49 V. There is an influence of the 7th and 9th harmonics on the output signal from a current converter with independent loops, and an influence of the 9th harmonic on the output signal from a current converter with series connected loops, and these harmonics have a negative effect on the measurement accuracy. The accuracy of measuring non-sinusoidal and asymmetrical currents by means of signals coming from a current converter with opposite (bifilar) connected loops is higher than the signals coming from current converter with independent loop and loops connected in series (Figures 8, 9 and 10).

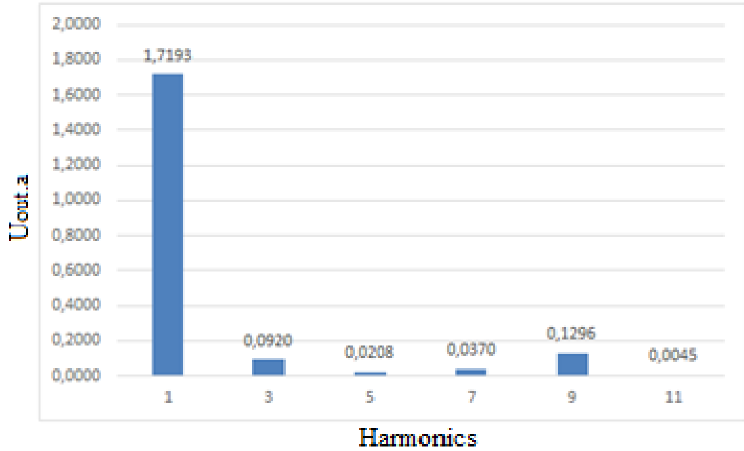

Figure 8. Harmonics of the output signal of the current converter with independent loop

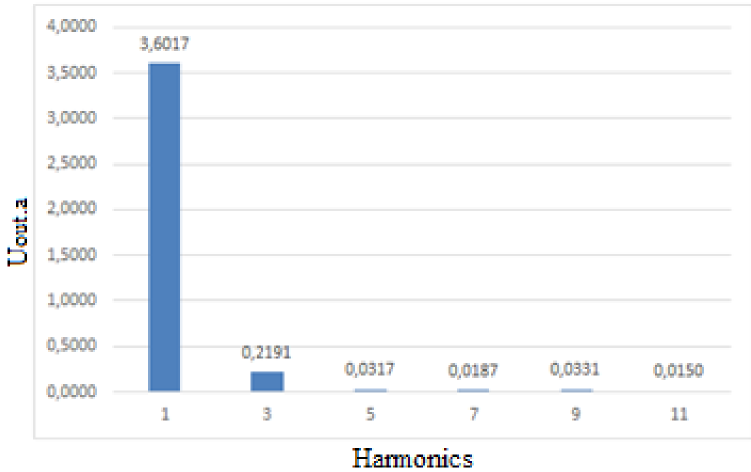

Figure 9. Harmonics of the output signal of the series connected current converter

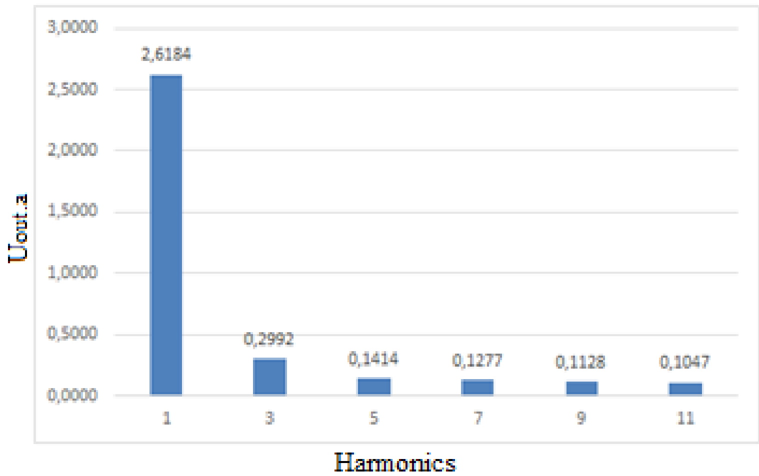

Figure 10. Harmonics of the output signal of the bifilar connected current converter

4. Conclusions

From the research, we conclude that the amount of primary currents flowing through the stator of the asynchronous motor, through the secondary voltages at the output of the sensing elements of the current converter are placed in the grooves of the asynchronous motor. The amount of symmetrical currents between the stator windings of one phase and between the phases of the stator windings, and the stator detection of high harmonics generated in the circuit, the quality of the element of the control and management system of the reactive power of the asynchronous motor gives its effect in use.

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