

Pulse-width modulation in the autonomous voltage inverter in identifying parameters of the three-phase asynchronous motor

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Abstract. This paper deals with control algorithm of a two-level autonomous voltage inverter with pulse-width modulation in forming test phase voltages for identification of parameters of a three-phase asynchronous motor. Necessary conversion is carried out, the laws of change of phase voltages of an autonomous inverter are obtained. The feasibility of using third order active Butterworth filters for determining first harmonics of phase voltages is shown. By means of computer simulation and experimental research, it is revealed that the required shapes of phase voltages can be implemented in a two-level autonomous voltage inverter with pulse-width modulation, and the presence of Butterworth filters does not introduce significant distortion and allows to obtain necessary phase voltage shapes in the generalized electric machine.

1 Introduction

For implementation of laws of frequency regulation of speed in the asynchronous motor (AC), it is necessary to be armed with data on current parameter values of phase-substitution and load circuit. This information allows to implement more accurate algorithms of frequency regulation of speed. And this provides energy efficiency and resource saving.

There are various methods of parameters identification [1 – 5]. In [6-13] efficiency of using continuous gradient method of minimum search of positive definite function for parametric identification of a three-phase asynchronous motor (AC) and its load is shown. In [7, 8, 11] identification is carried out by the five parameters of phase-substitution circuit of AC which include active winding resistance of stator R_1 , winding inductance of stator L_1 , mutual inductance M_m , active winding resistance of rotor R_2 , winding inductance of rotor L_2 . Load parameters are static moment M_s and joint inertia of moving parts J_Σ . The total number of identified parameters is seven.

In [7 - 10], a computer simulation of the identification processes of the parameters of a three-phase asynchronous motor (AC) and its load was carried out. The basis of the asynchronous motor model was the mathematical description of the generalized electrical machine (GEM). When simulating, the phase voltages of the stator winding were set in the form of test signals. The specifics of the operation of the frequency converter and the influence of pulse-width modulation (PWM) were not taken into account. PWM algorithms are given

in [14]. In this case, when identifying the parameters of the asynchronous motor, the shape and frequency of the output voltages of the frequency converter (FC) will depend on the laws of change in the test signals

The purpose of this article is to analyze the feasibility of technical implementation of the output voltages of the frequency converter with test signals and filtering the high-frequency components of these voltages.

2 Methods

In most cases, algorithms of frequency regulation of speed are based on mathematical description and parameters of the generalized electric machine [14, 15, 16]. Thus, for identification of parameters we use the equation system of the generalized electric machine (GEM) on the basis of three-phase asynchronous motor (AC) [7, 8, 11, 17, 18].

$$\begin{cases} u_{1d} = R_1 i_{1d} + L_1 \frac{di_{1d}}{dt} + M_m \frac{di_{2d}}{dt} - \omega_1 (L_1 i_{1q} + M_m i_{2q}) \\ u_{1q} = R_1 i_{1q} + L_1 \frac{di_{1q}}{dt} + M_m \frac{di_{2q}}{dt} + \omega_1 (L_1 i_{1d} + M_m i_{2d}) \\ 0 = R_2 i_{2d} + L_2 \frac{di_{2d}}{dt} + M_m \frac{di_{1d}}{dt} - \omega_2 (L_2 i_{2q} + M_m i_{1q}) \\ 0 = R_2 i_{2q} + L_2 \frac{di_{2q}}{dt} + M_m \frac{di_{1q}}{dt} + \omega_2 (L_2 i_{2d} + M_m i_{1d}) \\ J_\Sigma \frac{d\omega}{dt} = p_n (M_e - M_s) \\ M_s = p_p M_m (i_{2d} i_{1q} - i_{2q} i_{1d}) \end{cases} \quad (1)$$

where u_{1d} , u_{1q} - are stator winding phase voltages; i_{1d} , i_{1q} , i_{2d} , i_{2q} - are currents of stator and rotor winding;

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ω_1 - is angular velocity of rotating coordinate system d, q ; ω_2 - is angular slip velocity ($\omega_2 = \omega_1 - \omega$); ω - is angular rotation velocity of rotor, rad/s; p_p - is number of pole pairs; M_e - is electromagnetic torque; M_s - is static moment.

Transition from parameters and values of a three-phase asynchronous motor (AC) to the ones of the generalized electric machine (GEM) and vice versa is discussed in [17, 18]. Conversion of phase voltages of a GEM stator in voltages of a stator of the three-phase asynchronous motor (AC) takes the form [17, 18]

$$u_{1A} = u_{1d} \cos \alpha_1 - u_{1q} \sin \alpha_1 \quad (2)$$

$$u_{1B} = u_{1d} \cos\left(\alpha_1 - \frac{2\pi}{3}\right) - u_{1q} \sin\left(\alpha_1 - \frac{2\pi}{3}\right) \quad (3)$$

$$u_{1C} = u_{1d} \cos\left(\alpha_1 + \frac{2\pi}{3}\right) - u_{1q} \sin\left(\alpha_1 + \frac{2\pi}{3}\right) \quad (4)$$

where α_1 is shaft rotation angle of axis d of coordinate system d, q about axis A of stator.

Angle α_1

$$\alpha_1 = \int_0^t \omega_1(t) dt \quad (5)$$

Computer simulation of parameters identification processes of the asynchronous electric drive with motor AIR80A6U2 was carried out in [8]. Voltages $u_{1d}(t)$, $u_{1q}(t)$ and angle velocity $\omega_1(t)$ were changing in accordance with timing diagrams in Figure 1 and were characterized by the parameters presented in Table 1.

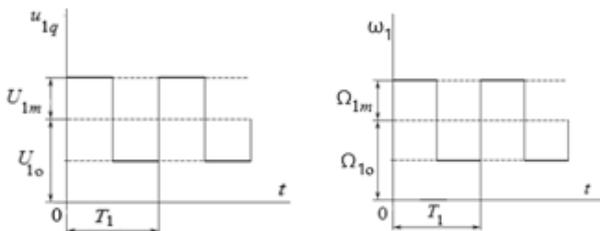


Fig. 1. Timing diagrams of functions $u_{1q}(t)$ and $\omega_1(t)$.

Table 1. Function parameters $u_{1q}(t)$ and $\omega_1(t)$.

Parameter name		Function	
		$u_{1q}(t)$	$\omega_1(t)$
Constant component	Designation	U_{1o}	Ω_{1o}
	Value, the unit of measurement	50 V	300 rad/s
Amplitude of variable component	Designation	U_{1m}	Ω_{1m}
	Value, the unit of measurement	25 V	150 rad/s
Frequency of variable component	Designation	f_1	
	Value, the unit of measurement	0.318 Hz	

From Figure 1 it is clear that the functions $u_{1q}(t)$ and $\omega_1(t)$ are periodical. Period of their variations is taken as T_1 . Let us agree to call $u_{1d}(t)$, $u_{1q}(t)$ and $\omega_1(t)$ test signals. Computer simulation in [8] confirmed efficiency, working capacity and high accuracy of the suggested identification method and of the algorithm that was worked out on its basis. For analysing feasibility of phase voltages of stator winding $u_{1A}(t)$, $u_{1B}(t)$, $u_{1C}(t)$ under test signals, computer simulation was conducted [19].

3 Results and Discussion

Results of computer simulation in the form of timing diagrams of angular velocity $\omega_1(t)$, rotation angle α_1 and voltages $u_{1q}(t)$, $u_{1A}(t)$ are given in Figure 2. Analysis of the curve $u_{1A}(t)$ shows that phase voltages are amplitude-frequency modulated oscillations. Amplitude changes according to variations of voltage amplitude $u_{1q}(t)$, and frequency changes according to angular velocity variations $\omega_1(t)$.

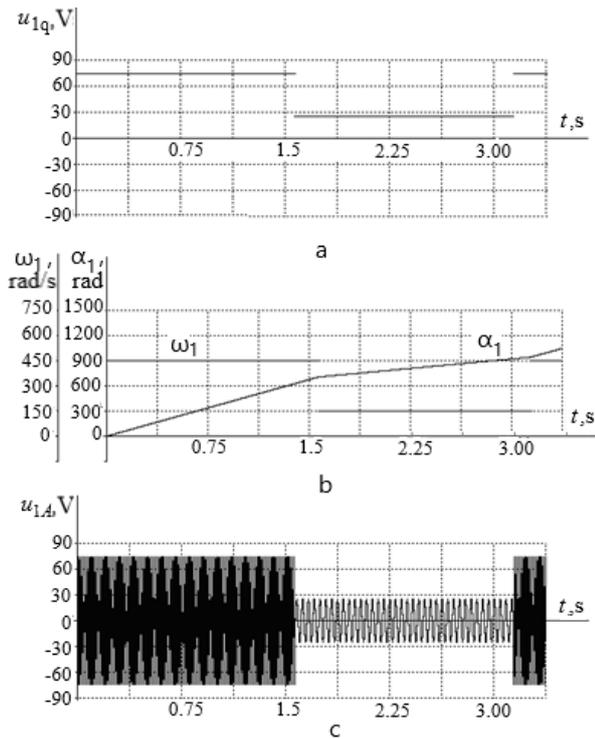


Fig. 2. Timing diagrams of voltage u_{1q} (a), angular velocity ω_1 and rotation angle α_1 (b), amplitude-frequency modulated voltage u_{1A} (c).

In a larger timescale, for the first and the second

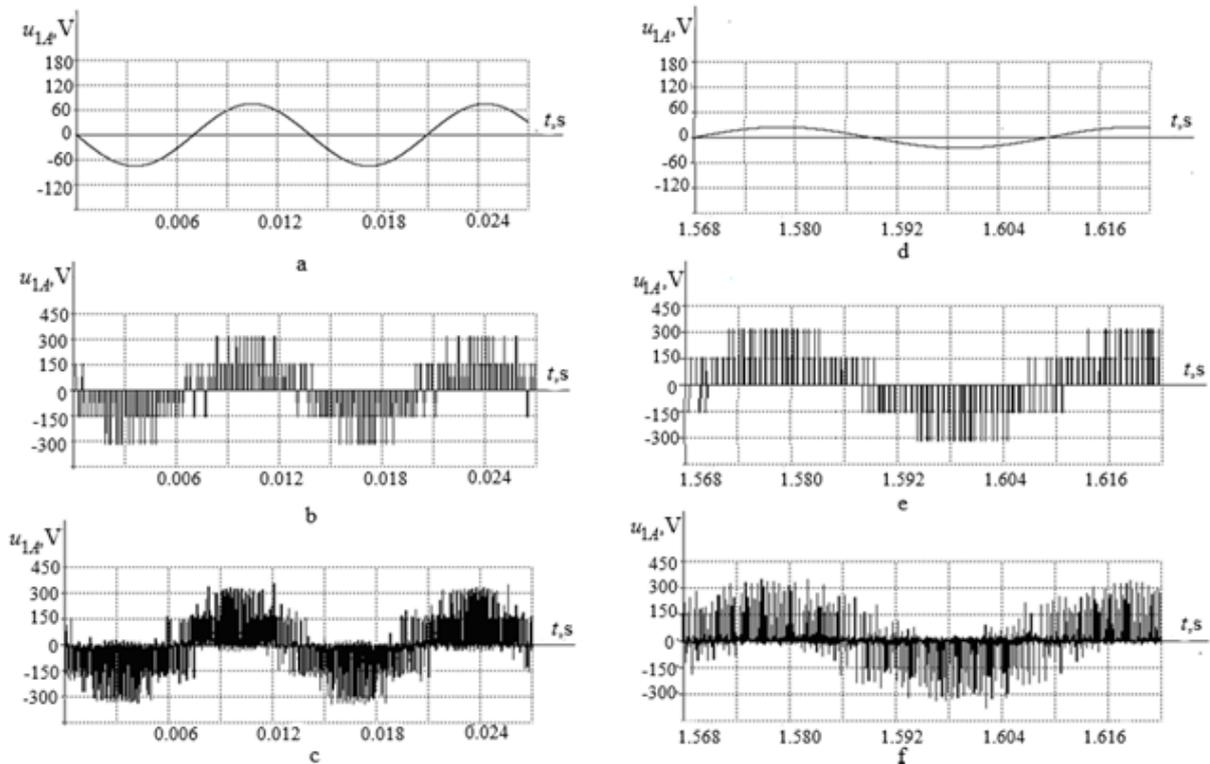


Fig. 3. Timing diagrams of voltage u_{1A} for the first (a, b, c) and the second (d, e, f) half of the period T_1 a, d – amplitude-frequency modulated voltage; b, e – calculated curve with PWM; c, f – experimental curve with PWM).

halves of period T_1 , the curve $u_{1A}(t)$ is shown in Figure 3 a, d. During the first half of period T_1 , voltage $u_{1A}(t)$ varies with time according to harmonic law with amplitude 75 V and frequency 71.6 Hz, and during the second half of period T_1 with amplitude 25 V and frequency 23.8 Hz. In a similar way, with angle shift $-2\pi/3$ and $2\pi/3$, voltages $u_{1B}(t)$, $u_{1C}(t)$ will change correspondingly.

To implement phase voltages $u_{1A}(t)$, $u_{1B}(t)$, $u_{1C}(t)$, it is necessary to change simultaneously their root-mean-square values and frequency.

In most modern asynchronous electric drives, indirect frequency converters (FC) are used. They comprise uncontrolled rectifier (UR) and two-level autonomous voltage inverter (AVI). To operate transistors of the autonomous voltage inverter, pulse-width modulation (PWM) is applied. Phase voltages of AVI with PWM represent pulse string, amplitude and duration of which change directly with control voltages.

Simulation of AVI with PWM was conducted providing three-phase mains supply of indirect frequency converter (FC) has voltage 390 V, frequency 50 Hz. In this case rectified voltage in DC link [21] takes the form of

$$U_d = 1.35 \cdot U_{IL} \quad (6)$$

where U_{IL} is root-mean-square value of line-to-line supply voltage.

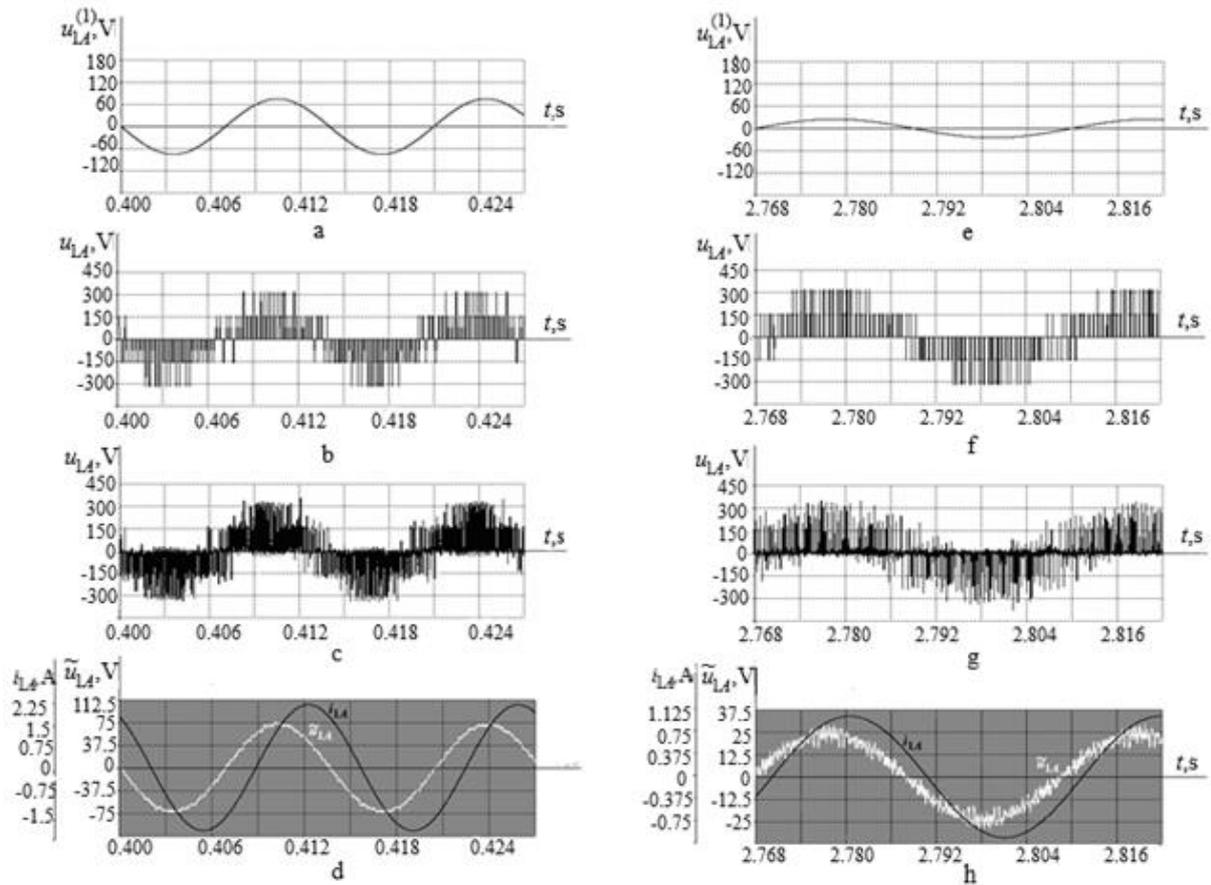


Fig. 4. Timing diagrams for the first (a, b, c, d) and second (e, f, g, h) halves of the period T_1 (a, e – first (main) harmonic $u_{1A}^{(1)}$; b, f – calculated curve u_{1A} with PWM; c, g - experimental curve u_{1A} with PWM; d, h - experimental curves voltage \tilde{u}_{1A} in the output of low-pass filter (LPF) and current i_{1A})

Not taking account of voltage drop in diodes of uncontrolled rectifier, in accordance with (6), we get

$$U_d = 1.35 \cdot 380 = 513 \text{ V}$$

In simulation, voltage drop in diodes of uncontrolled rectifier and in on-transistors of AVI was taken into consideration. Control voltages of AVI were taken as proportional to voltages $u_{1A}(t)$, $u_{1B}(t)$, $u_{1C}(t)$.

Results of computer simulation are presented in Figure 3 b, 3 e in the form of timing diagrams of phase voltages $u_{1A}(t)$ for the first and the second halves of period T_1 . Analysis of the diagrams shows that phase voltages of AVI with PWM are periodical time functions. They represent pulse string with amplitude 165 V and 330 V with reposes at zero-low. Duration and pulse height change according to variations of amplitude-frequency modulated control voltages. Pulse heights are equal to $\frac{1}{3}U_d$ and $\frac{2}{3}U_d$. This corresponds with description of PWM algorithm in [14, 20, 22]. Results of computer simulation are in agreement with theory and applications of power-operated converter equipment and variable frequency electric drive.

Experimental research was conducted in the scientific laboratory at Kazan National Research Technological University using indirect frequency converter (FC). The objective of the experiment is qualitative analysis of phase voltage curves of AVI with PWM along with test signals. Powerpart of with PWM was carried out with intelligent power modul (IPM) *PS22A73* by *Mitsubishi Electric*. Actuating system was performed with microcontroller *dsPIC30F3010*.

Frequency of pulse-width modulation was taken equal to 16 kHz. Experiment results are presented in Figure 3 c and Figure 3 f in the form of timing diagrams of phase voltages $u_{1A}(t)$ for the first and second halves of period T_1 . Comparative qualitative analysis of timing diagrams highlights good agreement of calculated (Figure 3 b, 3 e) and experimental curves (Figure 3 c, 3 f).

In pulse-width modulation (PWM), output voltages of frequency converter (FC) represent pulse string. Duration of the pulses changes proportionally to control voltages. Impact of PWM leads to occurrence of high-frequency components in phase voltage spectrum of FC.

Thus, for identification of parameters of three-phase asynchronous motor it is necessary to perform filtration

of phase voltages of FC with their further conversion [22, 23].

The aim of computer simulation is to analyse the curves of output voltages of indirect frequency converter (FC) with identification of parameters of three-phase asynchronous motor. By means of computer simulation, for the first and second halves of period T_1 , amplitude-frequency modulated voltage curves $u_{1A}^{(l)}(t)$ and calculated curves $u_{1A}(t)$ with PWM are obtained. The curves are presented in Figure 4 a, b and Figure 4 e, f, correspondingly.

Evidently, that in phase voltage spectrum of FC there are high-frequency components. For high-frequency components cutoff, low-pass filters (LPF) are used. Taking into considerations [24 - 28], analysis of circuitry and LPF characteristics was conducted. It was found that for filtration of phase voltages of (FC), it is reasonable to use third order Butterworth filters. Transfer function of such filter is given [28]

$$W(p) = \frac{k_f}{T_f^3 p^3 + 2T_f^2 p^2 + 2T_f p + 1} \quad (7)$$

where k_f , T_f are transmission factor and filter time constant.

Filter time constant differs according to cutoff frequency f_c

$$T_f = \frac{1}{2\pi f_c} \quad (8)$$

Cutoff frequency of LPF was taken equal to 5 kHz and was chosen considering the following :

1) minimum ω_{1min} and maximum ω_{1max} circular frequencies of the desired signal in Figure 5 are evaluated on account of values Ω_{1o} and Ω_{1m} of function $\omega_1(t)$ from Table 1;

2) circular frequency of reference voltage ω_{ref} is determined by PWM frequency which was set equal to 16 kHz;

3) effect of LPF on voltage conversion should be minimal.

In Figure 5 frequency response of third order Butterworth filter with cutoff frequency 5 kHz is shown. The response is determined on account of transfer function proved that k_f equals 1.

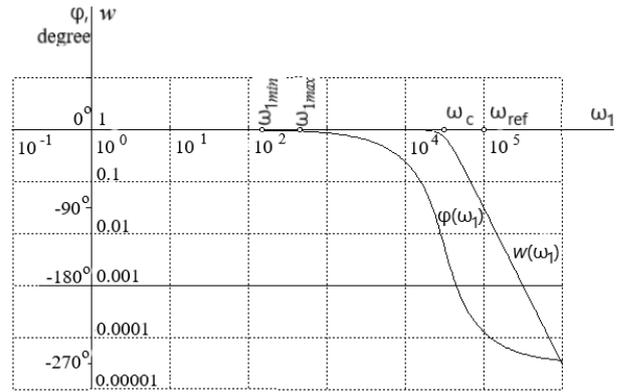


Fig. 5. Frequency response of third order Butterworth filter.

Analysis of amplitude-frequency characteristics (AFC) in Figure 5 shows that with circular frequency ω_1 lower than circular cutoff frequency ω_c , it is at the level of 1, while with circular frequency ω_1 higher than ω_c , it has the slope of 60 dB/dec. This is decisive advantage when choosing LPF type. Evidently, that amplitude distortion with circular frequencies of the desired signal ω_{1min} and ω_{1max} will be minimal. Analysis of circuit phase response in Figure 5 shows, that in the field of circular frequency of the desired signal ω_{1min} and ω_{1max} , the filter will not cause significant lag.

Experimental setup scheme is given in Figure 6. The sensor unit in Figure 6 comprises voltage sensing devices and current sensing devices, Hall effect devices, rotation velocity sensors and angular accelerometers. Hall devices are installed in stator bore in orthogonal axes. Filter bank comprises six third order Butterworth filters. Frequency converter (FC) is not shown in Figure 6.

The aim of the experiment is analysis of output voltage curves of third order Butterworth filters and analysis of results of conversion of output voltage of the filters into voltages of coordinate system d, q .

Results of the experiment are presented in Figure 4 c, d, g, h in the form of timing diagrams of phase voltages of frequency converter (FC) and output voltages of LPF for the first and second halves of period T_1 .

In Figure 7b there are timing diagrams of voltages $\tilde{u}_{1d}(t)$, $\tilde{u}_{1q}(t)$ formed on account of LPF output voltages. Experimental timing diagrams of output voltages of LPF in Figure 4 d, h are combined with timing diagrams of phase currents $i_{1A}(t)$. Phase current curves of the asynchronous motor represent fairly smooth harmonic functions and, thus, do not need filtration. Experimental curves are performed using packet *Power Crap* 3.3. Conversion of output voltages of LPF into phase voltages of stator winding of GEM takes the form of [17, 18]

$$\tilde{u}_{1d} = \frac{2}{3} \left[\tilde{u}_{1A} \cos \alpha_1 + \tilde{u}_{1B} \cos \left(\alpha_1 - \frac{2\pi}{3} \right) + \tilde{u}_{1C} \cos \left(\alpha_1 + \frac{2\pi}{3} \right) \right] \quad (9)$$

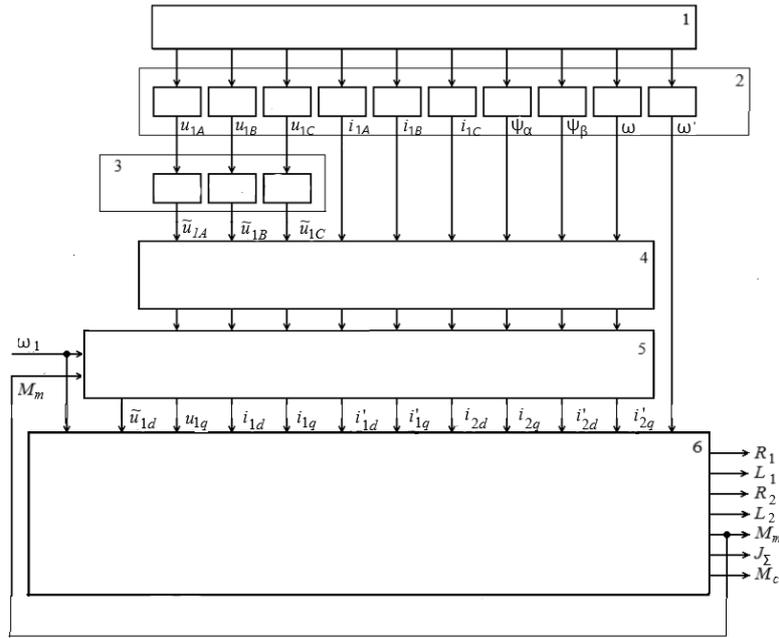


Fig. 6. Experimental setup diagram (Block 1 - Induction motor; block 2 - Sensor unit; block 3 - Filter unit; block 4 - Analog-to-digital converter; block 5 - Coordinate converter; block 6 - Parameter identification device).

$$\tilde{u}_{1q} = -\frac{2}{3} \left[\tilde{u}_{1A} \sin \alpha_1 + \tilde{u}_{1B} \sin \left(\alpha_1 - \frac{2\pi}{3} \right) + \tilde{u}_{1C} \sin \left(\alpha_1 + \frac{2\pi}{3} \right) \right] \quad (10)$$

Curves of output voltages of LPF in Figure 4 d, h are not ideally smooth harmonic functions. In spectrum of LPF output voltages there is high-frequency ripple. Most significantly they are revealed in the second half of period T_1 (Figure 4 h). This is explained by relatively small amplitude value of the first harmonic of phase voltage $u_{1A}^{(1)}(t)$ which is 25V. On account of (5), (9), (10), curves $u_{1d}(t)$, $u_{1q}(t)$ are formed, they are given in Figure 7 b. Because of the PWM effect, the curves contain high-frequency ripple with amplitude no more than 3 V.

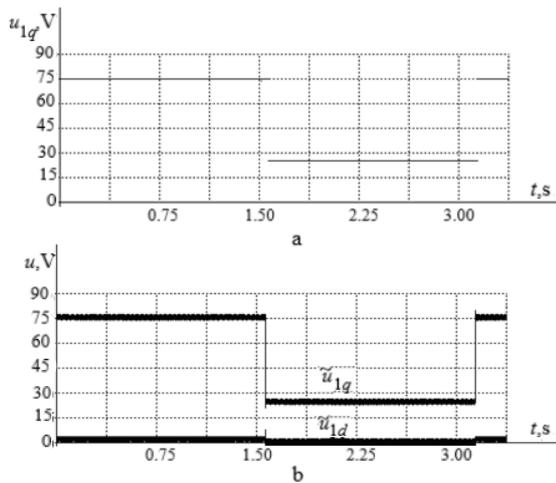


Fig. 7. Calculated (a) and experimental (b) curves of phase voltages of GEM stator.

For qualitative evaluation of effect of third order Butterworth filters, analysis of frequency response was conducted, it is presented in Figure 5. Results are shown in Table 2.

Table 2. Results of analysis of the filter frequency response.

Frequency response, units of measurement	Circular frequencies		
	$\omega_{1\min}$	$\omega_{1\max}$	ω_{ref}
$w(\omega_1)$	1	1	0.03
$A(\omega_1)$, dB	0	0	-30.3
$\phi(\omega_1)$, degree	-1.59	-2.13	-233

According to data of Table 2, with circular frequencies of the desired signal $\omega_{1\min}$ and $\omega_{1\max}$, amplitude variations of LPF output voltage are not registered. Phase lag is equal to 1.59° and 2.13°, correspondingly. Circular frequency ω_{ref} in this case is considered as interfering frequency. At this frequency, amplitude attenuation of LPF output voltage and phase lag by 233° are observed.

4 Conclusion

The conducted analysis allowed to find out that third order Butterworth filters do not significantly influence the desired signal and provide efficient cutoff of high-frequency interference. Experimental research allowed to establish, that the use of indirect frequency converter (FC) with PWM and Butterworth filters makes it possible to a high precision to perform transition in phase voltages of GEM stator winding. When this happens, identification processes stability is reserved,

and in identification of the aforementioned parameters of a three-phase asynchronous motor and its load, with initial deflection from true values by 50%, relative error is not higher than 7% [20].

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