Control System with Sinusoidal PWM Three-Phase Inverter with a Frequency Scalar Control of Induction Motor

Yuri N. Dementyev
Department of Electric Drives and Equipment
National Research Tomsk Polytechnic University
Tomsk, Russia
E-mail: dementev@tpu.ru

A. D. Bragin
Department of Electric Drives and Equipment
National Research Tomsk Polytechnic University
Tomsk, Russia
E-mail: lflenylol@gmail.com

N.V. Kojain
Department of Electric Drives and Equipment
National Research Tomsk Polytechnic University
Tomsk, Russia
E-mail: kojain@rambler.ru

L.S.Udut
Department of Electric Drives and Equipment
National Research Tomsk Polytechnic University
Tomsk, Russia
E-mail: udut@tpu.ru

Abstract — **The principles of implementation of the control system with sinusoidal PWM inverter voltage frequency scalar and vector control induction motor are reviewed. Comparisons of simple control system with sinusoidal PWM control system and sinusoidal PWM control with an additional third-harmonic signal and gain modulated control signal are carried out. There are shown the maximum amplitude and actual values phase and line inverter output voltage at the maximum amplitude of the control signals. Recommendations on the choice of supply voltage induction motor electric drive with frequency scalar control are presented.**

Keywords — control system; PWM; induction motor; frequency scalar control; three-phase inverter;

I. INTRODUCTION

Generally modern variable frequency induction motor drive contains a two-level (tier) frequency converter with controlled or uncontrolled converter, which work with constant, small angles control and invert [1, 2]. Rectifier loaded on a stand-alone voltage inverter operating in a pulse width modulation (PWM). This structure of frequency converter allows providing high power factor of power circuit for the drive independently of drive mode and the implementation of laws frequency vector control to achieve the best performance of dynamic and static control. Thus, of particular interest for study is the principles of the implementation of sinusoidal PWM three-phase inverter with frequency induction motor control, allowing to provide work induction motor for given values of maximum speed of the electric drive and maximum torque of static load.

II. THREE-PHASE INVERTER CONTROL SYSTEMS

The aim of the article is to study the control system with sinusoidal PWM and third harmonic three-phase inverter drive, providing satisfactory mechanical characteristics of variable frequency induction motor drive at the speed setpoint of the electric drive and torque of static load.

The system of three-phase sinusoidal PWM inverter has common to all three phases of the inverter reference signal is a sawtooth waveform with unit amplitude and frequency fig. 1, 2 [3]. In the simplest case, three sinusoidal PWM control signals are set to the input PWM block:

$$u^*_{1a} = u^*_{1m} \cdot \mathrm{Cos}(2\pi \cdot f_1 \cdot t);$$

$$u^*_{1b} = u^*_{1m} \cdot \mathrm{Cos}(2\pi \cdot f_1 \cdot t - \frac{2\pi}{3});$$

$$u^*_{1c} = u^*_{1m} \cdot \mathrm{Cos}(2\pi f_1 \cdot t - \frac{4\pi}{3}),$$

where $u^*_{1m} \le 1$.

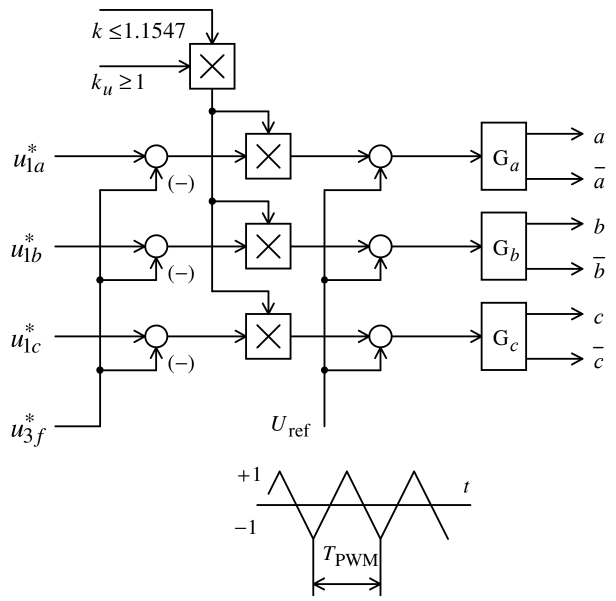

Fig. 1. Sinusoidal PWM with additional third harmonic in control signal of inverter

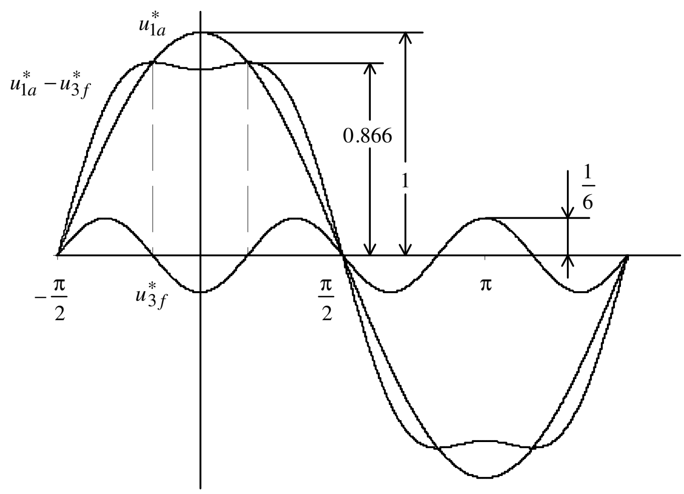

Fig. 2. Form of control signal with additional third harmonic

Common to all controls the third harmonic signal are added in control signal in the systems with sinusoidal PWM and third harmonic:

$$u_{3f}^* = \frac{1}{6} \cdot u_{1m}^* \cdot \mathrm{Cos}(2\pi \cdot 3 \cdot f_1 \cdot t)$$

Introduction the third harmonic in inverter control system leads to a change in shape and reduce $\sqrt{3}/2 = 0.866$ times the amplitude of the resultant control signal at the input of the PWM block. It allows to increase the amplitude of the control signals in $k = 2/\sqrt{3} = 1.1547$ time to the amplitude of the sawtooth voltage reference.

Comparative evaluation of simple control system with sinusoidal PWM ($u_{3f}^* = 0$, $k = 1$) and control system with additional the third harmonic signal u_{3f}^* and gain of modulated control signal $k = 1.1547$ in the table 1. The maximum current and amplitude values of the output voltage phase $U_{ph.m}$, U_{ph} and linear $U_{lin.m}$, U_{lin} of the inverter at an amplitude the control signals $u_{1m}^* = 1$ are presented for comparison. DC bus voltage at rated motor load is taken equal $U_d = 1.35 \cdot U_c$.

That would be the inverter output voltage with sinusoidal PWM and third harmonics in the control signal to provide the effective value of the rated phase voltage motor $U_{1ph.n.} = 220$ V, linear voltage must satisfy the following condition

$$U_n > \frac{\sqrt{3} \cdot \sqrt{2} \cdot U_{1ph.n}}{1.35} = \frac{\sqrt{3} \cdot \sqrt{2} \cdot 220}{1.35} = 399.2 \text{ V}.$$

Increase control signal allows to increase the amplitude of the first harmonic of the output phase voltage inverter to the maximum value, because in control systems with sinusoidal PWM control signal exceeding the reference value of the sawtooth signal ($u_{1m}^* > 1$) does not cause loss of operability of the system.

$$U_{i.ph.m} = \frac{2 \cdot U_d}{\pi} = 0.6366 \cdot U_d$$

($U_c = 380$ V $U_{иф.м} \approx 326.6$ V).

However, this leads to a substantial increase of higher odd harmonics (over the third harmonic) (fifth harmonic up to 20%, the seventh - up to 14.3%) in the output inverter signal (inverter similarly with **π-** switching).

Systems with vector PWM are controlled by sinusoidal signals and have similar characteristics to the sinusoidal PWM with addition of the third harmonic [4, 5].

Vector PWM do not have a reference voltage and does not exceed the amplitude of the control signal a limiting value because the excess leads to disruption of its operability. Frequency converter control system is adjusted according to the voltage-frequency response U_1 / f_1 at a voltage $U_{1ref} = U_{1ph\ n}$ and frequency $f_{1ref} = f_{1n}$ (characteristic 1 in Fig. 3) in electric drive with frequency scalar control. The inverter forms the characteristic $U_и / f_1$ which corresponds to a voltage $U_i = U_{i.ph.max}$ at a frequency $f_{1ref} = f_{1n}$ (the characteristic 2 of Fig. 3). A fundamental factor in scalar control is specified frequency f_{1ref}, as a result the inverter forms the an output voltage set frequency, but the amplitude of the voltage determines the characteristics of the inverter U_i / f_1. As a result, for example, maximum value of the inverter output voltage at $f_{1ref} = 50$ Hz and $U_n = 380$ V mains voltage is less than the nominal phase voltages in the motor $U_{i.ph.max} < 220$ V (see. Table. 1) [7].

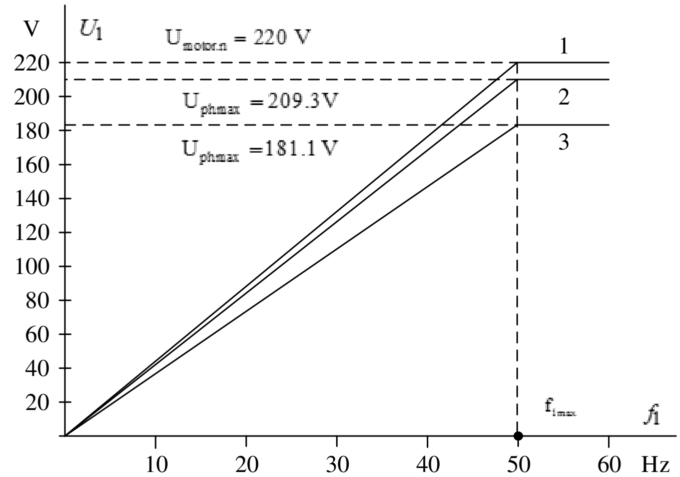

Fig. 3. The voltage-frequency response of: 1 - set in the drive control system; 2 and 3 - the characteristics of the inverter with sinusoidal PWM and third harmonic k = 1.1547, and with a simple sinusoidal PWM

TABLE I. PARAMETERS OF THE INVERTER OUTPUT VOLTAGE DEPENDING ON THE IMPLEMENTATION SINUSOIDAL PWM CONTROL SYSTEM

Simple control system with sinusoidal PWM	**Control system with additional the third harmonic signal and gain of modulated control signal**
$u^*_{3f} = 0$, $k = 1$, $u^*_{1m} = 1$	$u^*_{3f} = \frac{1}{6} \cdot u^*_{1a\,m} \cdot \mathrm{Cos}(2\pi f_1 \cdot t)$, $k = 1.1547$, $u^*_{1m} = 1$
$U_c = 380$ V, $U_d = 1.35 \cdot 380 = 513$ V	
$U_{i.ph.m} = \frac{U_d}{2} = 0.5 \cdot U_d = 256.5$ V $U_{iph} = \frac{U_d}{2 \cdot \sqrt{2}} = 0.353 \cdot U_d = 181.37$ V $U_{i.lin.m} = \frac{\sqrt{3} \cdot U_d}{2} = 0.866 \cdot U_d = 444.27$ V $U_{i.lin} = \frac{\sqrt{3} \cdot U_d}{2 \cdot \sqrt{2}} = 0.612 \cdot U_d = 314.14$ V	$U_{i.ph.max} = \frac{U_d}{\sqrt{3}} = 0.577 \cdot U_d = 296.18$ V $U_{i.ph} = \frac{U_d}{\sqrt{3} \cdot \sqrt{2}} = 0.408 \cdot U_d = 209.43$ V $U_{i.lin.m} = 1.0 \cdot U_d = 513$ V $U_{i.lin} = \frac{U_d}{\sqrt{2}} = 0.707 \cdot U_d = 362.74$ V

At a given frequency f_{1ref} the motor will not work for a given value of voltage $U_{1ref} = U_{1ph.n.} \cdot \frac{f_{1ref}}{f_{1n}}$ and at a voltage inverter $U_{i.ph} = U_{i.ph.max} \cdot \frac{f_{1ref}}{f_{1n}}$, which depends on the way of the PWM and input voltage. The motor operates at a specified frequency f_{1ref} with lower voltage, because voltage of the inverter $U_{i.ph}$ is always less than the specified value $U_{1ph.n} \cdot \frac{f_{1ref}}{f_{1n}}$ at mains voltage $U_n < 400$ V. It would increase motor current and a decrease in the critical torque at a constant value of the static torque load, because value of the flux is less than the nominal value [8, 9]. The inverter voltage will always be greater than a predetermined $U_{i.ph} > U_{1ph.n} \cdot \frac{f_{1ref}}{f_{1n}}$ if the voltage is $U_n > 400$ V, to limit it to the level $U_{i.ph.max} = U_{1ph.n}$ should reduce the amplitude of the control signals, depending on the actual value of the DC bus voltage U_d by implementing conditions

$$k = \frac{\sqrt{3} \cdot \sqrt{2} \cdot U_{1ph.n}}{U_d} \cdot 1.1547 \le 1.1547 . \qquad (1)$$

As it shown at fig 2.

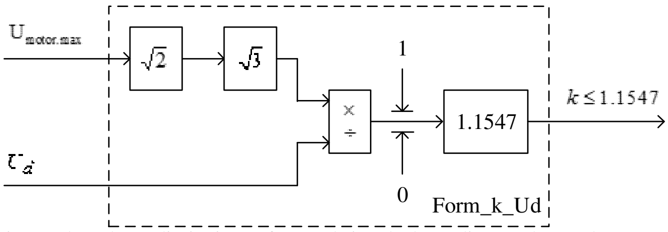

Fig. 4. The scheme limitations of control signals depending on the DC bus voltage

Fig. 5 shows the mechanical characteristics of the natural 1 ($f_1 = 50$ Hz and $U_1 = U_{1ph.n}$) and limit the mechanical characteristics of 2 or 3 AV250S6 motor ($P_n = 45$ kWt, $n_n = 1000$ round per minute) with its power voltage supply from the inverter, respectively, for the two cases:

1. $U_n = 380$ V, *sinusoidal PWM* with additional the third harmonic signal *k*=1.1547 ($U_{i.ph.max} = 209.43$ V);
2. $U_n = 380$ V, simple *sinusoidal PWM* ($U_{i.ph.max} = 181.37$ V).

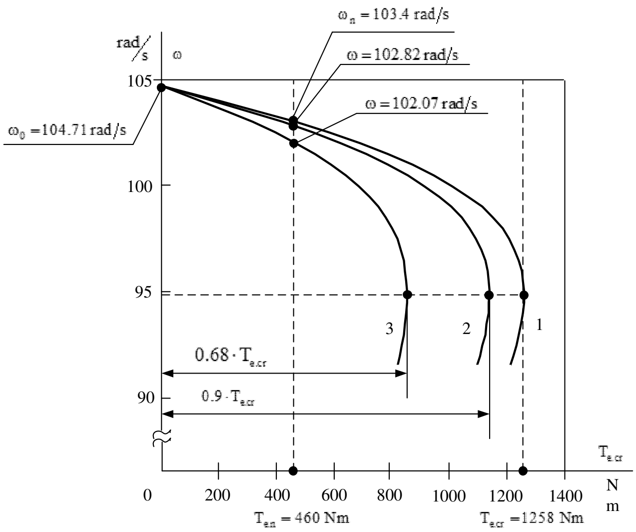

Fig. 5. Limit the mechanical characteristics of the motor AB250S6 with scalar control: 1 - with natural $f_{1n} = 50$ Hz and $U_{1ph.n} = 220$ V; 2 - $f_1 = 50$ Hz and $U_{i.ph.max} = 209.43$ V; 3 - $f_1 = 50$ Hz and $U_{i.ph.max} = 181.37$ V

From the characteristics shown in Fig. 3 and 5, it follows that the inverter control system may be performed based on the PWM sinusoidal superimposed third harmonic and gain *k*=1.1547. But, in this case, when the drive is powered from the mains voltage of $U_n = 380$ V at the output of the inverter does not provide rated motor voltage of $U_{1ph.n} = 220$ V. As a result, the stiffness and critical torque of speed-torque characteristics of the motor are decreases. Motor operates with poor flux and it leads to an increase of stator current at a constant load torque on the shaft [9, 10].

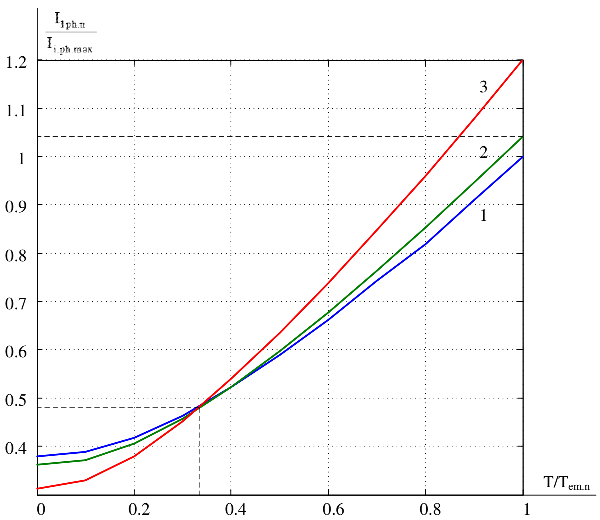

Fig. 6. Characteristics consumed by the motor AB250S6 current at 50 Hz and the maximum value of the phase voltage of the inverter, respectively, equal to: 220 V (1), 209.43 V (2) and 181.37 V (3).

Characteristics consumed by the motor AB250S6 current at 50 Hz and the maximum value of the phase voltage of the inverter, respectively, equal to: 220 V (characteristic 1), 209.43 V (characteristic 2) and 181.37 V (characteristic 3) are shown in Fig. 6. Motor voltage must be maintained equal to the nominal order to reduce the motor current and heat stress at high loads, while the supply voltage must be greater than 380 V. It is advisable to reduce the motor voltage at low loads to reduce the motor current and heat stress, such as by excluding third harmonic of the PWM control signals.

It's necessary to do one of the following conditions to ensure satisfactory speed-torque characteristics of IM variable frequency drive for given values of speed and torque of the static load by sinusoidal PWM control system with additional of the third harmonic:

- Feed the inverter from the power supply voltage $U_n \geq 400$ V, limiting the maximum voltage of the inverter at $U_{i.ph.max} = 220$;

- additionally increase the amplitude of control signals u^*_{1a}, u^*_{1b} and u^*_{1c} in $k_u = (1.1 \div 1.15)$ times, that will lead to deterioration of the harmonic content of the inverter output voltage as noted above;

- Select a motor with a power reserve

$$k_{Pz} \geq \frac{U_{1ph.n}}{U_{i.ph.max}}.$$

that will provide the engine with a weak flux without overheating;

- Limit the maximum frequency control f_1, for example, take the value of $f_{1\,max} = 45$ Hz and set the voltage-frequency characteristic U_1 / f_1 of type 1 (Fig. 7) at the maximum specified voltage

$$U_{1\,max} = \left(\frac{220}{209.3}\right) \cdot 220 \cdot \left(\frac{45}{50}\right) = 208.1 \text{ V}$$

and gain of control signals $k_u = 1$ or type 2 (Fig. 7) at the maximum specified voltage

$$U_{1\,max} = 220 \cdot \left(\frac{45}{50}\right) = 198 \text{ V}$$

and $k_u = \frac{220}{209.3} = 1.051$ that will limit the maximum motor speed at the level $\omega_{эп.макс} \approx 0.9 \cdot \omega_{дв.н}$.

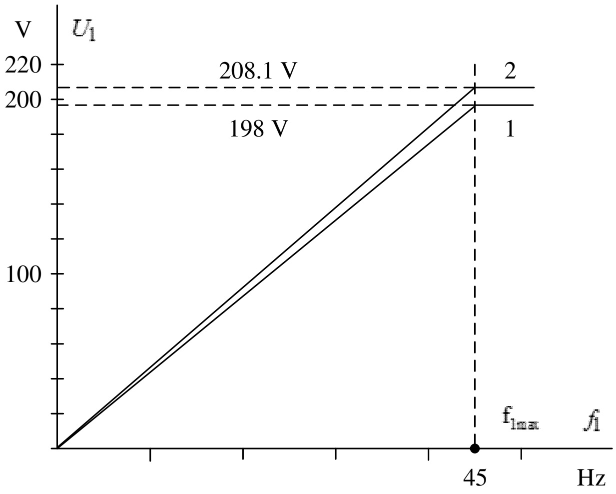

Fig. 7. The voltage-frequency characteristics of the control system by limiting the maximum frequency f_{1ref}

The introduction of the third harmonic in the frequency converter control signals with scalar control causes fluctuations in current, torque and motor speed with the third harmonic frequency [11, 12]. Therefore, the amplitude of the third harmonic is advisable to adjust the values as a function of frequency f_1

$$u_{3f}^* = \frac{1}{6} \cdot u_{1m}^* \cdot \frac{f_{1ref}}{f_{1n}} \cdot \mathrm{Cos}(2\pi \cdot 3 \cdot f_1 \cdot t)$$

III. Features of selection of frequency converter voltage with scalar control and accounting of the PWM inverter output voltage

If the inverter has a sinusoidal PWM inverter system with the additional the third harmonic signal in the control signal and gain control signals $k = 1.1547$ and power supply voltage is selected, then for a given value of the maximum frequency $f_{1max} \le 50$ Hz or speed of electric drive $\omega_{ed.max} \le \omega_{motor.n}$ should be take the maximum value of the output phase voltage inverter:

$$U_{i.ph.max} = 1.05 \cdot U_{1ph.n} \cdot \frac{f_{1max}}{50} \approx 1.05 \cdot U_{1ph.n} \cdot \frac{\omega_{ed.max}}{\omega_{motor.n}} \ \mathrm{V}$$

then the required voltage DC bus of inverter and power voltage supply must satisfy the following conditions:

$$U_d \ge \sqrt{3} \cdot \sqrt{2} \cdot U_{i.ph.max}, \ \mathrm{V};$$

$$U_n \ge \frac{U_d}{1.35}, \ \mathrm{V}.$$

For a given value of the maximum frequency $f_{1max} > 50$ Hz or the speed of the electric $\omega_{ed.max} > \omega_{motor.n}$ (dual-zone electric) is taken

$$U_{i.ph.max} = 1.05 \cdot U_{1ph.n}, \ \mathrm{V}$$

With a known voltage of power voltage supply and voltage of DC bus inverter and the maximum value of the inverter output voltage, respectively, are:

$$U_d = 1.35 \cdot U_c, \ \mathrm{V};$$

$$U_{i.ph.max} = \frac{U_d}{\sqrt{3} \cdot \sqrt{2}}. \ \mathrm{V}.$$

In this case, the maximum speed of the electric drive when the motor work with a nominal flux will be limited to

$$\omega_{ed.max} \approx \omega_{motor.n} \cdot \frac{1}{1.05} \cdot \frac{U_{i.ph.max}}{U_{1ph\,n}} \ \mathrm{rad/s}$$

It should be kept in mind that the actual value of the maximum output voltage of the inverter depends on the voltage and the motor load:

$$U_{i.ph.max} = (1.41 \div 1.35) \cdot \frac{(0.85 \div 1.1) \cdot U_n}{\sqrt{3} \cdot \sqrt{2}}$$

If $U_{i.ph.max} > 1.05 \cdot U_{1ph\,n}$, then it should be limited to the level $U_{i.ph.max} = 1.05 \cdot U_{1ph.n}$, reducing the amplitude of the control signals as a function of the inverter DC bus voltage U_d in accordance with the condition (1).

Conclusions

1. It has been established that the inverter drive control system may be configured based on the PWM sinusoidal superimposed third harmonic.
2. Introduction of the third harmonic into the inverter control signals to the drive in scalar control causes fluctuations in the motor current, torque and speed to the third harmonic frequency. Therefore, the amplitude of the third harmonic is advisable to adjust the values as a function of frequency.
3. Primarily it should strive to provide the nominal values of linkages motor when working with the specified maximum speed when selecting the voltage of power voltage supply of IM electric drive with scalar control.
4. Motor voltage must be maintained equal to the nominal order to reduce the motor current and heat stress at high loads at the same supply voltage must be greater than 380 V. motor motor voltage appropriate to reduce for small loads for normal thermal state, for example, by excluding the third harmonic of a PWM control signals.

References

[1] Braslavsky I.Ys. Energy-efficient induction motor electric drive: Textbook for students of higher educational institutions. Moscow, «Akademia» Publ., 2004. 256 p.

[2] Brodovsky V.N., Ivanov E.S. Drives with frequency-current control. Moscow, Energy Publ., 1974. 168 p.

[3] Vector control of induction motor electric drive. Novosibirsk, NGTU Publ., 1999. 66 p.

[4] Pankratov V.V., Nos O.V. Optimization of dynamic modes in induction motor electric drive with the limitations. Electro mechanic. no. 4 (1999): 48-53.

[5] Pankratov V.V., Zima E.A. Energy optimal vector control of induction motor electric drive: Textbooks. Novosibirsk, NGTU Publ., 2005. 120 p.

[6] Polyakov V.N., Taran A.A., Shrajner P.T. Algorithm for the numerical solution of the problem of extreme control of induction motor electric drive with restrictions on current and voltage. Electro mechanic. no. 11 (2001): 45-48.

[7] Haritonov S.A., Berestov V.M. Analysis of sinusoidal PWM with natural sample (methodical aspect)// Technical electrodynamics. Special Issue: Power Electronics and energy efficiency. Part 2. Kiev, 2002: 31-37.

[8] Rudakov V.V., Stolyarov I.I., Dartau V.A. Induction motor electric drive with vector control. Leningrad. Energoatomizdat Publ., 1987. 136 p.

[9] Sandler A.S., Sarbatov R.S. Automatic frequency control of induction motors. Moscow, Energy Publ., 1974. 328 p.

[10] Sokolovskij G.G. AC drives with frequency control: Textbook for students of higher educational institutions«Akademia» Publ., 2006. 272 p.

[11] Shrejner R.T. Mathematical modeling of AC drives with solid-state frequency converters. Ekaterinburg. URO RAN Publ., 2000. 654 p.

[12] Blaschke F. Das Prinzip der feldorientierung die Grundlage fur die Transvektor – Regelung von Drehfeldmaschinen.//Siemens Zeitschrift, 1971/Bd.45, – H.10. – S. 757-760.