

## The Study Methods of Increase Efficiency Algorithms Pulse width Modulation in AC Electric Drives

**Bogdan Y. Vasilev**

Electromechanical department, Saint-Petersburg Mining University, Russia

---

### Article Info

#### Article history:

Received May 22, 2016

Revised Aug 25, 2016

Accepted Sep 09, 2016

---

#### Keyword:

Converter

Electric drive

Electromagnetic compatibility

Induction motor

Pulse-width modulation

---

### ABSTRACT

In the paper describes the AC electric drive, which consists of the induction motor and the semiconductor converter. Structure of the frequency converter, which includes a three-phase bridge inverter on based fully controlled transistors, is considered. The algorithm of pulse width modulation, which used in the majority of the electric drives, is discussed. The characteristics and shortcomings of the algorithm is shows. Algorithmically methods to improve the efficiency of the inverter-promodulation control signal. The efficiency of this method in different variations is given. The level electromagnetic compatibility inverter and efficiency various control algorithms are analyzed. The conclusions about feasibility of using the method promodulation.

*Copyright © 2016 Institute of Advanced Engineering and Science.  
All rights reserved.*

---

### Corresponding Author:

Bogdan Y. Vasilev,  
Electromechanical department,  
Saint-Petersburg Mining University,  
2, 21st Line, St Petersburg-199106, Russia.  
Email: vasilev.bu@yandex.ru

---

## 1. INTRODUCTION

Present automatic electrical drives, which used in industrial machines, mechanisms and technologies, usually, consisted from semiconductor inverters and induction motors. The frequency converter electrical drives, power not exceeding 1000 kW, usually, based on two-section scheme and consisted from uncontrolled diode rectifier (or active front end rectifier) and fully controlled transistor inverter [1-10]. The effective operation of the induction motor (to be exact, level of electromagnetic compatibility frequency converter with induction motor and power characteristics electrical drive) determined by method of forming output voltage of inverter, in many. Different control algorithms inverter provides a different levels, in particular, the parameters likes of total harmonic distortion of current and voltage in output of inverter, power factor, utilization factor voltage inverter, etc [11-16]. That is why, the question of development different control algorithms for frequency converters (inverters) and the study of their efficiency, currently, is highly relevant.

## 2. BLOCK SCHEME ELECTRICAL DRIVE WITH INDUCTION MOTOR AND INVERTER

The scheme electrical drive, where control induction motion is carried out using three-phase two-level inverter, is shown in Figure 1. The inverter is made by three-phase bridge circuit and is based on fully controlled insulated-gate bipolar transistors, which are designated by VT1, VT2, VT3, VT4, VT5, VT6 in Figure 1. The diodes are included in the reverse direction to the transistors and are designated by VD1, VD2, VD3, VD4, VD5, VD6 in Figure 1. The combinations of transistors and diodes are designated by semiconductor modules M1, M2, M3, M4, M5, M6 in Figure 1.

The filter consisting from two capacitors – C, between which DC voltage ( $U_{dc}$ ) is distributed uniform, installed on input of the inverter. Using two equal capacitors on input of the inverter is necessary for measuring the signal zero-sequence. This signal can be measured between zero point DC-link (point «0» between the capacitors) and point of connection the stator windings of the induction motor (point «N»).

The following assumptions have been made for study of working modes the inverter electrical drive with induction motor and efficiency control algorithms inverter:

- semiconductor switches inverter (diodes and transistors) are ideal switch;
- semiconductor transistors are considered as fully controlled keys with two-way conductivity;
- time setting semiconductor switches is zero;
- input DC voltage is constant.

Stator winding the induction motor are presented in form of active-inductive load, which is installed on output of the inverter: phase «A» stator winding – resistance  $R_A$  and inductance –  $L_A$ ; for phases stator windings «B» and «C» – resistance  $R_B$ , inductance –  $L_B$  and resistance  $R_C$  and inductance –  $L_C$ , respectively.

The stator winding induction motor can be replaced by active-inductive load, if we make the following assumptions in the mathematical description of the induction motor:

- Phase winding motor are symmetric and rated on  $120^\circ$ ;
- Electric loss in steel are not available;
- Stator-to-rotor gap is constant;
- Magnetic system the drive is not saturated.

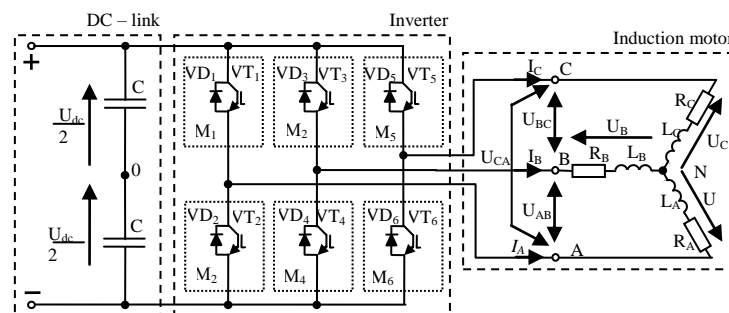


Figure 1. Scheme of the system «inverter - induction motor»

Also, in Figure 1, following designators are made:  $U_{AB}$   $U_{BC}$   $U_{CA}$  – line-to-line voltage on output of the inverter (on stator windings of induction motor);  $U_A$ ,  $U_B$ ,  $U_C$  – line-to-earth voltage on output of the inverter (on stator windings of induction motor).

### 3. CONTROL SYSTEM INVERTER ON BASED THE ALGORITHM PULSE-WIDTH MODULATION (PWM)

For converting direct voltage to alternating voltage, forming specified amplitude and frequency of the alternating voltage and controlling semiconductor switches inverter electrical drive are widely used control algorithms pulse-width modulation (PWM).

The inverter assembled on the three-phase bridge, may be in the eight working conditions. Three semiconductor switches may be in closed condition in each working conditions of the inverter, alone from each complementary pairs (stand of the inverter) and different group switches (cathode or anode group). Connection scheme stator winding induction drive to direct current bus with help of the inverter is shown in Figure 2. When all semiconductor switches cathode or anode group turn on, then voltage is zero in output of the inverter.

Two switches one stand of the inverter close inadmissible because this will lead to short circuit the source direct voltage. Combinations from two switches other stand are using for transition from one working condition to another condition. Defined output voltage vector is formed in compliance with the working conditions of the inverter. Eight vectors of output voltage of the inverter that corresponding the working conditions of the inverter and hodograph vector of output voltage of the inverter are shown in Figure 3. Conditions semiconductor switches of the inverter that corresponding all vectors of output voltage are presented in Table 1 (sign « + » – corresponding include state the transistor of inverter, sign « - » –

corresponding exclude). Values of line-to-line voltage and line-to-ground voltage in output of the inverter are presented in Table 2.

Table 1. Combinations Semiconductor Switches Inverter in Working Conditions

Switches Inverter	Vectors Voltage in Output Inverter							
	U <sub>0</sub>	U <sub>1</sub>	U <sub>2</sub>	U <sub>3</sub>	U <sub>4</sub>	U <sub>5</sub>	U <sub>6</sub>	U <sub>7</sub>
VT <sub>1</sub>	-	+	+	-	-	-	+	+
VT <sub>2</sub>	+	-	-	+	+	+	-	-
VT <sub>3</sub>	-	-	+	+	+	-	-	+
VT <sub>4</sub>	+	+	-	-	-	+	+	-
VT <sub>5</sub>	-	-	-	-	+	+	+	+
VT <sub>6</sub>	+	+	+	+	-	-	-	-

Table 2. Values Voltage in Output of the Inverter

Number Scheme	Vectors Voltage	Voltage in Output of the Inverter							
		Line-to-Line			Line-to-Ground				
		U <sub>AB</sub>	U <sub>BC</sub>	U <sub>CA</sub>	U <sub>A</sub>	U <sub>B</sub>	U <sub>C</sub>		
0	U <sub>0</sub>	0	0	0	0	0	0	0	
1	U <sub>1</sub>	U <sub>dc</sub>	U <sub>dc</sub>	U <sub>dc</sub>	$\frac{1}{3} U_{dc}$	$\frac{-2}{3} U_{dc}$	U <sub>dc</sub>	$\frac{1}{3} U_{dc}$	U <sub>dc</sub>
2	U <sub>2</sub>	U <sub>dc</sub>	U <sub>dc</sub>	U <sub>dc</sub>	$\frac{2}{3} U_{dc}$	$\frac{-1}{3} U_{dc}$	U <sub>dc</sub>	$\frac{-1}{3} U_{dc}$	U <sub>dc</sub>
3	U <sub>3</sub>	U <sub>dc</sub>	U <sub>dc</sub>	U <sub>dc</sub>	$\frac{1}{3} U_{dc}$	$\frac{1}{3} U_{dc}$	U <sub>dc</sub>	$\frac{2}{3} U_{dc}$	U <sub>dc</sub>
4	U <sub>4</sub>	U <sub>dc</sub>	U <sub>dc</sub>	U <sub>dc</sub>	$\frac{-1}{3} U_{dc}$	$\frac{2}{3} U_{dc}$	U <sub>dc</sub>	$\frac{-1}{3} U_{dc}$	U <sub>dc</sub>
5	U <sub>5</sub>	U <sub>dc</sub>	U <sub>dc</sub>	U <sub>dc</sub>	$\frac{-2}{3} U_{dc}$	$\frac{1}{3} U_{dc}$	U <sub>dc</sub>	$\frac{1}{3} U_{dc}$	U <sub>dc</sub>
6	U <sub>6</sub>	U <sub>dc</sub>	U <sub>dc</sub>	U <sub>dc</sub>	$\frac{-1}{3} U_{dc}$	$\frac{-1}{3} U_{dc}$	U <sub>dc</sub>	$\frac{2}{3} U_{dc}$	U <sub>dc</sub>
7	U <sub>7</sub>	0	0	0	0	0	0	0	

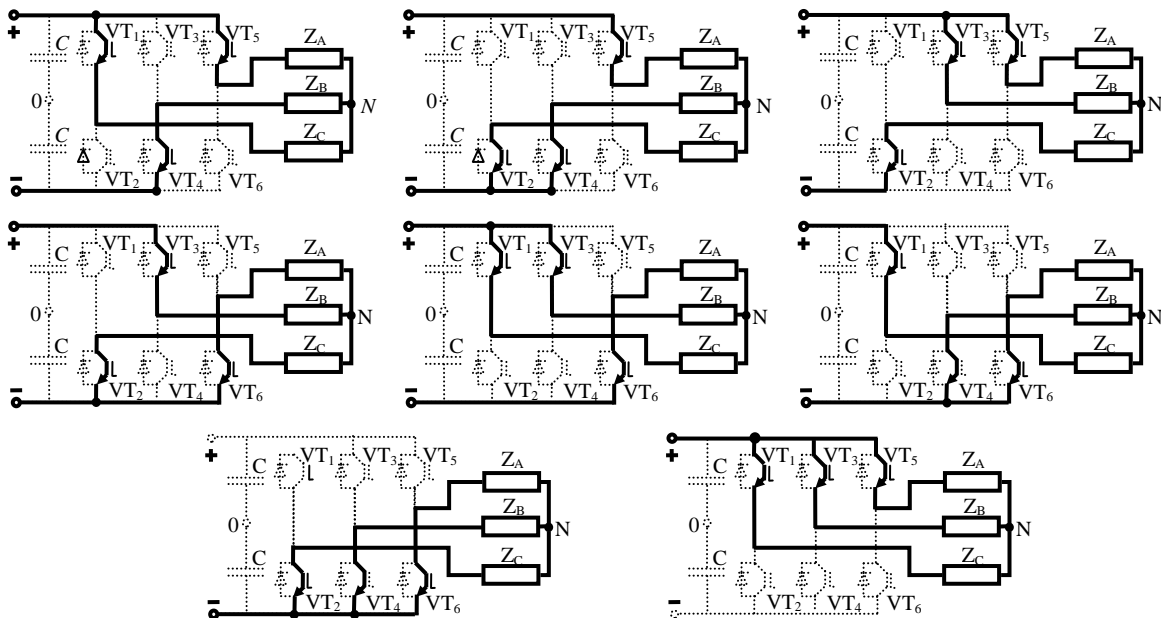


Figure 2. Connection Scheme Stator Winding Induction Drive to Direct Current Bus with Help of the Inverter

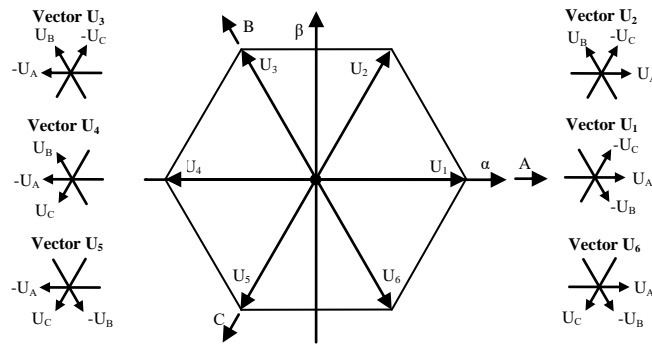


Figure 3. Hodograph vector of output voltage of the inverter

The algorithm PWM widely used to control semiconductor switches inverter and forming alternating voltage with a specified amplitude and frequency. Block scheme of the PWM is shown in Figure 4. A principle of the algorithm PWM is based on a comparison of the control signal ( $U_{Aa}$ ,  $U_{Bb}$ ,  $U_{Cc}$ ) and carrier signal ( $U_s$ ). At time when the reference signals are equal control pulse formed and fed to the corresponding transistor of the inverter. If control signal is sinusoidal waveform, to waveform voltage in output of the inverter (average values voltage on period modulation) change on sinusoidal law. This algorithm is called sinusoidal PWM. The process formation alternating output voltage of the inverter is shown in Figure 5 and Block scheme the algorithm of control PWM with promodulation is shown in Figure 6.

For example, at time 0.75 sec on output of the inverter vector voltage  $U_4$  is formed, scheme connection of the inverter corresponds to the fourth scheme, is shown in Figure 2. Line-to-line and line-to-ground voltage at output of the inverter are, accordingly:  $U_{AB}=U_{dc}$ ,  $U_{BC}=U_{dc}$ ,  $U_{CA}=U_{dc}$ ,  $U_A=U_{dc}$ ,  $U_B=U_{dc}$ ,  $U_C=U_{dc}$ . At time 0.5 sec winding phase « A » is disconnected from the bus with direct voltage and direct voltage is evenly distributed between the phases « B » and « C ». The main drawback of the algorithm sinusoidal PWM is low use factor voltage in inverter.

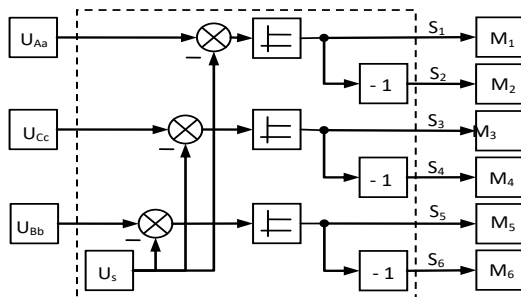


Figure 4. Block Scheme the Algorithm of Control PWM

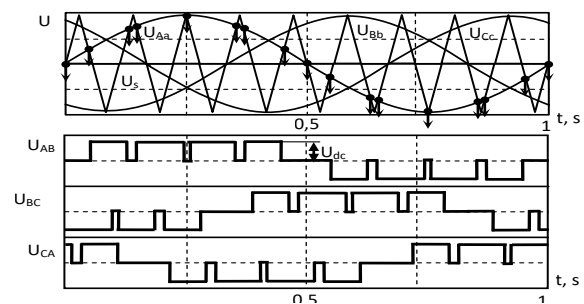


Figure 5. The Process Formation alternating Voltage on Output of the Inverter

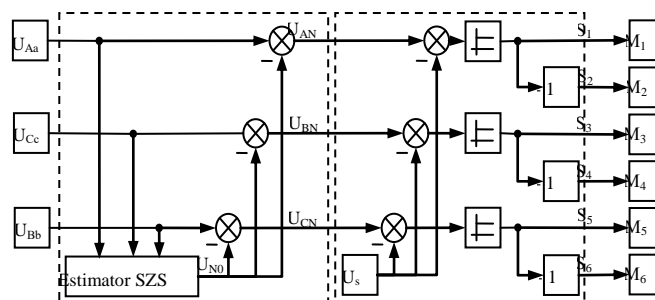


Figure 6. Block Scheme the Algorithm of Control PWM with Promodulation

#### 4. MODIFICATION THE ALGORITHM PWM

For increase amplitude of the output voltage of the inverter with PWM can be using provisional modulation control signal. This operation is called promodulation. For that signal zero-sequence  $U_{N0}$  (SZS) with special form add to the control signal. This signal is called signal promodulation and control algorithm is called «PWM with promodulation».

Block scheme the control algorithm PWM with promodulation is shown in Figure 6. Block «Estimator SZS» calculates required amplitude and frequency signal zero-sequence dependent on amplitude and frequency control signal.

The signals zero-sequence may have different forms. The implementation of control algorithm PWM sinusoidal promodulation third harmonic signal zero sequence is calculated as follows

$$U_{N0} = 0.15 A \sin(3\omega t), \quad (1)$$

where  $A$  is amplitude of the control signal and  $\omega t$  is frequency of the control signal.

When using sinusoidal predmodulyatsii third harmonic the control signal has form, which shown in Figure 7(a). Form signals for control algorithm PWM with triangular promodulation third harmonic are shown in Figure 7(b). When using triangular promodulation signal zero sequence is calculated as follows

$$U_{N0} = 0.25 A \arcsin[\sin(3\omega t)]. \quad (2)$$

In Figure 7(a) and (b), following designators are made:  $U_{AN}$   $U_{BN}$   $U_{CN}$  – the resulting control signal. Using different forms signal zero sequence provided different levels of electromagnetic compatibility inverter with load that in this case induction motion.

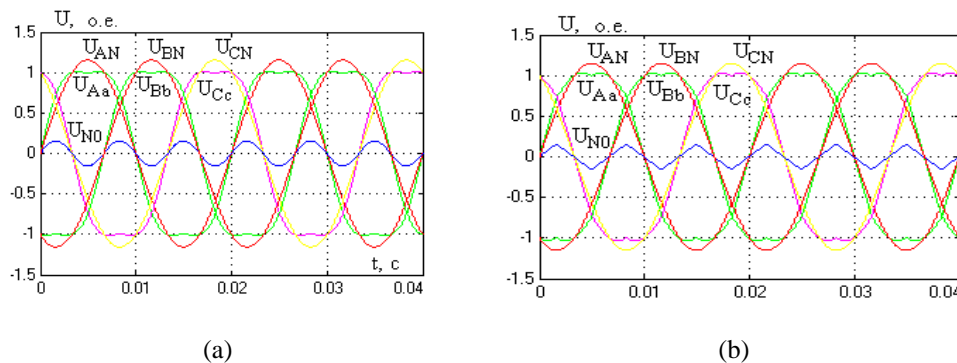


Figure 7. Form signal control algorithm PWMwith promodulation

#### 5. THE STUDY CONTROL ALGORITHMS INVERTER AND ANALYSIS OF THE RESULTS

Forms currents and first harmonics voltage at output of the inverter with sinusoidal PWM, PWM sinusoidal promodulation third harmonic and PWM triangular promodulation third harmonic are shown in Figure 8(a)-(c), respectively. The given curves was obtained with factor modulation  $KM=1$  and frequency carrier signal  $f_s=1000$  Hz.

Diagrams of relationships of the total harmonic distortion factor of current at output of the inverter on values the factor modulation at different frequencies carrier signal are shown in Figure 9. In Figure 8(a) – inverter with sinusoidal PWM; in Figure 8(b) – inverter with PWM sinusoidal promodulation third harmonic; in Figure 8(b) – inverter with PWM triangular promodulation third harmonic.

Diagrams of relationships of the power factor on the frequency carrier signal at different values the factor modulation are shown in Figure 10. In Figure 9(a) – inverter with sinusoidal PWM; in Figure 9(b) – inverter with PWM sinusoidal promodulation third harmonic; in Figure 9(b) – inverter with PWM triangular promodulation third harmonic.

Minimum distortion of the current curve in entire range of variation modulation factor ( $THDI \approx 0$ ) is provided with used the sinusoidal PWM when frequency carrier signal  $f = 10$  kHz. When the frequency of carrier signal is 1000 Hz and the modulation factor is 1 to total harmonic distortion factor of current is 5.5 %.

When used PWM sinusoidal promodulation third harmonic on the frequency carrier signal  $f_s=10$  kHz is provided the minimum value of total harmonic distortion factor of current is about 7.5 %. When

the frequency of carrier signal is 1000 Hz and the modulation factor is 1 to total harmonic distortion factor of current is 9.5 %.

Total harmonic distortion factor of current with used PWM triangular promodulation third harmonic is largest values from three methods of controlling inverter and is 13 % at the frequency carrier signal is 1000 Hz and modulation factor is 1. When increasing the value frequency carrier signal to 10 kHz and modulation factor to 1.15 then total harmonic distortion factor of current is 10 %.

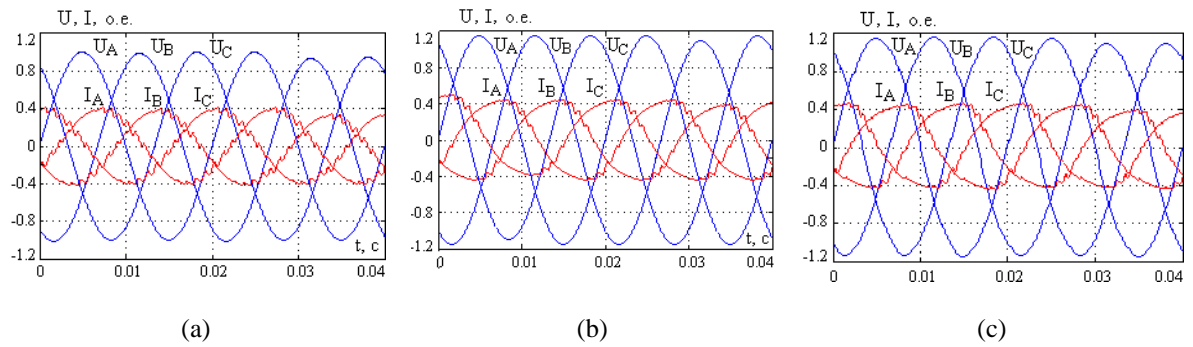


Figure 8. The first harmonic voltage and current at output of the inverter with different control

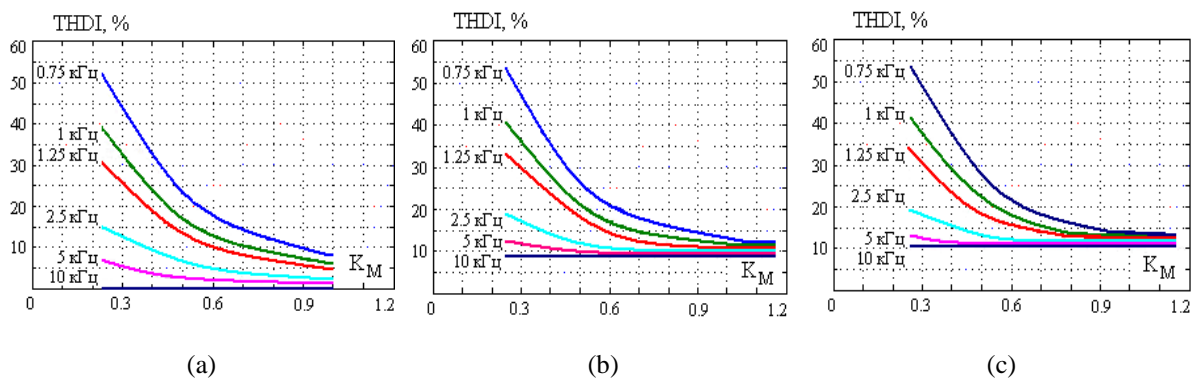


Figure 9. Diagrams of relationships of the total harmonic distortion factor of current on values the factor modulation at different frequencies carrier signal

From Figure 9 shows that increase power factor occurs when increase carrier signal that typical for all methods controlled of the inverter. When PWM with promodulation and modulation factor is 1.15 to at high frequencies carrier signal power factor is 0.7. The maximum possible value power factor is 0.7864.

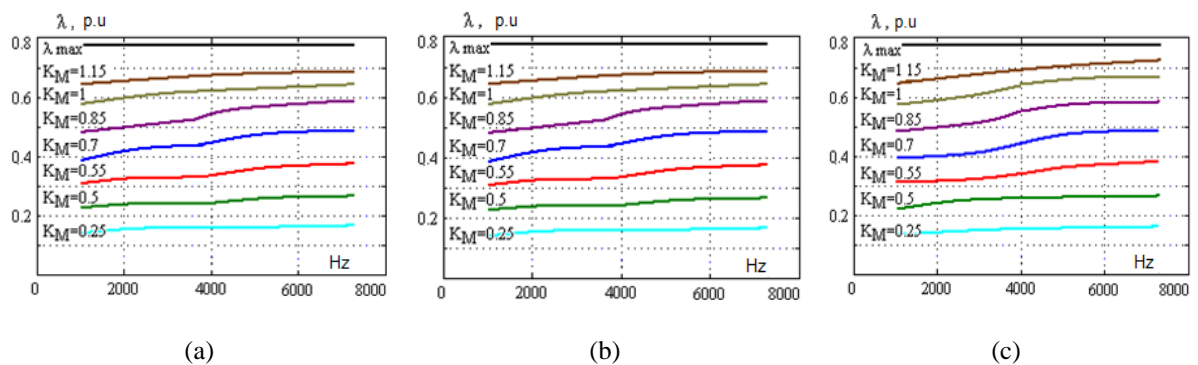


Figure 10. Diagrams of relationships of the power factor on the frequency carrier signal at different values the factor modulation

## 6. CONCLUSION

This paper has reviewed control methods semiconductor switches of the inverter:

- a. sinusoidal PWM;
- b. PWM with sinusoidal promodulation third harmonic;
- c. PWM with triangular promodulation third harmonic.

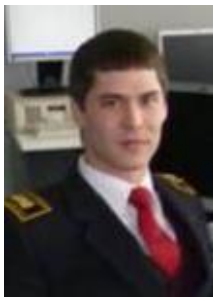
It is shown that use the control algorithm PWM promodulation (sinusoidal or triangular) can increase the amplitude voltage at output of the inverter on 15 %. However, in this increasing the total harmonic distortion factor of current at output of the inverter.

When selected the control algorithm of the inverter appropriate to give the preference the system PWM with sinusoidal promodulation third harmonic. Main disadvantages are related with increased value of the total harmonic distortion factor may be removed by decreasing the switching frequency (frequency carrier signal).

## REFERENCES

- [1] Schreiner R, Kalygin A, Krivovoyaz A. AC drives based on direct frequency converters with PWM.: *Ural Branch of RAS*, 2012.
- [2] Kozyaruk A. Direct torque control in AC drive machinery mining industry. *Saint Petersburg Mining Institute*, 2008.
- [3] Pronin M, Vorontsov A. Powerfully controllable semiconductor converters (modeling and calculation). *Electric power*, 2003.
- [4] Usoltsev A. Frequency control of induction motors. *ITMO University*, 2006.
- [5] Vinogradov A., Vector control of electric AC drive. *Ivanovo State University Power Energy*, 2008.
- [6] Vasiliev B., Automated electric drive objects mineral resource complex (application, modeling, research). *National university of mineral resources «Mining institute»*, 2014.
- [7] Sozanski K. Digital Signal Processing in Power Electronics Control Circuits. *Springer*, 2013.
- [8] Bose K. Modern Power Electronics and AC Drives. *Prentice Hall*, 2002.
- [9] Doncker R, Pulle W, Veltman A. Advanced electrical drives: analysis, modeling, control: *Springer*. 2011.
- [10] Rodriguez J, Cortes P, Predictive Control of Power Converters and Electrical Drives. *John & Sons*. 2012.
- [11] Peter A. Motion Control in Offshore and Dredging. *Springer*, 2010.
- [12] Holmes D, Lipo T. Pulse width modulation for power converters: principles and practice. *IEEE Press*. 2003.
- [13] Hariram B, Marimuthu N. Space vector switching patterns for different applications a comparative analysis. *Proceedings of the IEEE International Conference on Industrial Technology*. 2005, pp. 1444-1449
- [14] Narayanan G, Ranganathan V. Synchronised PWM strategies based on space vector approach. Part 1: Principles of waveform generation. *IEE Proceedings on Electric Power Applications*. 1999; 146(3): 267-275.
- [15] Akkarapaka A, Dheerendra S. International. Digital Implementation of DSVPWM Control for EV fed through Impedance Source Inverter. *Journal of Power Electronics and Drive System*. 2015; 6 (3): 477 – 485.
- [16] Jamuna V, Gayathri J. Monicka. Multi Carrier based Multilevel Inverter with Minimal Harmonic Distortion. *International Journal of Power Electronics and Drive System*. 2015; 6 (2): 356 – 361.

## BIOGRAPHY OF AUTHOR



Graduated from Uchtincskiy technical university in 2010. Received P.H.D. degree in National Mineral Resources University in 2013. He is assistant professor in electrical energy and electromechanics department since 2013. His research interest includes electromagnetic compatibility providing, electrotechnical systems for energy industry