VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

Vytautas BLEIZGYS

RESEARCH AND APPLICATION OF INVERTER CONTROLLED USING SPACE VECTOR MODULATION PRINCIPLE

SUMMARY OF DOCTORAL DISSERTATION

TECHNOLOGICAL SCIENCES,
ELECTRICAL AND ELECTRONIC ENGINEERING (01T)

Vilnius LEIDYKLA TECHNIKA 2012

Doctoral dissertation was prepared at Vilnius Gediminas Technical University in 2008–2012.

Scientific Supervisor

Prof Dr Algirdas BAŠKYS (Vilnius Gediminas Technical University, Technological Sciences, Electrical and Electronic Engineering – 01T).

The dissertation is being defended at the Council of Scientific Field of Electrical and Electronic Engineering at Vilnius Gediminas Technical University:

Chairman

Prof Dr Habil Romanas MARTAVIČIUS (Vilnius Gediminas Technical University, Technological Sciences, Electrical and Electronic Engineering – 01T).

Members:

Prof Dr Habil Gintautas DZEMYDA (Vilnius University, Technological Sciences, Informatics Engineering – 07T),

Prof Dr Habil Vilius Antanas GELEŽEVIČIUS (Kaunas University of Technology, Technological Sciences, Electrical and Electronic Engineering – 01T),

Prof Dr Habil Roma RINKEVIČIENĖ (Vilnius Gediminas Technical University, Technological Sciences, Electrical and Electronic Engineering – 01T),

Dr Rimantas SIMNIŠKIS (State Research Institute Center for Physical Sciences and Technology, Physical Sciences, Physics – 02P).

Opponents:

Prof Dr Habil Steponas GEČYS (Kaunas University of Technology, Technological Sciences, Electrical and Electronic Engineering – 01T),

Prof Dr Habil Romualdas NAVICKAS (Vilnius Gediminas Technical University, Technological Sciences, Electrical and Electronic Engineering – 01T).

The dissertation will be defended at the public meeting of the Council of Scientific Field of Electrical and Electronic Engineering in the Senate Hall of Vilnius Gediminas Technical University at 10 a. m. on 11 June 2012.

Address: Saulėtekio al. 11, LT-10223 Vilnius, Lithuania.
Tel.: +370 5 274 4952, +370 5 274 4956; fax +370 5 270 0112;
e-mail: doktor@vgtu.lt

The summary of the doctoral dissertation was distributed on 10 May 2012.

A copy of the doctoral dissertation is available for review at the Library of Vilnius Gediminas Technical University (Saulėtekio al. 14, LT-10223 Vilnius, Lithuania).

© Vytautas Bleizgys, 2012

VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

Vytautas BLEIZGYS

ERDVINIO VEKTORIAUS MODULIAVIMO PRINCIPU VALDOMO INVERTERIO TYRIMAS IR TAIKYMAS

DAKTARO DISERTACIJOS SANTRAUKA

TECHNOLOGIJOS MOKSLAI,
ELEKTROS IR ELEKTRONIKOS INŽINERIJA (01T)

Vilnius LEIDYKLA TECHNIKA 2012

Disertacija rengta 2008–2012 metais Vilniaus Gedimino technikos universitete.
Mokslinis vadovas
prof. dr. Algirdas BAŠKYS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, elektros ir elektronikos inžinerija – 01T).
Disertacija ginama Vilniaus Gedimino technikos universiteto Elektros ir elektronikos inžinerijos mokslo krypties taryboje:
Pirmininkas
prof. habil. dr. Romanas MARTAVIČIUS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, elektros ir elektronikos inžinerija – 01T).
Nariai:
prof. habil. dr. Gintautas DZEMYDA (Vilniaus universitetas, technologijos mokslai, informatikos inžinerija – 07T),
prof. habil. dr. Vilius Antanas GELEŽEVIČIUS (Kauno technologijos universitetas, technologijos mokslai, elektros ir elektronikos inžinerija – 01T),
prof. habil. dr. Roma RINKEVIČIENĖ (Vilniaus Gedimino technikos universitetas, technologijos mokslai, elektros ir elektronikos inžinerija – 01T),
dr. Rimantas SIMNIŠKIS (Valstybinis mokslinių tyrimų institutas Fizinių ir technologijos mokslų centras, fiziniai mokslai, fizika – 02P).
Oponentai:
prof. habil. dr. Steponas GEČYS (Kauno technologijos universitetas, technologijos mokslai, Elektros ir elektronikos inžinerija – 01T),
prof. habil. dr. Romualdas NAVICKAS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, Elektros ir elektronikos inžinerija – 01T).
Disertacija bus ginama viešame Elektros ir elektronikos inžinerijos mokslo krypties tarybos posėdyje 2012 m. birželio 11 d. 10 val. Vilniaus Gedimino technikos universiteto senato posėdžių salėje.
Adresas: Saulėtekio al. 11, LT-10223 Vilnius, Lietuva.
Tel.: (8 5) 274 4952, (8 5) 274 4956; faksas (8 5) 270 0112;
el. paštas: doktor@vgtu.lt
Disertacijos santrauka išsiuntinėta 2012 m. gegužės 10 d.
Disertaciją galima peržiūrėti Vilniaus Gedimino technikos universiteto bibliotekoje (Saulėtekio al. 14, LT-10223 Vilnius, Lietuva).
VGTU leidyklos „Technika“ 2011-M mokslo literatūros knyga.

© Vytautas Bleizgys, 2012

Introduction

Topicality of the Problem

In developed countries 60–70 % of electricity is consumed by the electric motors. About 90 % of all motors used in industry are AC induction motors. The frequency converters, which convert the standard one or three phase AC voltage to variable frequency variable amplitude three-phase AC voltage for motor supply, are used for control of AC induction motor speed and torque. The main functional block of frequency converter is inverter, which develops the AC voltage from the DC voltage. The frequency converter market increases annually by 8.9 % since 2007 and will reach 11 milliard USD in 2012. The market growth is promoted by competitive price, constant technical innovation, penetration into wider range of applications and necessity to save the energy and to control the technologies. Therefore, the research that allows us to develop advanced frequency converters with the reduced power losses in the inverter and in the frequency converter – supplied AC induction motor is topical and has practical value. Directly the topicality of works is proved by the interest of industry in the development of the frequency converters for serial production, which is reflected by the projects, during accomplishment of which the results presented in dissertation were obtained.

Object of Research

The inverter controlled using space vector modulation principle.

The Aim of the Work

The main aim is to perform the research of the inverter controlled using space vector modulation principle and to develop the inverter voltage amplitude control method, which allows reducing the power losses in the inverter and motor.

Tasks of the Work

The following tasks have to be solved to achieve the aim of the work:

1. Investigate the inverter controlled by space vector modulation method with the averaged pulse durations. Compare the obtained results with the results gained using classical space vector modulation method.

2. Find and investigate the inverter voltage first harmonic amplitude dependences on frequency, which correspond to minimal power losses in the AC induction motor.

3. Develop and investigate the inverter voltage first harmonic amplitude control method, which allows us maintaining the minimal current of motor in the situation when motor load changes randomly.

4. Investigate the impact of the IGBT transistor control circuit structure and parameters on the temperature of inverter, develop and analyze the circuit for the dead time introduction in the IGBT transistor-based inverter.

5. Investigate the transitions of overvoltage generated in the inverter during the motor deceleration.

Methods of Research

The experimental and analytical methods were applied in the work. The experimental investigations have been performed using experimental models of inverter and frequency converter test bench. The inverter control algorithms were realized using embedded system based on the digital signal processor, the programs of signal processor were created using C programming language.

Scientific Novelty of Work

The following scientific novelties to the field of Electrical and Electronic Engineering were disclosed:

1. The experimental results, which prove that space vector modulation method with the averaged pulse durations allows us to achieve lower power losses in the inverter and AC induction motor as compared to the case when classical space vector modulation method is used, were obtained.

2. The inverter voltage first harmonic amplitude dependences on frequency, which correspond to minimal power losses in the AC induction motor for the cases when motor load is independent on rotation speed and decreases linearly with the speed, are found. It is shown that the obtained dependencies do not coincide with the now-days recommended to use dependencies based on the linear and square amplitude control laws.

3. The new inverter voltage first harmonic amplitude control method, which allows us maintaining the minimal current of motor in the situation when motor load changes randomly, is developed and investigated.

4. The IGBT transistor control circuit, which introduces the dead time in the IGBT transistor-based inverter, is developed. It allows refusing the dead time realization by the digital signal processor and, as a consequence, lets us to avoid the damage of inverter in case of processor failure.

Practical Value

The results of the dissertation were applied for the development of specialized frequency converters used in the AC induction motor drives of energy saving ventilation and water supply systems. The research was related with the following projects:

Projects financed by industry

1. The development of specialized frequency converter for control of advanced ventilation systems fan motors. 2007–2010, contract No. U-2007/8, head A. Baškys, contracting authority JSC "Ventmatika".
2. The development of frequency converter for advanced water supply systems. 2011–2012, contracts No. 308-S095 and 3400-S155, head A. Baškys, contracting authority JSC "Tamona".

High technology development programme projects

3. The investigation and development of frequency converters and their introduction into the serial production. 2007–2009, contract No. B-13/2007, head A. Baškys, contracting authority Lithuanian State Science and Study Foundation (LVMSF).
4. Development of specialized frequency converter for the serial production. 2012–2013, No. 31V-37, head A. Baškys, contracting authority Agency for Science, Innovation and Technology (MITA).

Defended Propositions

1. The space vector modulation method with the averaged pulse durations as compared to the classical space vector modulation method allows us to reduce the temperature of inverter and AC induction motor by 2–10 ^{o}C and 2–3 ^{o}C, accordingly.
2. The inverter voltage first harmonic amplitude has to be increased by up to 25 % in comparison to this one obtained by linear and square amplitude control laws, to achieve the minimal power losses in the AC induction motor.
3. The inverter voltage first harmonic amplitude control method based on the motor minimal current tracking allows us to maintain the minimal current in the situation when motor load changes randomly.

The Scope of the Scientific Work

The thesis is presented in the Lithuanian language. It consists of introduction, four chapters and the list of 75 references. The thesis comprises 102 pages, 53 figures, 25 formulas and 2 tables.

1. Overview of Inverter Principle and Voltage Forming Methods

The inverter application areas and the principles of the three phase inverter are discussed. The voltage forming methods of inverter, which are used for the control of AC induction motors, are analyzed. The conclusions of the first chapter of dissertation are presented and dissertation tasks are formulated.

Nowadays the Space Vector Modulation (SVM) method is widely used for forming of three-phase voltage in the inverter. The three-leg inverter (Fig. 1a), which forms the three-phase voltage, has six active states called base states in SVM method. The base states are presented by the hexagonal diagram (Fig. 1b). The vector $\mathbf{V}_{\mathbf{ref}}$, which corresponds to the voltage generated by the inverter, is formed by the neighboring base states.

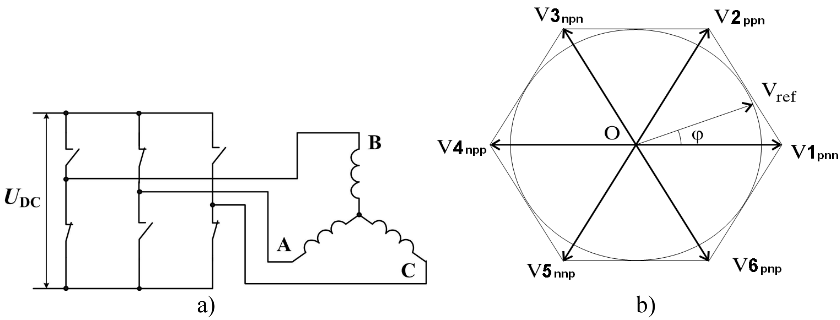

Fig. 1. Inverter with the connected motor (a) and hexagonal diagram, which presents the SVM principle (b)

In the generally used conventional SVM method the durations $T_1(\theta)$ and $T_2(\theta)$, at which the neighboring base states of the inverter are active during the forming of the $\mathbf{V}_{\mathbf{ref}}$, are calculated using well known expressions

$$\begin{aligned} T_1(\theta) &= T_c\ m\ \sin(\pi/3 - \theta), \\ T_2(\theta) &= T_c\ m\ \sin(\theta), \\ T_0(\theta) &= T_c - T_1(\theta) - T_2(\theta), \end{aligned} \quad (1)$$

where θ is the angle of $\mathbf{V}_{\mathbf{ref}}$ relative to the initial point of period and coincides with the φ in Fig.1b, $T_c = 1/f_c$ is the period of the carrier signal, which determines the θ change discreteness $\Delta\theta$, m is modulation coefficient, which determines the amplitude of the first harmonic (A_1) of generated voltage. The frequency of the first harmonic of the voltage formed by the inverter, which determines the rotation speed of the motor, is called phase frequency (f_p).

2. The Investigation of the Inverter Controlled by Space Vector Modulation Method with Averaged Pulse Length

The space vector modulation method with the averaged pulse durations (SVM_{AVER}) is described. The investigation results of power losses in the inverter and AC induction motor are presented. They were obtained for the cases when space vector modulation method with the averaged pulse durations and conventional space vector modulation method are used.

Author published four scientific articles dedicated to the scope of chapter (Baškys *et al* 2008; Baskys *et al* 2009; Baškys *et al* 2009; Baskys *et al* 2010).

The peculiarity of the SVM_{AVER} method as compared to the conventional SVM method is the only fact that activity durations of the neighboring base states are calculated on the basis of trigonometric function integrals

$$
\begin{aligned}
T_1(\theta,\ \Delta\theta) &= (T_c\ m\ /\Delta\theta)\int_{\theta}^{\theta+\Delta\theta}\sin(\pi/3-x)\mathrm{d}x,\\
T_2(\theta,\ \Delta\theta) &= (T_c\ m\ /\Delta\theta)\int_{\theta}^{\theta+\Delta\theta}\sin(x)\mathrm{d}x\ .
\end{aligned}
\qquad (2)
$$

The base state activity periods in this method are fitted not to the initial angle θ, as it is in the conventional SVM based on (1), but to the interval [θ, θ + Δθ]. The investigation shows that using pulses with averaged lengths allows improving the initial part of the voltage spectrum (Fig. 2).

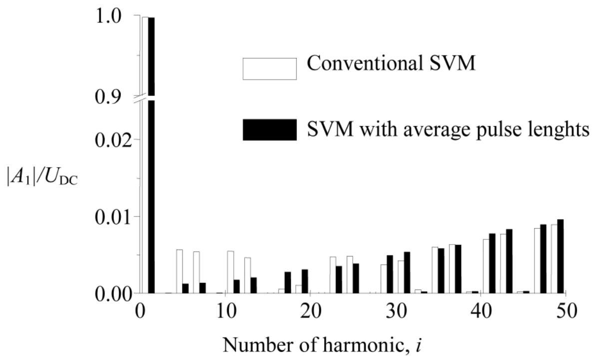

Fig. 2. The spectrum of the voltage generated by SVM with averaged pulse lengths and conventional SVM methods at $f_p = f_{nom}$ = 50 Hz

The investigation of the efficiency of the AC induction motor fed by the inverter, which provides the three-phase AC voltage formed using the SVM_{AVER}

method based on (2), using a conventional SVM method based on (1) and when the motor is fed directly from the electrical net by pure sinus three-phase 400 V, 50 Hz voltage, was performed.

The direct measurement of the motor efficiency is complicated. Therefore, the motor temperature was used as a criterion for the evaluation of efficiency of the AC induction motor in this work. The lower value of the motor temperature at a given rotation speed and motor load torque (M) corresponds to the higher motor efficiency for this concrete motor operating point and vice versa. The transient of motor case temperature in respect of ambient temperature (T_M–T_a) was measured and the steady-state temperature was fixed. Additionally, the amplitude of the motor supply current (I_A), amplitude of the first harmonic (A_1) of generated voltage and rotor sleep (S) were measured. The investigation was performed at f_p = 50 Hz only because of the lack of the pure sinus three-phase AC voltage source with the variable frequency for the motor supply. The energy consumed by the motor and, as a consequence, the absolute energy losses at f_p = 50 Hz should be higher as compared to the lower frequencies, therefore, more accurate analysis results can be obtained. The investigations were performed using 1.5 kW, 1400 rpm AC induction motor at nominal load M = 10 Nm. The frequency converters developed in the Center for Physical Sciences and Technology (CPST) based on the SVM_{AVER} and conventional SVM methods were used. The obtained results were compared with those gained using standard frequency converters 605B (produced by Eurotherm firm) and ACS401 (produced by ABB firm), which are based on the conventional SVM method. The investigation results are presented in Fig. 3.

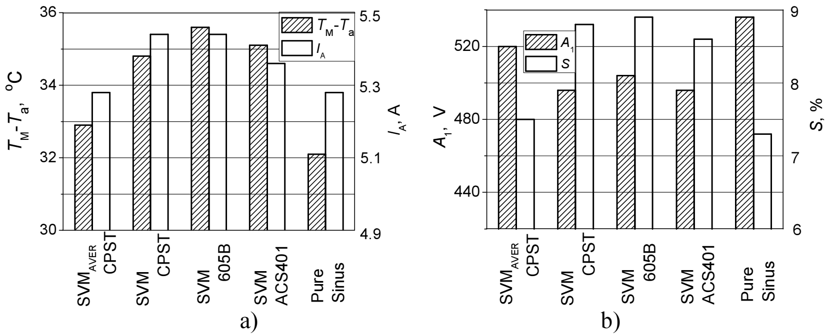

Fig. 3. The AC induction motor case steady-state temperature in respect to ambient temperature (T_M–T_a) (a), the amplitude of the phase current (I_A) (a), the amplitude of the motor line voltage 1st harmonic (A_1) (b) and the rotor slip (S) (b) of the motor fed by the voltage formed using SVM_{AVER} and conventional SVM methods and fed by the pure sinus voltage

The obtained results show (Fig. 3a) that the SVM_{AVER} method provides a lower motor case steady-state temperature and the motor phase current, i.e. a higher motor efficiency as compared to the conventional SVM method. This is caused by lower amplitudes of harmonics in the initial part of the spectrum of voltage formed using the SVM_{AVER} method (Fig. 2).

It is natural that the highest efficiency is guaranteed by the pure sinus supply voltage. However, the steady-state temperature of the case of the motor fed by the pure sinus voltage was only by about 1 ^{o}C lower as compared to the situation when the SVM_{AVER} method-based voltage was used (Fig. 3a). This fact demonstrates that the efficiency of the motor fed by the voltage formed using the SVM_{AVER} method at f_p = 50 Hz is close to that provided by the pure sinus voltage.

The impact of output voltage modulation strategies on power losses in the inverter were investigated experimentally. The direct measurement of inverter power losses is complicated and not accurate; therefore, they were evaluated indirectly by measurement of heat sink temperature. The investigation was performed using 4 kW, 2900 rpm AC induction motor. The temperature of inverter heat sink was analyzed for cases when output voltage was formed using SVM_{AVER} and conventional SVM methods. The investigation results are given in Fig. 4. They present the transients of heat sink temperature T_h in respect to ambient temperature T_a.

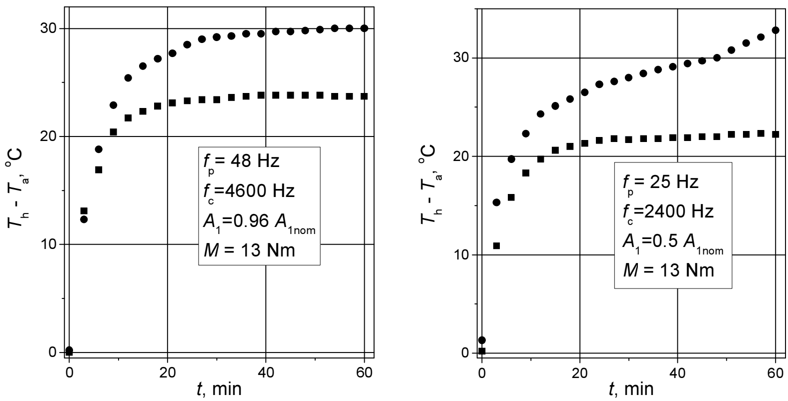

Fig. 4. The transients of inverter heat sink temperature in respect to ambient temperature for case when voltage is formed using SVM_{AVER} (square dots) and conventional SVM method (round dots) at nominal motor load torque for various phase and carrier frequencies and linear control of A_1

It is seen that employment of SVM_{AVER} method allows us to reduce the heat sink temperature (reduce the power losses in inverter), as compared to the case when conventional SVM method is used.

3. Analysis of the Inverter Voltage First Harmonic Amplitude Control Methods

The inverter voltage first harmonic amplitude control problem is analyzed. The investigation has been performed and the inverter voltage first harmonic amplitude dependences on frequency (on motor speed), which correspond to minimal power losses in the AC induction motor, at various motor load torques were found. The inverter voltage first harmonic amplitude control method based on the motor minimal current tracking proposed by the author is described.

Author published two scientific articles dedicated to the scope of chapter (Bleizgys, Baskys 2010; Bleizgys *et al* 2011).

The torque of the motor at given f_p, which sets the motor rotation velocity, is determined by the inverter voltage first harmonic amplitude. The current of motor windings and, as a consequence, the motor torque decreases if f_p increases at the constant voltage amplitude. Therefore, the AC induction motor characteristics require that the amplitude of the applied voltage should be changed proportionally to f_p. One of the main problems in the development of frequency converters is to maintain the required law of voltage amplitude variation. The two main amplitude variation laws are widely propagated: linear $A_1=k_l f_p$ and square $A_1=k_s f_p^2$, where k_l and k_s are proportionality coefficients. It is recommended to use the linear law in the case when the motor is loaded by the torque, which is close to nominal and is independent of the motor rotation velocity (independent of f_p), the square one – in the case when it decreases with f_p.

The investigation has been performed in the range of f_p from 15 Hz to 50 Hz at the nominal 13 Nm motor load and decreased 6.5 Nm, 3.25 Nm loads. The obtained I_A, T_m and calculated S dependences at f_p = 25 Hz and nominal motor load M = 13 Nm are presented in Fig. 5. It is seen that the I_A reaches the minimal value at the motor supply voltage amplitude, which is 24 % higher as compared to that suggested by the linear law.

The dependences of the inverter output voltage first harmonic relative amplitude on f_p for linear and square amplitude variation laws and their comparison with the experimentally obtained dependences for various motor loads that correspond to the maximal efficiency of the motor, at which the motor supply phase current amplitude I_A is minimal, are presented in Fig. 6.

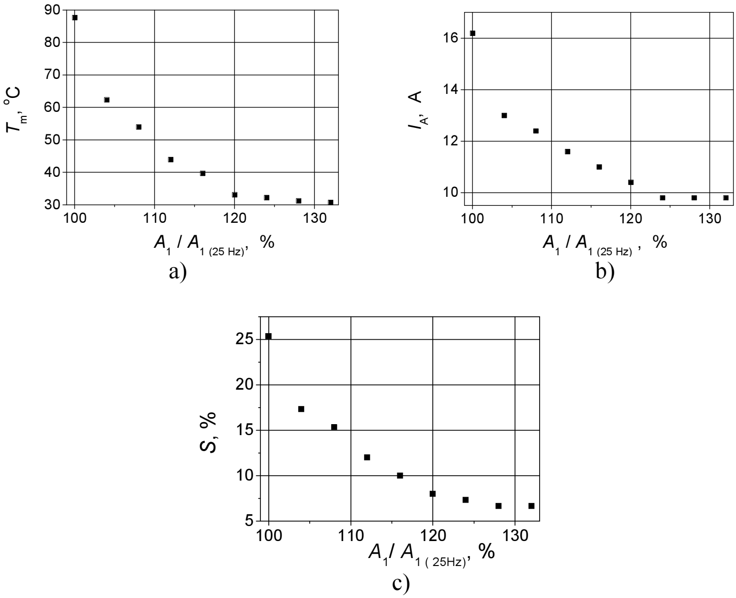

Fig. 5. The dependences of motor temperature (a), motor phase current amplitude (b) and rotor slip (c) on the relative amplitude of the inverter output voltage first harmonic at f_p = 25 Hz and nominal M = 13 Nm motor load torque. The $A_{1\,(25\,Hz)}$ is the amplitude of voltage at 25 Hz for the case of the linear amplitude variation law ($A_{1(25\,Hz)}$ = 0.5 $A_{1\,(50\,Hz)}$, where $A_{1\,(50\,Hz)} \approx$ 560 V is the amplitude of the motor supply voltage at f_p = 50 Hz)

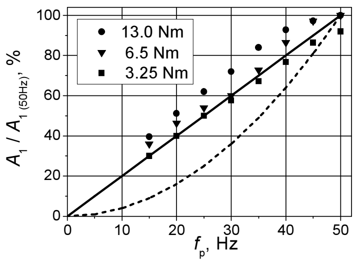

Fig. 6. The dependence of the relative amplitude of the inverter output voltage first harmonic on phase frequency for linear (solid line) and square (dashed line) amplitude variation laws and their comparison with the experimentally obtained dependences for various motor load torques that correspond to the maximal efficiency of the motor, at which the motor case temperature and phase current amplitude are minimal. The $A_{1\,(50\,Hz)}$ is the amplitude of the motor supply voltage at f_p = 50 Hz

The AC induction motor supply voltage amplitude linear and square variation laws used in the variable speed drives based on the frequency converters do not provide the best efficiency of the motor. The employment of the obtained corrected motor supply voltage amplitude variation dependences for different motor load torque allows us maintaining the high efficiency of the investigated standard AC motor supplied by the frequency converter.

The inverter voltage first harmonic amplitude (A_1) control method based on the motor minimal current tracking was created. The purpose of the A_1 control is to keep the A_1 value, at which the efficiency of the motor is close to maximal, i.e., at which the I_A would be close to minimal. The results obtained during the experimental investigation show that I_A depends strongly on motor load at given speed and has the only minimum. The single variable optimization problem should be solved continuously in the real time for the tracing of I_A minimum. The algorithm for estimation of I_A minimum used in proposed A_1 control method is shown in Fig. 7.

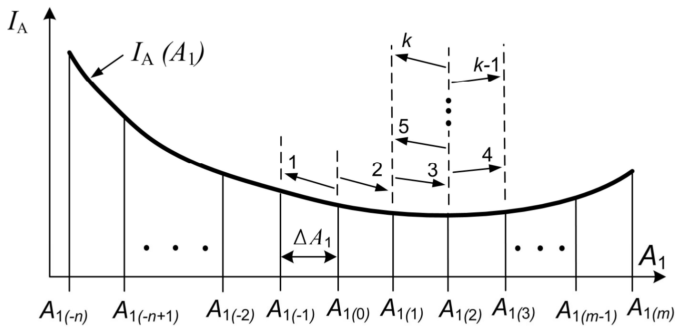

Fig. 7. The algorithm of motor phase current amplitude minimum tracing

The width of zone $\Delta A_1 = 0.03A_{1(0)}$ was chosen for the realization of the algorithm. The discrete change of A_1 values and measurement of I_A was provided every 0.5 s during the function $I_A(A_1)$ minimum search in the real application.

The proposed inverter output voltage first harmonic amplitude control method, which is some alternative for the vector control, allows us to vary the amplitude automatically in such a way that the efficiency of the motor at given motor load torque and rotation speed would be maximal. The realization of the method is simpler and cheaper as compared to the vector control methods.

4. Investigation of the Transistor Control Circuit Impact on Power Losses and Analysis of Overvoltage in the Inverter

The control problem of the IGBT (Insulated Gate Bipolar Transistor) transistors, which are used as switches in the inverters for control of AC induction motors, is analyzed. The developed IGBT transistor control circuit that introduces the dead time in the IGBT transistor-based inverter and allows increasing the reliability of inverter operation is described. The affect of IGBT transistor control circuit structure and parameters on the transistor dynamics and power losses in the inverter is investigated. The inverter overvoltages generated during the motor deceleration are analyzed.

Author published three scientific articles dedicated to the scope of chapter (Baskys *et al* 2009; Bleizgys, Platakis 2010; Baskys *et al* 2011).

The developed IGBT transistor control circuit, which introduces the dead time, is presented in Fig. 8. The dead time is realized by the part of circuit, which includes transistor TR1, resistor R3 and capacitor C1. Developed control circuit introduces IGBT transistor switch on delay, without delaying the transistor switch off.

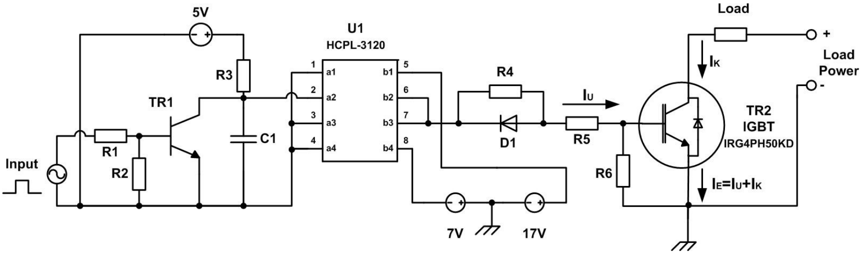

Fig. 8. The diagram of IGBT transistor control circuit with the switch on delay

The proposed realization of the dead time for the inverter switches in the IGBT transistor control circuit has substantial advantage against the dead time realization by the digital signal processor because lets us to avoid the damage of inverter in case of processor failure.

The impact of IGBT transistor control circuit parameters on the rise and fall time of the collector current and collector-emitter voltage was investigated. The influence of transistor control circuit parameters on heating of IGBT transistors was analyzed as well. The investigation has been performed at various resistances of resistor R5 in the cases when circuit, which contains D1 and R4, was shorted or not.

The temperature of IGBT transistor module has increased by 1 °C when resistance of R5 (Fig. 8), which determines the switching speed of IGBT transistor, was changed from 18 to 82 Ω. This fact shows that the switching losses in the IGBT transistors are lower than conducting losses.

If the AC induction motor rotation velocity during the deceleration exceeds the synchronous velocity, it starts to operate as a generator delivering current back into the DC bus of the inverter through the transistors, which operate as switches of the inverter. Therefore, the capacitors of the DC bus are charged and voltage of the DC bus increases. The maximal voltage value (overvoltage) depends on the motor deceleration rate, motor load and its inertness, capacitance of the DC bus capacitors and initial rotation velocity of the motor (rotation velocity, at which the deceleration starts). If the overvoltage of the DC bus exceeds the safe operation limits, the transistors of inverter switches, DC bus capacitors and other components used in the inverter can be damaged. There are lots of works dedicated to the investigation of the overvoltage in the inverter using simulation. However, during the frequency converter development process it is important to have accurate data, which can be obtained only experimentally. They are needed for the development of the overvoltage fault protection of the inverter.

The examples of the transients of the inverter DC bus voltage (U_{DC}), motor load torque (M) and motor speed (V_r) for the case when the overvoltage fault protection is not triggered are presented in Fig. 9.

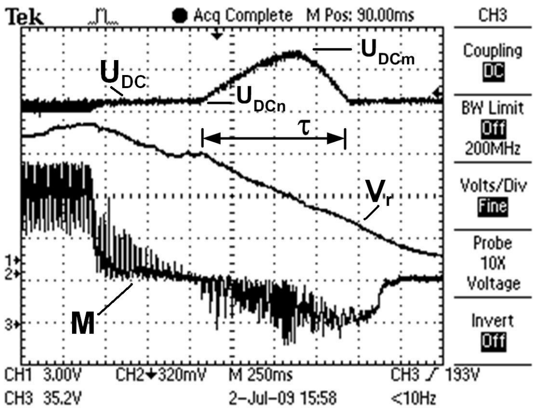

Fig. 9. The U_{DC} (upper curve, it has been measured using the 1/3 voltage divider, therefore 1 div ~ 100 V), V_r (middle curve, 1 div ~ 1000 rpm) and M (bottom curve, 1 div ~ 6 Nm) transients caused by the motor deceleration at D = 16.7 Hz/s and capacitance of the DC bus capacitor C = 470 μF

The investigation results show that increase of capacitance of the inverter supply filter capacitors allows decreasing the overvoltage in the inverter caused by the motor deceleration slightly. The inverter overvoltage duration (τ) dependence on motor deceleration is not monotonous. The coordinate of function maximum depends on motor load torque.

General Conclusions

1. The application of space vector modulation method with the averaged pulse durations as compared to the classical space vector modulation method allows us to reduce the temperature of inverter and AC induction motor by 2–10 ^{o}C and 2–3 ^{o}C, accordingly. This is caused by lower amplitudes of low frequency harmonics and switching frequency and by the fact that switches are not commutated at maximal current in the case when voltage is formed using space vector modulation method with the averaged pulse durations.

2. The nowadays used linear and square inverter voltage first harmonic amplitude control laws do not coincide with the amplitude dependencies on frequency that correspond to minimal power losses in the AC induction motor. The inverter voltage first harmonic amplitude has to be increased by up to 25 % in comparison to this one obtained by linear and square amplitude control laws, to achieve the minimal power losses in the AC induction motor.

3. The inverter voltage first harmonic amplitude control method based on the motor minimal current tracking allows us to maintain the minimal motor current in the situation when motor load changes randomly. It can by applied when motor load jumps follow with the frequency not higher than few tens of Hertz. Additionally, the proposed inverter voltage first harmonic amplitude control method allows us to decrease the motor load overshoot when load changes steeply.

4. The temperature of IGBT transistor module has increased by 1 ^{o}C when resistance of resistors, which determine the switching speed of IGBT transistor, that are connected to transistor gate was changed from 18 to 82 Ω. This fact shows that the switching losses in the IGBT transistors are lower than conducting losses.

5. The proposed realization of the dead time for the inverter switches in the IGBT transistor control circuit has substantial advantage against the dead time realization by the digital signal processor because lets us to avoid the damage of inverter in case of processor failure.

6. The increase of capacitance of the inverter supply filter capacitors allows decreasing the overvoltage in the inverter caused by the motor deceleration slightly. In the analyzed case, the increase of capacitance by 87 %

enables to lower the overvoltage by 7.5 % only. This can be explained by the fact that the capacitor voltage is proportional to square root of energy used for capacitor charging.

7. The inverter overvoltage duration dependence on motor deceleration is not monotonous. The coordinate of function maximum depends on motor load torque.

List of Published Papers on the Topic of the Dissertation

In the Reviewed Scientific Journals

Baskys, A.; Bleizgys, V.; Gobis, V. 2009. The impact of output voltage modulation strategies on power losses in inverter. *Electronics and Electrical Engineering*. Kaunas: Technologija, No. 6 (94), p. 47–50. ISSN 1392-1215. (ISI Web of Science).

Bleizgys, V.; Platakis, A. 2010. Valdymo grandinių įtakos IGBT tranzistoriaus dinaminiams parametrams tyrimas. *Elektronika ir elektrotechnika:* Mokslas – Lietuvos ateitis. Straipsnių rinkinys. Vilnius: Technika. 2 tomas, Nr. 1, p. 59–62. ISSN 2029-2341 / ISSN 2029-2252.

Bleizgys, V.; Baskys, A. 2010. The impact of supply voltage amplitude variation law on AC induction motor efficiency in variable speed drive. *Solid State Phenomena* vol. 164, 2010, p. 1–4. ISSN 1012-0394. (ISI Web of Science).

Baskys, A.; Bleizgys, V.; Lipinskis, T. 2011. An analysis of the inverter overvoltage generated by the motor. *Przegląd Elektrotechniczny (Electrical Review)*, R. 85 Nr. 5, p. 275–278. ISSN 0033-2097. (ISI Web of Science).

Bleizgys, V.; Baskys, A.; Lipinskis, T. 2011. Induction Motor Voltage Amplitude Control Technique Based on the Motor Efficiency Observation. *Electronics and Electrical Engineering*, Kaunas: Technologija, No. 3(109), p. 89–92. ISSN 1392-1215, ISSN 2029-5731. (ISI Web of Science).

In the other editions

Baškys, A.; Gobis, V.; Zlosnikas, V.; Augustinas, D.; Košur, V.; Dervinis, A.; Bleizgys, V. 2008. Dažnio keitiklių tyrimo stendas. *Puslaidininkių fizikos instituto XIX mokslinės konferencijos darbai*. Vilnius. p. 125–128. ISBN 978-9955-750-02-4.

Baškys, A.; Gobis, V.; Augustinas, D.; Košur, V.; Vaitekūnas, V.; Dervinis, A.; Demidova, A.; Zlosnikas, V.; Bleizgys, V.; Platakis, A. 2009. Specializuotas dažnio keitiklis. *Puslaidininkių fizikos instituto XX mokslinės konferencijos darbai*. Vilnius. p. 141–144. ISBN 978-9955-750-04-8.

Baskys, A.; Bleizgys, V.; Zlosnikas, V. 2009. Investigation of the overvoltage in the inverter caused by the motor deceleration. *Proc. of 19th int. conf. on electromagnetic disturbances EMD.* Bialystok, Poland, 23–25 September, 2009, p. 19–22. ISBN 978-83-60200-72-8.
Baskys, A.; Bleizgys, V.; Gobis, V. 2010. SVPWM method with the averaged pulse length versus conventional modulation method. *Proceedings of the 12th Biennial Baltic Electronic Conference*, Tallinn: Tallinn University of Technology, 2010, p. 321–322, ISBN 978-1-4244-7357-1, ISSN 1736-3705. (ISI Web of Science, IEEE).

About the Author

Vytautas Bleizgys was born in Vilnius on 18 of April, 1984.

Bachelor's degree in Electrical and Electronic Engineering, Faculty of Electronics, Vilnius Gediminas Technical University, in 2006. Master of Science in Electrical and Electronic Engineering, Faculty of Electronics, Vilnius Gediminas Technical University, in 2008. In 2008–2012 – PhD student at Department of Computer Engineering of Vilnius Gediminas Technical University. At present – Assistant in Department of Computer Engineering of Vilnius Gediminas Technical University and engineer in Electronic Systems Laboratory of State Research Institute Center for Physical Sciences and Technology.

ERDVINIO VEKTORIAUS MODULIAVIMO PRINCIPU VALDOMO INVERTERIO TYRIMAS IR TAIKYMAS

Darbo aktualumas

Išsivysčiusiose šalyse apie 60–70 % elektros energijos sunaudoja elektros variklių pavaros. Apie 90 % pramonėje naudojamų elektros variklių yra trifaziai asinchroniniai (toliau – asinchroniniai) varikliai. Asinchroninių variklių sukimosi greičio ir maksimalaus sukimo momento valdymui naudojami dažnio keitikliai, kurie standartinio vienfazio arba trifazio elektros tinklo kintamąją įtampą keičia į keičiamo dažnio ir amplitudės trifazę kintamąją įtampą. Pagrindinis dažnio keitiklio funkcinis mazgas yra inverteris. Jis formuoja kintamąją įtampą iš nuolatinės įtampos. Tyrimai rodo, kad nuo 2007 m. dažnio keitiklių, skirtų asinchroninių variklių valdymui, rinka kasmet auga 8,9 % ir 2012 m. sieks 11 milijardų JAV dolerių. Rinkos augimas yra sąlygojamas nuolatinio šių prietaisų tobulinimo, kuris gerina jų savybes ir išplečia pritaikymo galimybes, bei vis didėjančio poreikio valdyti technologijas ir taupyti energiją. Todėl tyrimai, leidžiantys kurti tobulesnius dažnio keitiklius su mažesniais nuostoliais inverteryje bei įgalinčius siekti mažesnių nuostolių variklyje, yra aktualūs dėl didelės praktinės vertės.

Disertacijoje pateiktų darbų aktualumą tiesiogiai įrodo Lietuvos elektronikos įmonių užsakomieji darbai ir Lietuvos valstybinio mokslo ir studijų fondo bei Mokslo inovacijų ir technologijų agentūros finansuoti Aukštųjų technologijų plėtros programos projektai dažnio keitiklių serijinei gamybai sukurti, kuriuos vykdant buvo gauti disertacijoje pateikti tyrimų rezultatai.

Tyrimų objektas

Darbo tyrimų objektas yra dažnio keitiklio, skirto asinchroninių elektros variklių valdymui, inverteris, valdomas erdvinio vektoriaus moduliavimo principu.

Darbo tikslas

Šio darbo tikslas – ištirti erdvinio vektoriaus moduliavimo principu valdomą inverterį ir sukurti jo formuojamos įtampos amplitudės valdymo metodą, leidžiantį sumažinti galios nuostolius inverteryje ir variklyje.

Darbo uždaviniai

Darbo tikslui pasiekti darbe reikia spręsti šiuos uždavinius:

1. Ištirti inverterį, kurio įtampa formuojama erdvinio vektoriaus moduliavimo metodu su integruota impulsų trukme ir gautus rezultatus palyginti su tyrimų rezultatais, kai naudojamas klasikinis erdvinio vektoriaus moduliavimo metodas.
2. Surasti ir ištirti inverterio formuojamos įtampos pirmosios harmonikos amplitudės, užtikrinančios mažiausius galios nuostolius variklyje, priklausomybes nuo dažnio.
3. Sukurti ir ištirti inverterio formuojamos įtampos pirmosios harmonikos amplitudės valdymo metodą, kuris leidžia palaikyti mažiausią variklio su atsitiktinai kintančia apkrova srovę.
4. Ištirti inverterio raktų dvipolių tranzistorių su izoliuota užtūra (angl. IGBT – *Insulated Gate Bipolar Transistor*) valdymo grandinių įtaką inverterio temperatūrai ir sukurti bei ištirti grandinę, vėlinančią raktų atidarymą.
5. Ištirti inverterio viršįtampių, generuojamų stabdomo asinchroninio variklio, pereinamuosius procesus.

Tyrimų metodika

Darbe taikomi eksperimentiniai ir analitiniai metodai. Eksperimentiniai tyrimai atlikti naudojant dažnio keitiklio inverterio bandomuosius pavyzdžius ir specialų dažnio keitiklių tyrimo stendą. Inverterio valdymo algoritmai įgyvendinami įterptinėje sistemoje su signalų procesoriumi, sudarant programas C programavimo kalba.

Darbo mokslinis naujumas

Rengiant disertaciją buvo gauti šie elektros ir elektronikos inžinerijos mokslui nauji rezultatai:

1. Gauti eksperimentiniai tyrimų rezultatai, įrodantys, kad erdvinio vektoriaus moduliavimo metodas su integruota impulsų trukme leidžia pasiekti mažesnių galios nuostolių inverteryje ir variklyje, lyginant su šiuo metu dažnio keitikliuose naudojamu klasikiniu erdvinio vektoriaus moduliavimo metodu.
2. Surastos inverterio formuojamos įtampos pirmosios harmonikos amplitudės priklausomybės nuo dažnio, užtikrinančios mažiausius galios nuostolius variklyje, kai variklis apkraunamas pastovaus momento ir tiesiškai nuo sukimosi greičio mažėjančio momento apkrova. Įrodyta, kad šios priklausomybės nesutampa su šiuo metu siūlomomis tokioms apkrovoms taikyti priklausomybėmis, aprašomomis atitinkamai tiesiniu ir kvadratiniu įtampos amplitudės valdymo dėsniais.
3. Sukurtas naujas inverterio formuojamos įtampos pirmosios harmonikos amplitudės valdymo metodas varikliams su atsitiktinai kintančia mechanine apkrova valdyti, leidžiantis palaikyti mažiausią variklio srovę.
4. Pasiūlyta IGBT tranzistorių valdymo schema, kurioje, siekiant išvengti inverterio sugadinimo sutrikus signalų procesoriaus darbui, naudojamas IGBT tranzistoriaus atidarymo vėlinimas, atsisakant vėlinimo realizavimo signaliniu procesoriumi.

Darbo rezultatų praktinė reikšmė

Disertacijos rezultatai pritaikyti kuriant specializuotus dažnio keitiklius, skirtus energiją tausojančių vėdinimo sistemų ventiliatorių ir modernių vandens tiekimo sistemų siurblių pavarų su asinchroniniais varikliais valdymui. Disertacija susietas su šiais mokslo tiriamaisiais projektais:

Ūkio subjektų užsakomieji projektai

1. Specializuoto dažnio keitiklio, skirto pažangių ventiliavimo sistemų ventiliatorių elektros variklių valdymui, sukūrimas, užsakovas UAB „Ventmatika“, 2007–2010 m., vadovas A. Baškys, sutarties reg. Nr. U-2007/8, 250 tūkst. Lt.

2. Dažnio keitiklio, skirto pažangioms vandens tiekimo sistemoms, kūrimas, užsakovas UAB „Tamona“, 2011–2012 m., vadovas A. Baškys, sutarčių reg. Nr. 308-S095 ir 3400-S155, 85 tūkst. Lt.

Aukštųjų technologijų plėtros programos projektai

3. Dažnio keitiklių tyrimas, kūrimas ir įdiegimas į serijinę gamybą, 2007–2009 m., sutarties reg. Nr. B-13/2007-2009, vadovas A. Baškys, finansavo Lietuvos valstybinis mokslo ir studijų fondas, 840 tūkst. Lt.

4. Specializuoto dažnio keitiklio sukūrimas serijinei gamybai, 2012–2013 m., reg. Nr. 31V-37, vadovas A. Baškys, finansuoja Mokslo inovacijų ir technologijų agentūra, 700 tūkst. Lt.

Ginamieji teiginiai

1. Erdvinio vektoriaus moduliavimo metodas su integruota impulsų trukme, lyginant su klasikiniu erdvinio vektoriaus moduliavimo metodu, leidžia sumažinti 2–10 ^{o}C inverterio raktų ir 2–3 ^{o}C – asinchroninio variklio korpuso temperatūrą.

2. Norint pasiekti mažiausius galios nuostolius asinchroniniame variklyje reikia inverterio pirmos harmonikos amplitudes, gautas pagal tiesinio ir kvadratinio valdymo dėsnius, padidinti iki 25 %.

3. Inverterio formuojamos įtampos pirmosios harmonikos amplitudės valdymo metodas, grįstas variklio srovės mažiausios vertės sekimu, leidžia palaikyti mažiausią variklio srovę, kintant variklio apkrovai.

Darbo apimtis

Darbą sudaro įvadas, 4 skyriai, išvados, literatūros sąrašas ir autoriaus publikacijų sąrašas. Bendra apimtis – 102 puslapiai, 53 iliustracijos, 2 lentelės, 25 numeruotos formulės ir 75 literatūros šaltiniai.

Pirmajame skyriuje aptariamos inverterio panaudojimo sritys, analizuojami inverterio trifazei kintamajai įtampai formuoti principai. Nagrinėjami inverterio, skirto asinchroninių variklių valdymui, išėjimo įtampos formavimo metodai. Pateikiamos pirmojo skyriaus išvados ir formuluojami disertacijos uždaviniai.

Antrajame skyriuje aprašomas erdvinio vektoriaus moduliavimo metodas su integruota impulsų trukme, pateikti galios nuostolių inverteryje ir asinchroniniame variklyje tyrimo naudojant erdvinio vektoriaus moduliavimo metodą su integruota impulsų trukme ir klasikinį erdvinio vektoriaus moduliavimo metodą rezultatai.

Trečiajame skyriuje analizuojama asinchroninio variklio, maitinamo dažnio keitiklio inverteriu, įtampos pirmosios harmonikos amplitudės valdymo problema. Atlikti tyrimai ir nustatytos inverterio išėjimo įtampos pirmosios harmonikos amplitudės priklausomybės nuo dažnio (variklio sukimosi greičio) įvairiems variklio apkrovos sukimo momentams, atitinkančios didžiausią variklio naudingumo faktorių. Aprašytas autoriaus pasiūlytas naujas inverterio išėjimo įtampos pirmosios harmonikos amplitudės valdymo metodas su variklio mažiausios srovės sekimu.

Ketvirtajame skyriuje analizuojama IGBT tranzistorių, naudojamų dažnio keitiklių inverteriuose, valdymo problema. Pasiūlyta patobulinta IGBT tranzistorių valdymo schema, realizuojanti IGBT tranzistoriaus atidarymo vėlinimą aparatiškai, leidžianti padidinti inverterio darbo patikimumą. Ištirta tranzistoriaus valdymo grandinių įtaka jo dinaminiams parametrams ir inverterio galios nuostoliams. Atlikti inverterio viršįtampių, generuojamų stabdomo variklio, tyrimai.

Bendrosios išvados

1. Erdvinio vektoriaus moduliavimo (toliau EVM) metodo su integruota impulsų trukme taikymas, lyginant su klasikinio EVM metodo taikymo atveju, leidžia sumažinti 2–10 °C inverterio raktų ir 2–3 °C – asinchroninio variklio korpuso temperatūrą. Tai sąlygojama mažesnėmis inverterio įtampos, gautos naudojant EVM metodą su integruota impulsų trukme, žemo dažnio harmonikų amplitudėmis, mažesniu raktų junginėjimosi dažniu ir tuo, kad raktų tranzistoriai nejunginėja variklio apvijų srovės, kai jomis teka didžiausia momentinė variklio srovė.

2. Šiuo metu naudojami tiesinis ir kvadratinis inverterio pirmosios harmonikos amplitudės valdymo dėsniai neatitinka inverterio įtampos pirmosios harmonikos amplitudės priklausomybių nuo dažnio, leidžiančių pasiekti mažiausių galios nuostolių variklyje. Norint pasiekti mažesnių galios nuostolių asinchroniniame variklyje, būtina inverterio pirmosios harmonikos amplitudę valdyti taip, kad ji būtų iki 25 % didesnė nei nustatyta naudojant tiesinį ir kvadratinį amplitudės valdymo dėsnius.

3. Sukurtas inverterio įtampos pirmosios harmonikos amplitudės valdymo metodas su variklio srovės mažiausios amplitudės sekimu garantuoja mažiausią variklio srovės vertę nusistovėjus variklio apkrovos sukimo momento šuolio sukeltam pereinamajam procesui. Be to, jis leidžia sumažinti apkrovos sukimo momento šuolį, staigiai padidėjus apkrovai, tuo sumažinant variklio mechaninę perkrovą. Siūlomasis įtampos pirmosios harmonikos amplitudės valdymo metodas gali būti panaudotas, kai variklio apkrovos sukimo momento šuoliai vyksta santykinai mažu dažniu, neviršijančiu kelių dešimtųjų herco dalių.

4. Keičiant tranzistoriaus užtūros grandinės rezistorių, kurie lemia tranzistoriaus atidarymo ir uždarymo trukmes, nominalus nuo 18 iki 82 Ω, inverteryje naudojamo IGBT tranzistorių modulio temperatūra padidėjo 1 ^{o}C. Tai rodo, kad tranzistoriaus junginėjimosi galios nuostoliai yra maži, lyginant su galios nuostoliais, sukuriamais baigtinio atviro tranzistoriaus laidumo.

5. Sukurta grandinė, kurioje IGBT tranzistoriaus atidarymas vėlinamas rakto valdymo schemoje. Toks sprendimas, lyginant su vėlinimo įgyvendinamu signalų procesoriumi, yra geresnis, nes leidžia išvengti inverterio sugadinimo, sutrikus signalų procesoriaus darbui.

6. Inverterio maitinimo šaltinio filtro kondensatorių talpos didinimas nedaug sumažina viršįtampį, sukeliamą inverterio grandinėje stabdomo variklio. Padidinus kondensatoriaus talpą 87 %, viršįtampis sumažėjo 7,5 %, nes kondensatoriaus įtampa proporcinga energijos, kuri tiekiama kondensatoriaus įkrovimui, kvadratinei šakniai.

7. Inverterio viršįtampio trukmės priklausomybės nuo variklio stabdymo pagreičio ekstremumų maksimumo koordinatės priklauso nuo variklio apkrovos sukimo momento.

Trumpos žinios apie autorių

Vytautas Bleizgys gimė 1984 m. balandžio 18 d. Vilniuje.

Vilniaus Gedimino technikos universiteto Elektronikos fakultete įgijo elektros ir elektronikos inžinerijos bakalauro (2006 m.) ir magistro (2008 m.) laipsnius. 2008–2012 m. – Vilniaus Gedimino technikos universiteto Kompiuterių inžinerijos katedros doktorantas ir asistentas, nuo 2008 m. – Valstybinio mokslinių tyrimų instituto Fizinių ir technologijos mokslų centro Elektroninių sistemų laboratorijos inžinierius.

Vytautas BLEIZGYS

RESEARCH AND APPLICATION OF
INVERTER CONTROLLED USING SPACE
VECTOR MODULATION PRINCIPLE

Summary of Doctoral Dissertation
Technological Sciences, Electrical and Electronic Engineering (01T)

Vytautas BLEIZGYS

ERDVINIO VEKTORIAUS MODULIAVIMO
PRINCIPU VALDOMO INVERTERIO
TYRIMAS IR TAIKYMAS

Daktaro disertacijos santrauka
Technologijos mokslai, elektros ir elektronikos inžinerija (01T)

2012 05 03. 1,5 sp. l. Tiražas 70 egz.
Vilniaus Gedimino technikos universiteto
leidykla „Technika“,
Saulėtekio al. 11, 10223 Vilnius,
http://leidykla.vgtu.lt
Spausdino UAB „Ciklonas“
J. Jasinskio g. 15, 01111 Vilnius