



Andrius PETROVAS

**DYNAMIC MODELS OF THREE PHASE
INDUCTION MOTORS**

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

1390

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

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VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

Andrius PETROVAS

**TRIFAZIŲ ASINCHRONINIŲ VARIKLIŲ
DINAMINIAI MODELIAI**

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

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Mokslinis vadovas

prof. habil. dr. Roma RINKEVIČIENĖ (Vilniaus Gedimino technikos universitetas, technologijos mokslai, elektros ir elektronikos inžinerija – 01T).

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General Characteristic of the Dissertation

Scientific problem. Development of controlled induction drives requires to elaborating dynamic model of induction motor. For modelling of unconventional motors, such as linear motors or motors with saturated magnetic circuit the electrodynamic motor model can be used, but it requires a lot of computer resources. Therefore the model, describing asymmetrical motor dynamics adequately is required. The calculations speediness of that model should not be much greater than that of motor model in transformed linear frame.

Aim and tasks of the work. The aim of dissertation is to develop mathematical and computer models of induction motor in phase coordinate system at various ways of stator windings connection, transform this model for investigation of dynamics of linear induction motor, and carry out computer models for investigation of frequency-controlled induction motors.

The tasks for achieving the aim:

1. Ascribe a motor by system of ordinary differential equations, with no requirements for symmetry of electric circuits.
2. Derive differential equations for all stator windings connection modes of induction motor.
3. Elaborate computer models according to derived differential equations.
4. Investigate transients at motoring and generating modes of induction motor with carried out model.
5. Develop computer model of scalar controlled electric drive on the base of carried out induction motor model, simulate performance of that drive.
6. Develop model of induction drive controlled by current channel on the base of elaborated induction motor model in phase coordinate system; examine operation modes of that drive.

Scientific novelty of the work

1. Elaborated mathematical and computer models of asymmetrical induction motor in phase coordinate system.
2. Carried out mathematical and computer model in phase coordinate system of symmetrical induction motor, witch are applicable to investigate motors with non-symmetrical.
3. Carried out induction motor model at various motor windings connection way.
4. Elaborated computer model of non-symmetrical induction motor

matched with *Simulink* system which can be easily used for investigation of complex mechatronic systems.

5. Developed universal program model of induction motor, which is applicable for specialized mathematical software.
6. Developed model of non-symmetrical linear induction drive.

Methods of investigation. Methods of mathematical and computer modeling, numerical solution of ordinary differential equations and functional as well as object programming methods are used.

Practical value of the work. Developed model of induction motor can be used at designing and investigating controlled induction drives, where consideration of non-symmetrical electric circuit is desirable.

Dissertation proposes

1. Mathematical and computer models in phase coordinate system of non-symmetrical induction motors with all possible connections ways of stator windings.
2. Results of simulation of non-symmetrical linear induction motor.
3. Model of scalar control of linear induction drive and results of simulations.
4. Simulations results of overvoltages in the direct current bus of frequency converter.
5. Model of induction drive controlled by “current channel” method and results of simulation.

The scope of the scientific work. Dissertation comprises introduction, for chapters and conclusions. Reference consists of 122 sources. The volume of dissertation is 103 pages.

Introduction

The first induction motor was designed in 1888 and since that time process of their investigation and improvement continuously moved forward. It is possible to state, that conventional induction motor is investigated quite well. Application of obtained knowledge results in successfully design, control and modeling. Therefore since 1888 construction of motors and control methods also were in progress. Linear induction motor with non-symmetrical electric circuit was designed and modern control methods with frequency commutating processes often cause saturation of their magnetic circuit. Therefore at

investigation of dynamics of linear induction motors many non-solved problems appear.

Some kinds of dynamic models of non-symmetrical induction motors at present are used. The most popular are models in transformed reference frame and electrodynamic models. The first of them employs Kirchhoff's laws, the second one – Maxwell equations. The main shortcoming of model in transformed reference frame – it can not be used for simulation of motors with non-symmetrical electrical circuits. In this case the number of differential equations becomes so large that specialized methods and a lot of computer resources should be used.

Therefore it is desirable to have model of induction motors, which could be used to investigate dynamics of non-linear or non-symmetrical induction motor and more effectively use computer resources, than electrodynamic model, i.e. it should be free of the main shortcoming of electrodynamic model.

The dissertation discusses with such mathematical and computer model. On the base of this model, the computer models for investigation of controlled drives are developed.

1. Models of Induction Motor

The simplest and the oldest model of induction motor is so called “*T*” model. The main his drawback – it is inapplicable to simulate dynamic modes. Just models in transformed reference frame and electrodynamic model are applicable to simulate dynamic modes.

Model in transformed reference frame is based on electric circuits. Differential equations of composing model are being derived with application Kirchhoff's laws for motor windings. Assumptions about symmetry of electric and magnetic circuits allows to simplify equations and get a set of non-linear first order differential equations, which can be solved by applicable numerical methods.

Models in transformed reference frame are widely used to investigate transients of induction motors. The many control methods, for example, vector control, are employing these models. The set of model equations comprise three first order differential equations, and the methods, used to solve that are not complex, therefore simulation is speedy.

The main imperfectness of transformed reference frame model – it is inapplicable for non-symmetrical motors. This shortcoming matches the assumption of symmetry of motor electric and magnetic circuits.

Electrodynamical model is based on electromagnetic field theory; with mathematical background is Maxwell equations. In order to carry out

electrodynamic model, all electromagnetic processes are described by Maxwell's equations. This way of problem solution has some advantages and disadvantages.

The main shortcoming is related with Maxwell's equations mathematical nature. From a view of mathematic, they are nonlinear partial difference equations. Analytical solution of these equations is possible just for simplest cases where used assumptions simplify the problem. In most cases finite element methods or finite difference methods are used. It should be noted, that solution of this type of equations by numerical methods requires a lot of computer resources.

The main advantage of electrodynamic model is its universality. It is applicable to investigate dynamic processes in symmetrical and non-symmetrical as well as saturated motor.

One of advanced model is neurons network model of induction motor. It is applicable to investigate dynamic processes in symmetrical and non-symmetrical motors with great speediness. The main shortcoming of this model – it is developed on the empirical links, not deterministic.

2. Model of Induction Motor in Phase Coordinate System

Proposed in the dissertation model of induction motor in phase coordinate system is applicable to solve discussed problems. Comparison of elaborated model with models in transformed reference frame or with electrodynamic model gives possibility to form model directly according to non-linear differential equations of induction motor with assumption about non-symmetry of electric circuits. From the view of mathematics, mathematical model in phase coordinate system comprise nonlinear differential equations. Numerical methods, such as Runge-Kutt, Adams and other can be applied to solve that.

These methods do not require great calculation resources, as finite difference or finite elements methods. Therefore elaborated model is free of transformed reference frame or electrodynamic model shortcomings.

The windings of simple pole pair induction motor are shown in Fig 1. Electrical parameters, characteristic a winding, such as inductance of winding L and resistance R are denoted at each winding. Each parameter of phase winding is supplied by indices, showing its dependence to proper phase winding. Stator phase windings are denoted with indices A, B, C and rotor – with a, b, c . All motor windings, shown in Fig 1, are coupled magnetically. Influence of developed magnetic field to other windings is denoted by mutual inductance.

Mutual inductance of windings x and y is denoted as M_{xy} , where x and y are indices of windings. As $M_{xy} = M_{yx}$, therefore further in formulas indices are

written in order with Latin alphabet and the capital letters will be written before uppercase that.

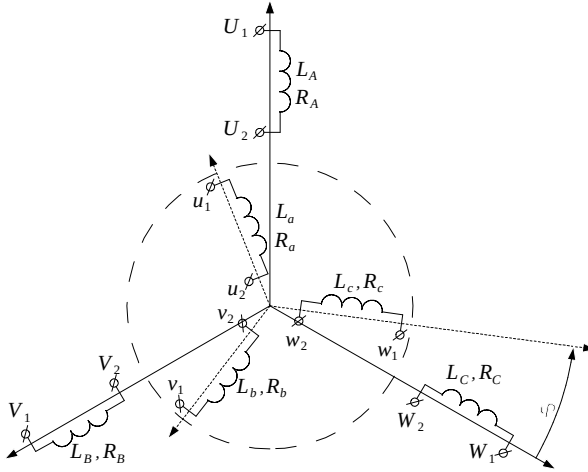


Fig 1. Windings of three-phase single pole pair motor

Mathematical model in phase coordinate system comprises these sets of equations:

1. KVL for motor windings;
2. Equations of entire magnetic flux;
3. Equations, describing mechanical rotational movement of rotor or translational for linear motors.

Equations of the first and second items depend on connections way of motor windings and have the different form for each connections.

Dissertation proves that developed electromagnetic torque does not depend on way of windings connection. It can be calculated by expression, derived by author:

$$\begin{aligned}
 M_{em} = & -(M_{Aa}i_Ai_a + M_{Bb}i_Bi_b + M_{Cc}i_Ci_c) \sin \varphi - \\
 & (M_{Ab}i_Ai_b + M_{Bc}i_Bi_c + M_{Ca}i_Ci_a) \sin \left(\varphi + \frac{2\pi}{3} \right) - \\
 & (M_{Ac}i_Ai_c + M_{Ba}i_Bi_a + M_{Cb}i_Ci_b) \sin \left(\varphi - \frac{2\pi}{3} \right);
 \end{aligned} \tag{1}$$

where M_{em} is electromagnetic torque.

Expression of equations of movement or the Newton's law depends on type of motor. Movement of revolving motor rotor is ascribed by main law of rotational movement. For linear induction motor conventional form of Newton's law is applied. In the dissertation is presented the system of equations, derived for induction motor at star connected stator windings with neutral wire as this:

$$\mathbf{M}(t) \cdot \begin{pmatrix} i'_A \\ i'_B \\ i'_C \\ i'_a \\ i'_b \\ i'_c \\ \phi' \\ \omega' \end{pmatrix} = \begin{pmatrix} u_A - R_A i_A \\ u_B - R_B i_B \\ u_C - R_C i_C \\ u_a - R_a i_a \\ u_b - R_b i_b \\ u_c - R_c i_c \\ \omega \\ M_{em} + \sum M \end{pmatrix}; \quad (2)$$

where ω is angular speed of rotor; $M(t)$ is matrix of 8×8 elements of time depending coefficients; $\sum M$ is sum of external torques, applied to rotor; $u_A, u_B, u_C, u_a, u_b, u_c$ are instantaneous values of phase voltages.

Coefficients, entering matrix $M(t)$ in Eq. 2 are harmonic time functions, resulting to consider set of equations (2) as set of first order nonlinear differential equations and requiring to solve that by numerical methods. Expression of matrix $M(t)$ and equations of model in extended form are presented in dissertation.

Model, described above, is applicable to consider non-symmetry of motor, because no assumptions about symmetry of electrical circuit were made and any parameter of motor, for example, as winding resistance, inductance can be chosen individually and independently from others.

3. Computer Models of Induction Motor

Equations of induction motor, derived in phase coordinate system, can not be solved analytically, therefore computer models are requested, where those equations being solved by numerical methods.

In dissertation development of computer model is shown in *Matlab* software. Universal algorithm of computer model is presented in Fig 2.

Developed and presented in Fig 2 algorithm is applicable to solve equations

of induction motor, derived in phase coordinate system, by numerical methods integrated in *Matlab* system. Algorithm for calculation derivatives of state space equations is proposed. All equations, mentioned in Fig 2, are given in dissertation.

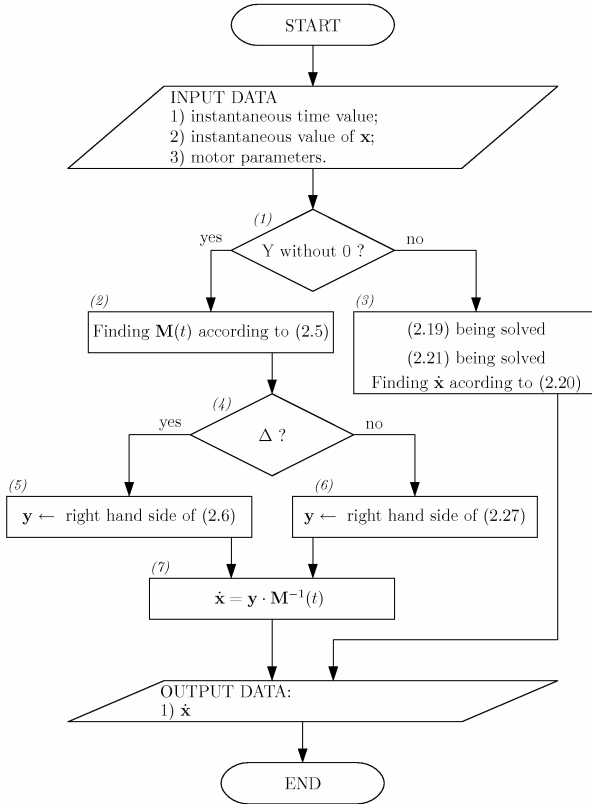


Fig 2. Universal algorithm of programmed motor model

According to differential equations of discussed mathematical model, objective *Simulink* motor model is developed. It is not universal and change with different way of windings connection. Models, developed for symmetrical motor are presented in dissertation.

4. Models of Controlled Electric Drives

Adequacy of model is verified by simulation of controlled and non-controlled performance of symmetrical induction motor. Possibility to model electric motor with non-symmetrical electric circuit is verified by simulation of operation of linear induction motor.

Construction of linear induction motor, as non-symmetrical kind of induction motors is considered. Consideration of non-symmetrical of electric circuit is assumed by reducing values of mutual inductance of windings placed at different ends of induction motors is considered. Considerations of non-symmetry of magnetic circuit is assumed by reducing values of mutual inductance of windings placed at different ends of inductor and secondary element, i.e. $M_{AC} = \alpha M_{AB}$; $M_{ac} = M_{Ca} = \alpha M_{SR}$; $M_{ac} = \alpha M_{ab}$, where $\alpha = [0,5; 0,6; \dots; 1]$.

Developed motor model in phase coordinate system is applied at designing of motor, controlled by frequency converter model, i.e., simulation of system frequency inverter – motor simulation. For simulation of motor is used in *Matlab* programmed model, and frequency converter is modeled by program changing of motor phase voltages according to control law.

Because stepwise changing of motor supply voltages model is nonlinear, therefore simulation time is divided into short intervals, during which values of voltages of frequency converter are constant and simulation of motor performance in each interval is fulfilled separately. Algorithm of this program is given in Fig 3.

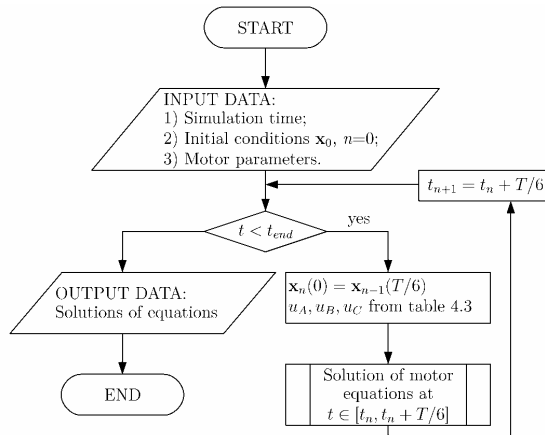


Fig 3. Program algorithm to simulate system inverter-motor

Simulation of system inverter-motor is fulfilled for frequency inverter, controlled by 180° algorithm at control law $U/f = \text{const.}$, giving constant breakdown torque.

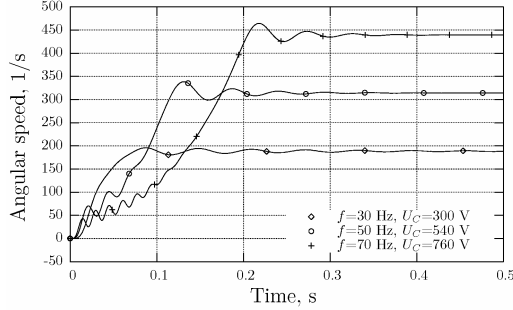


Fig 4. Starting transients of rotor angular speed

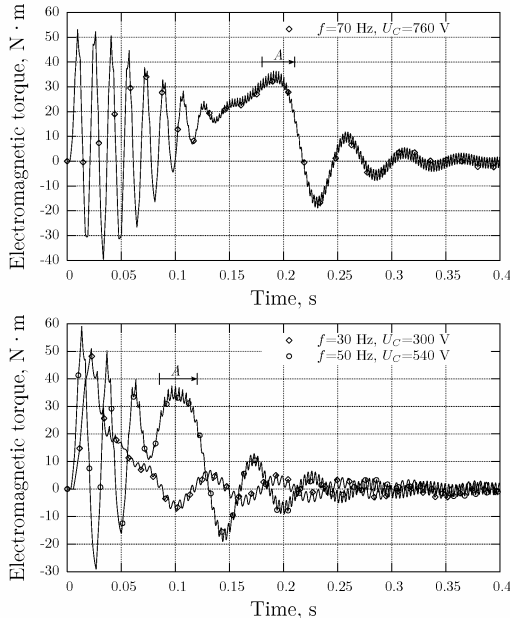


Fig 5. Starting transients of electromagnetic torque

Figures 4 and 5 indicate the control law $U/f = \text{const.}$ resulting constant breakdown torque and possibility to change speed continuously.

Elaborated model in phase coordinate system is applied in developing of system rectifier-inverter-motor model. While rectifier does not transfer current back to supply network, in this system at operating of motor in regenerative mode, current charges on filter capacitor.

Model of system rectifier-inverter-motor has changeable structure and differs and discussed model inverter-motor, in which, during short intervals of simulation time, voltages of frequency converter had constant values; here the conditions of switching on or off rectifier diodes should be considered, which are not determined in advance. Algorithm of this program is presented in Fig 6. Speed transients at different rotor speed are presented in Fig 7.

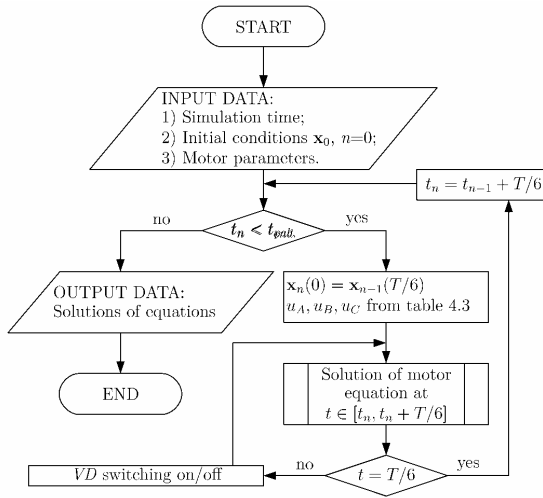


Fig 6. Algorithm of program to simulate system rectifier-inverter-motor

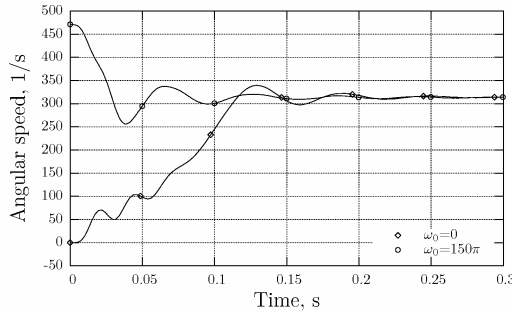


Fig 7. Transients of speed at regenerative mode

Starting transients of filter capacitor voltage at different rotor speed are presented in Fig 8.

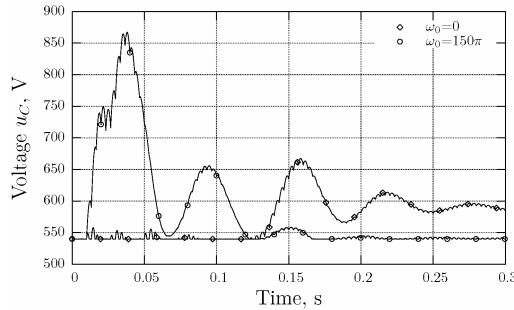


Fig 8. Transients of voltage across capacitor

Results of simulation of system rectifier-inverter-motor gives possibility to observe overvoltages across filter capacitor appeared at regenerative mode of motor. The most dangerous situation happens at starting motor with initial rotor speed exceeding synchronous. At this situation overvoltages exceed about 40 % the rated voltage.

Elaborated objective *Simulink* model is applied at developing model of drive controlled by current channel method. The block diagram of that model is presented in Fig 9.

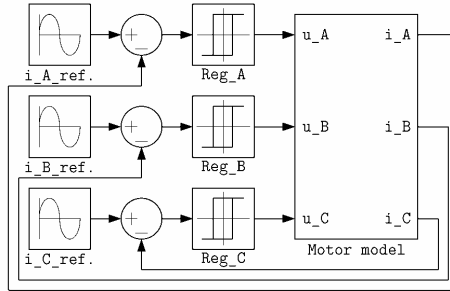


Fig 9. Block diagram of model if drive, controlled by current channel

The subsystem **Motor model** in Fig 9 comprises a model of induction motor in phase coordinate system. It is formed to use phase voltages as input signals and phase currents as outputs. Three reference blocks as **i_A_ref**, **i_B_ref** and **i_C_ref** determine changing stator phase currents by sine law, and nonlinear regulators **Rer_A**, **Reg_B** and **Reg_C** whose hysteresis loop width corresponds to current channel width. The main results of simulation are

presented in Fig 10 and Fig 11. Stator current at the beginning of transient process is shown by solid line. The limits of channel are presented by dash lines.

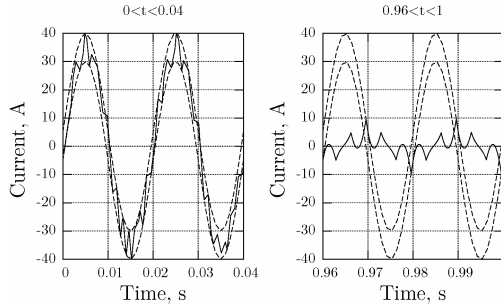


Fig 10. Stator current at the beginning of transient process ($0 < t < 0.04$) and end of that ($0.96 < t < 1$)

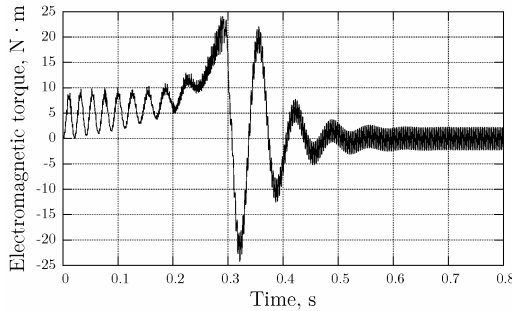


Fig 11. Transients of electromagnetic torque at control by current channel method

Results of simulation of frequency converter controlled by “current channel method” indicate, that block diagram of drive, given in Fig 9 limits just maximum value of stator current, therefore at the end of transients process the current of non-load motor decreases and is not hold inside the channel.

Analysis of rotor speed transients shows that control by current channel method effectively limits overshoot of speed in the beginning, nevertheless at the end of process, when the current is not hold inside channel and non-controlled process of current begins, the speed overshoot reaches about 50 % of rated value. Therefore current channel method is recommended to apply together with other methods, for example, vector control.

General Conclusions

1. Analysis of commonly used mathematical models of induction motor indicate that at present there is lack of elaborated effective model to investigate dynamics of asymmetrical induction motor
2. Developed model of induction motor is phase coordinate system on the basis of generalized differential equations of motor without assumption of linearity and symmetry electrical circuits is applicable to investigate dynamic modes and performance of motor, controlled by frequency converter.
3. Mathematical models developed in phase coordinate system for the motor comprise the set of ordinary nonlinear first order differential equations; therefore they could be solved by numerical methods with elaborated computer model.
4. Number of state-space variables of the motor model in phase coordinate system depends on motor winding connection way and is equal to six, at Y connection without neutral wire and eight, at Δ connection or Y connection with neutral wire.
5. Non-symmetry of electrical circuit is described by different parameters of stator or rotor windings. Developed model allows setting up parameters of each winding individually, therefore elaborated model is applicable to simulate non-symmetrical motors.
6. On the base of developed motor model, models of controlled by frequency converter drive were carried out. Motor controlled by frequency converter operates in transient mode. Steady-state current amplitude at no load 4.7 times exceeds the amplitude of rated current.
7. Elaborated model to control frequency converter by current channel method indicate reduction of torque and speed overshoot of starting transients. Limitation of current amplitude at 40 A results in increasing of speed transient time about twice.
8. Developed model with changeable structure of system “rectifier-inverter-motor” gives possibility to simulate filter capacitor overvoltages appeared at starting or regenerative braking mode. An overvoltage exceeds 40 % the rated voltage at set up lower value of speed, while rotor rotates with speed exceeding synchronous speed.

List of Published Works on the Topic of the Dissertation

List of Articles Referred in the ISI Date Base

1. BAŠKYS, A.; RINKEVIČIENĖ, R.; JEGOROV, S.; PETROVAS, A. Modeling of a Meshatronic System with the AC Induction Motor Supplied by the Frequency Converter. *Solid State Phenomena, Mechatronic Systems and Materials*. Trans Tech Publications Ltd, 2006, Vol. 113, p. 25–28. ISSN 1012–0394.
2. RINKEVIČIENĖ, R.; PETROVAS, A. Modelling AC Induction Drive in PSpice. *Electronics and Electrical Engineering*, 2007, No. 1(73), p. 29–32. ISSN 1392-1215.

List of Articles Referred in the International ISPEC Date Base

3. RINKEVIČIENĖ, R.; PETROVAS, A. New model of linear induction drive. *Electronics and Electrical Engineering*, 2004, No. 2(51), p. 25–28. ISSN 1392–1215.
4. RINKEVIČIENĖ, R.; PETROVAS, A. Model of linear induction drive. *Electronics and Electrical Engineering*, 2004, No. 1(50), p. 28–33 (in Lithuanian). ISSN 1392–1215.
5. RINKEVIČIENĖ, R.; PETROVAS, A. Dynamic models of controlled linear induction drives. *Electronics and Electrical Engineering*, 2005, No. 5(61), p. 23–27. ISSN 1392–1215.
6. RINKEVIČIENĖ, R.; PETROVAS, A. Dynamic models of linear induction drives. *Information technology and control*, 2005, No. 1(34), p. 37–41. ISSN 1392–124X.

List of Articles in the International Scientific Conferences Proceedings

7. RINKEVIČIENĖ, R.; PETROVAS A. Model of frequency controlled linear induction drive. In *V workshop for candidates for a doctor's degree OWD'2003*, Warsaw: PTETiS, 2003, p. 341–343. ISBN 83-915991-5-9.
8. RINKEVIČIENĖ, R.; PETROVAS, A. Modelling of a controlled linear induction drive. In *Third International Conference on Systems, Signals & Devices SSD'05*, Vol II, Power Electrical Systems, IEEE, 2005, p. 1–5. ISBN 9973–959–01–9.
9. BAŠKYS, A.; RINKEVIČIENĖ, R.; PETROVAS, A. Simulation of Overvoltages in the System Frequency Converter – AC Induction Motor. In *The XVI International Conference “Electromagnetic*

Disturbances EMD 2006”, September 27–29, 2006, Kaunas, Lithuania. ISSN 1822-3249.

List of Articles in the Other Publications

10. RINKEVIČIENĖ, R.; PETROVAS, A. Modelling of asymmetrical feed linear induction drive. In *Proceedings of conference on "Electrical energetic and techlology"*. April 22–23, 2004, Kaunas. ISBN 9986-858-23-2.
11. PETROVAS, A. Modeling of induction motor feed by current inverter. In *Materials of Conference of Young Scientists. Electronics and Electrical Engineering*. Vilnius: Technika, 2004, p. 116–121. (in Lithuanian). ISBN 9986-05-803-1.
12. PETROVAS A. Research of characteristics of frequency controlled drive. In *Materials of Conference of Young Scientists. Electronics and Electrical Engineering*. Vilnius: Technika, 2004, P. 84–89. (in Lithuanian). ISBN 9986-05-695-0.

About the Author

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In 2001 graduated from the Electronics faculty of Vilnius Gediminas Technical University and obtained degree of Bachelor in Electrical Engineering. In 2000–2001 he spent one semester in Fachhochschule Würzburg – Schweinfurt as Socrates student.

In 2003 he gained the Master degree in Electrical Engineering at Vilnius Gediminas Technical University Electronics Faculty. At 2003 he started PhD studies in Automation department. In 2005 he spend a half of year as trainee at Munich Bundeswehr University in department of electrical drives and power electronic.

TRIFAZIŲ ASINCHRONINIŲ VARIKLIŲ DINAMINIAI MODELIAI

Mokslo problema. Konstruojant valdomas asinchronines pavaras būtina turėti dinaminį asinchroninio variklio modelį. Netradicinės konstrukcijos, tokių kaip tiesiaieigio, arba įsotintos magnetinės grandinės asinchroninių variklių dinamikai modeliuoti gerai tinka tik elektrodinaminis variklio modelis, tačiau pastarasis labai reiklus skaičiavimo mašinų resursams. Todėl būtinas modelis, kuris ne tik adekvačiai aprašo nesimetriškų asinchroninių variklių dinamiką, bet ir kurio greitaveika nebūtų daug mažesnė už tradicinio transformuotų koordinatų modelio greitaveiką.

Darbo tikslai ir uždaviniai

Darbo tikslai: sudaryti trifazio asinchroninio variklio matematinį ir kompiuterinį modelius fazinėje koordinatų sistemoje esant įvairiems variklio apvių jungimo atvejams, adaptuoti gautą modelį tiesiaieigio asinchroninio variklio dinamikos tyrimui, sudaryti modelius tirti dažniu valdomiems asinchroniniams varikliams.

Siekiant šio tikslo reikia išspręsti uždavinius.

1. Aprašyti variklį tokia paprastųjų diferencialinių lygčių sistema, kuriai nebūtų taikomi elektrinių grandinių simetriškumo reikalavimai.
2. Užrašyti diferencialines lygtis visiems trifazio variklio apvių jungimo būdams.
3. Pagal diferencialines lygtis sudaryti variklio kompiuterinius modelius.
4. Sudarytus modelius pritaikyti tiesiaieigio variklio modeliavimui.
5. Naudojant asinchroninio variklio modelį fazinėje koordinatų sistemoje, ištirti variklinį, generatorinį bei reversinį variklio darbo režimus.
6. Naudojant asinchroninio variklio modelį fazinėje koordinatų sistemoje, sudaryti skaliariškai valdomos asinchroninės pavaros kompiuterinį modelį, ištirti tokios pavaros darbo režimus.
7. Naudojant asinchroninio variklio modelį fazinėje koordinatų sistemoje, sudaryti srovės kanalu valdomos asinchroninės pavaros kompiuterinį modelį, ištirti tokios pavaros darbo režimus.

Mokslinis naujumas

1. Sudaryti nesimetriško asinchroninio variklio dinamikos tyrimams tinkami asinchroninio variklio fazinėje koordinatų sistemoje matematinis bei kompiuterinis modeliai.

2. Sudaryti simetriško asinchroninio variklio fazinėje koordinatų sistemoje matematinis bei kompiuterinis modeliai, kuriuos tikslinga taikyti tiriant simetriškos bet netiesiškos elektrinės grandinės variklius.
3. Sudarytas variklio modelis pritaikytas visiems nesimetriško asinchroninio variklio apvių sujungimo būdams.
4. Sudarytas *Simulink* sistemai tinkamas kompiuterinis nesimetriško asinchroninio variklio modelis, kurį paprasta naudoti modeliuojant sudėtingas mechatronines pavaras.
5. Sudarytas universalus programinis nesimetriško asinchroninio variklio modelis, kuris taikytinas darbui matematiniams skaičiavimams specializuotuose paketuose.
6. Sudarytas nesimetriškas asinchroninio variklio modelis pritaikytas tiesiaiegio variklio modeliavimui.

Tyrimų metodai. Darbe taikomi matematinio ir kompiuterinio modeliavimo, skaitiniai paprastųjų diferencialinių lygčių sprendimo ir funkcinio bei objektinio programavimo metodai.

Praktinė vertė. Sudarytas asinchroninio variklio modelis gali būti naudojamas projektuojant ir tiriant tokias valdomas asinchronines pavaras, kuriose įvertinami variklio elektrinės grandinės nesimetriškumai.

Ginamieji teiginiai

1. Matematiniai ir kompiuteriniai visiems trifazio variklio apvių jungimo atvejams pritaikyti nesimetriško asinchroninio variklio modeliai fazinėje koordinatų sistemoje.
2. Matematiniai ir kompiuteriniai visiems trifazio variklio jungimo atvejams pritaikyti simetriško variklio modeliai fazinėje koordinatų sistemoje.
3. Tiesiaiegio nesimetriškos elektrinės grandinės variklio imitavimo rezultatai.
4. Skaliariškai valdomos asinchroninės pavaros modelis ir imitavimo rezultatai.
5. Viršįtampių, atsirandančių dažnio keitiklio nuolatinės įtampos grandinėse, imitavimo rezultatai.
6. „Srovės kanalo“ metodu valdomos asinchroninės pavaros modelis ir imitavimo rezultatai.

Disertacijos struktūra

Disertaciją sudaro įvadas, keturi skyriai ir išvados. Disertacijoje remiamasi

122 šaltinių. Darbo apimtis 103 puslapiai.

Pirmajame skyriuje analizuojami dažniausiai naudojami dinaminiai asinchroninio variklio modeliai, jų privalumai ir trūkumai.

Antrajame skyriuje išvedamos asinchroninio variklio matematinio modelio fazinėje koordinačių sistemoje lygtys visiems variklio apvijų jungimo būdams. Išvestos lygtys užrašomos skaitiniams metodams tinkama forma.

Trečiajame skyriuje pateikti pagal matematinį modelį sukurti kompiuteriniai modeliai. Sudarytas *Matlab* programai pritaikytas universalus, t.y. tinkamas visiems apvijų jungimo atvejams, asinchroninio variklio kompiuterinis modelis. Variklio modelis pritaikytas ir dinaminių procesų modeliavimui skirtam *Simulink* paketui.

Ketvirtajame skyriuje asinchroninio variklio kompiuterinis modelis fazinėje koordinačių sistemoje pritaikytas nevaldomų ir valdomų pavarų imitavimui. Taipogi pateikti nesimetriško asinchroninio variklio paleidimo imitavimo rezultatai.

Darbo išvados

1. Dažniausiai naudojamų asinchroninio variklio matematinių modelių analizė rodo, kad šiuo metu nėra efektyvaus modelio nesimetriško asinchroninio variklio imitavimui.
2. Pagal apibendrintąsias asinchroninį variklį aprašančias netiesines diferencialines lygtis, nepriėmus jokių elektrinių grandinių simetriškumo sąlygų, sudarytas asinchroninio variklio fazinėje koordinačių sistemoje modelis, tinkamas asinchroninių variklių dinamikos ir darbo režimų, valdant jį iš dažnio keitiklio, tyrimams.
3. Variklio modelį fazinėje koordinačių sistemoje sudaro pirmosios eilės netiesinių diferencialinių lygčių sistema, todėl ji sprendžiama tik skaitiniais metodais, sudarant kompiuterinį variklio modelį.
4. Variklio modelio, sudaryto fazinėje koordinačių sistemoje diferencialinių lygčių būsenos kintamųjų skaičius priklauso nuo variklio apvijų jungimo schemas ir lygus 6, kai apvijos sujungtos žvaigžde be nulinio laido, ir 8 – kai apvijos sujungtos žvaigžde su nuliniu laidu arba trikampiui.
5. Variklio elektrinės grandinės nesimetriškumai apibūdinami skirtingais atskirų statoriaus (rotoriaus) apvijų parametrais. Sudarytame modelyje kiekvienos apvijos parametrai nustatomi individualiai, todėl gautą modelį galima pritaikyti nesimetriškiems varikliams modeliuoti.
6. Asinchroninio variklio modelio fazinėje koordinačių sistemoje pagrindu sudaryti valdomų elektros pavarų su dažnio keitikliais kompiuteriniai modeliai. Imitavimo rezultatai rodo, kad maitinamas iš dažnio keitiklio

variklis visą laiką dirba pereinamųjų procesų režimu. Variklio tuščiosios veikos fazinės srovės amplitudinė vertė 4,7 kartus viršija nominaliosios srovės amplitudinę vertę.

7. Sudarytas srovės kanalo metodu valdomos asinchroninės pavaros modelis. Taip valdant keitiklį, apriojamos statoriaus srovės bei momento vertės paleidimo metu. Apriojus srovės amplitudinę vertę 40 A, greičio pereinamasis procesas tęsiasi dvigubai ilgiau.
8. Sudarytas kintamos struktūros „lygintuvo-inverterio-variklio“ kompiuterinis modelis, leidžiantis tirti viršįtampius filtro kondensatoriuje. Imitavimo rezultatai rodo, kad paleidžiant variklį viršsinchroniniu greičiu viršįtampis siekia 40 %.

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**DYNAMIC MODELS OF THREE
PHASE INDUCTION MOTORS**

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

Andrius Petrovas

TRIFAZIŲ ASINCHRONINIŲ VARIKLIŲ DINAMINIAI MODELIAI

**Daktaro disertacijos santrauka
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