

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

Jonas KRIAUCIŪNAS

INVESTIGATION OF FREQUENCY CONTROLLED SENSORLESS INDUCTION MOTOR DRIVES

SUMMARY OF DOCTORAL DISSERTATION

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Introduction

Topicality of the problem. Because of simple construction, reliability, low maintenance cost and high efficiency three phase cage rotor induction motors are the most widely used as energy converters. About 90 % of all electric motors used in industry are induction motors. Analysis of modern literature shows that modeling and simulations are used to help to understand and properly control of dynamic systems processes. Induction motor drive system is non-linear system which is described by complicated and hardly solved differential equations. Therefore it is appropriate to apply computer models development and transients investigation methodology. Computer models allow to do simulations safely when different type loads are applied.

Usually sensors with moving mechanical parts are used to get feedback signal. Mentioned disadvantage reduce the reliability of the system, because over the time mechanical parts wear and increase the measurement error, cables used for data transferring can be damaged. Sometimes monitoring device can be far away from the operator panel, so extra cables are need, which increases system cost. In this case sensorless electric drives have some advantages. Sensorless induction motor or observer is computer model which mathematically calculates the desired system parameter value, for example, drive angular speed, measuring only stator currents and voltages.

Proportional integral derivative controller is the widest used speed controller in automatic control systems. Such controller in *Matlab*[®] *Simulink*[®] is designed for linear system control simulation while examined sensorless induction motor drive system is nonlinear. To solve this problem fuzzy logic method is used to tune each PID controller gain separately. The benefit of such solution is possibility to regulate non-linear system speed in all of working speed range with required system quality indices.

Rapid prototyping is a tool which allows to verify system operation in real-time when part of examined system is changed by its computer model.

Research object. The frequency controlled induction motor drive and their transients.

Aim of the work. The main aim is to investigate frequency controlled electric drive with non-linear PID controller transients whereby each gain coefficient is tuned using fuzzy logic method.

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

1. Develop simulation model of speed observer and analytically compare measured and calculated speed transients.
2. Develop and investigate scalar controlled sensorless induction motor drive simulation models with PID and fuzzy logic controllers.
3. Investigate real-time controlled induction motor drive system and perform analysis of experimental results. Verify adequacy of simulation results.

Methodology of research includes analytical, digital, experimental investigation and fuzzy logic methods as well as object-oriented computer models and simulation. Simulation models are developed in *Matlab*[®] *Simulink*[®] software. Experimental studies are carried out with specialized test bench at Electronic systems laboratory of Center for physical sciences and technology.

Scientific novelty. The following research results were obtained, that are relevant in the area of electrical engineering and electronics:

1. New simulation model of frequency controlled sensorless induction motor drive system with composite PID and fuzzy logic controller regulates motor speed in all of speed range.
2. New simulation model of scalar controlled sensorless induction motor drive system with speed observer allows calculation of actual motor speed without using specialized speed sensors, measuring only stator currents and voltages.
3. Developed real-time operating automatic control system using hardware in the loop technology where any part of the system can be changed by its computer model.

Practical value. The investigation methodology and obtained results can be used to design sensorless frequency controlled induction motor drives. Elaborated computer models can be easily improved and used to solve various engineering problems. Developed and tested by simulations systems can be used in real systems, for example, electro-mechanical speed sensors can be replaced by compact speed observers. This replacement allows decreasing system size, because not every electric motors producer provides the opportunity to install encoder on the shaft of the motor. The obtained results are useful to develop sensorless induction motor drives and research their transients. The topicality of work is proved by the high technology development programme project. During the implementation of it important results of the dissertation were obtained.

Defended propositions

1. Developed speed observer models are suitable to calculate motor steady-state speed and track speed changes with steady-state error 1.4 %, when motor setting speed and load are close to nominal values, while at no load speed observer steady-state error is 0.03 %.
2. Model of induction motor control system with composite fuzzy logic and PID controller is suitable to regulate motor speed in all of working speed range with static error ± 0.05 – ± 5 %.
3. Elaborated and experimentally investigated in real-time operating frequency controlled electric drive system is suitable to perform synthesis and analysis of separate components of the system when part of the investigated system is changed by its computer model.

The scope of scientific work. The dissertation is written in Lithuanian. The dissertation layout consists of four main chapters, list of references and list of author's publications on the subject of dissertation. The work covers 111 pages, 60 figures, 3 tables, 65 numbered formulas and 78 bibliographic sources. In the first chapter mathematical models and control methods of induction motors are reviewed. In the second chapter the development methodology and tools of induction motors computer models are presented. Simulation and experimental results of induction motor drive are presented in the third chapter.

1. Analysis of frequency controlled induction motor drives control methods and development of models

Dynamic performance of an AC machine is complex problem taking into account three phase rotor windings moving with respect to three-phase stator windings. The coupling coefficient changes continuously with the change of rotor position θ_r and machine model is described by differential equations with time varying mutual inductances. To simplify the problem solution, any three phase induction machine can be represented by an equivalent two phase machine in $d^s - q^s$ reference frame, where $d^s - q^s$ is direct and quadrature axes of stator as well as $d^r - q^r$ are direct and quadrature axes of rotor. The problem becomes simple, but problem of time varying parameters still remains. Park transformation refers the stator variables to a synchronous reference frame, fixed on the rotor. It results to all time varying inductances being eliminated. The other kind of transformation widely used is G. Kron transformation, relating both stator and rotor variables to a synchronously rotating reference frame that moves with the rotating magnetic field. Time varying inductances in

the voltage equations of an induction machine also can be eliminated by transforming rotor variables to variables associated with fictitious stationary windings. In this case, the rotor variables are transformed to a stationary reference frame fixed on the stator. This method was proposed by H. S. Stanley. Mathematical models of induction motors can be classified as shown in Fig. 1.

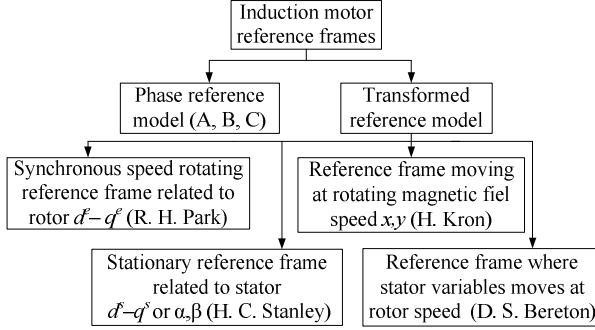


Fig. 1. Models of induction motors

A mathematical model of the induction motor in stationary reference frame $d^s - q^s$ can be written as:

$$\left\{ \begin{array}{l} \frac{d}{dt} \Psi_{qs}^s = u_{qs}^s - R_s \left(\frac{1}{L_s} + \frac{L_m^2}{(L_r L_s - L_m^2) L_s} \right) \cdot \Psi_{qs}^s + \frac{R_s L_m}{(L_r L_s - L_m^2)} \Psi_{qr}^s, \\ \frac{d}{dt} \Psi_{ds}^s = u_{ds}^s - R_s \left(\frac{1}{L_s} + \frac{L_m^2}{(L_r L_s - L_m^2) L_s} \right) \cdot \Psi_{ds}^s + \frac{R_s L_m}{(L_r L_s - L_m^2)} \Psi_{dr}^s, \\ \frac{d}{dt} \Psi_{qr}^s = -\frac{R_r L_s \Psi_{qr}^s}{L_r L_s - L_m^2} + \frac{R_r L_m}{L_r L_s - L_m^2} \Psi_{qs}^s - \omega \Psi_{dr}^s, \\ \frac{d}{dt} \Psi_{dr}^s = -\frac{R_r L_s \Psi_{dr}^s}{L_r L_s - L_m^2} + \frac{R_r L_m}{L_r L_s - L_m^2} \Psi_{ds}^s + \omega \Psi_{qr}^s. \end{array} \right. \quad (1)$$

Torque delivered by motor, is calculated as:

$$M_e = \frac{p L_m}{L_s L_r - L_m^2} \cdot (\Psi_{qs}^s \Psi_{dr}^s - \Psi_{ds}^s \Psi_{qr}^s). \quad (2)$$

A mathematical model of the induction motor in synchronous rotating reference frame $d^e - q^e$ is described by equations as:

$$\begin{aligned}
\frac{d\Psi_{qs}}{dt} &= U_{1m} \cos \gamma - \omega_e \alpha'_s \Psi_{qs} + \omega_e \alpha'_s K_r \Psi_{qr} + \omega_e \Psi_{ds}, \\
\frac{d\Psi_{ds}}{dt} &= U_{1m} \sin \gamma - \omega_e \alpha'_s \Psi_{ds} + \omega_e \alpha'_s K_r \Psi_{dr} - \omega_e \Psi_{qs}, \\
\frac{d\Psi_{qr}}{dt} &= -\omega_e \alpha'_r \Psi_{qr} + \omega_e \alpha'_r K_s \Psi_{qs} + (\omega_e - \omega_r) \Psi_{dr}, \\
\frac{d\Psi_{dr}}{dt} &= -\omega_e \alpha'_r \Psi_{dr} + \omega_e \alpha'_r K_s \Psi_{ds} - (\omega_e - \omega_r) \Psi_{qr}.
\end{aligned} \tag{3}$$

Developed electromagnetic torque is calculated as:

$$M_e = \frac{2}{3} p \frac{\omega_e K_r}{\sigma X_s} (\Psi_{qr} \Psi_{ds} - \Psi_{qs} \Psi_{dr}). \tag{4}$$

To control induction motor drives scalar or field oriented control methods can be choosed. The control method depends on requirements for controlled system. When high control accuracy is not required scalar control is used, e. g., for ventilation system, otherwise field oriented control is needed.

2. Investigation methods of sensorless frequency controlled induction motor drives

First of all, control speed requires its measurement. There are a lot of devices used for this purpose: tacho-generators, electrical-optical encoders and others. Almost all speed sensors are mechanical and they have moving parts also cables to transfer measured data. These disadvantages make system more unreliable. In order to avoid mentioned shortcomings problem to design new sensors without moving parts and cabling system appears. One of solution could be the speed observer. In this way the reliability and maintenance of the system would be increased. The motor speed can be calculated from the state equations using the $d^s - q^s$ stationary reference frame. Motor stator voltage equation in a $d^s - q^s$ reference frame for direct axis can be written as:

$$u_{ds}^s = i_{ds}^s R_s + L_{ls} \frac{d}{dt} (i_{ds}^s) + \frac{d}{dt} (\Psi_{dm}^s). \tag{5}$$

Substituting $\Psi_{dr}^s = \frac{L_r}{L_m} \Psi_{dm}^s - L_{lr} i_{ds}^s$ in (5) gives:

$$u_{ds}^s = \frac{L_m}{L_r} \frac{d}{dt} (\Psi_{dr}^s) + (R_s + \sigma L_s s) i_{ds}^s. \quad (6)$$

Similarly, the Ψ_{qr}^s expression can be derived as:

$$\frac{d}{dt} (\Psi_{qr}^s) = \frac{L_r}{L_m} u_{qs}^s - \frac{L_r}{L_m} (R_s + \sigma L_s s) i_{qs}^s. \quad (7)$$

The rotor flux linkage equations in a d^s - q^s reference frame can be given as:

$$\frac{d}{dt} (\Psi_{dr}^s) = \frac{L_m}{L_r} i_{ds}^s - \omega_r \Psi_{qr}^s - \frac{1}{T_r} \Psi_{dr}^s, \quad (8)$$

$$\frac{d}{dt} (\Psi_{qr}^s) = \frac{L_m}{L_r} i_{qs}^s - \omega_r \Psi_{dr}^s - \frac{1}{T_r} \Psi_{qr}^s. \quad (9)$$

Simplifying expressions and entering the variables the following mathematical model of speed observer is obtained:

$$\omega_r = \frac{1}{\hat{\Psi}_r^2} [(\Psi_{dr}^s \dot{\Psi}_{qr}^s - \Psi_{qr}^s \dot{\Psi}_{dr}^s) - \frac{L_m}{T_r} (\Psi_{dr}^s i_{qs}^s - \Psi_{qr}^s i_{ds}^s)]. \quad (10)$$

According to (10) equation can be designed computer model of speed observer.

To control speed of induction motor speed controller is required.

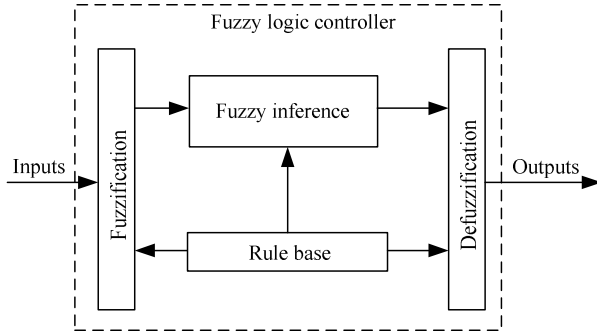


Fig. 2. Structure of a fuzzy logic controller

Usually in automatic control systems PID controller is used. PID controller given in *Matlab*[®] *Simulink*[®] software is developed for the control of linear

systems. As induction motor system is non-linear author proposed to use fuzzy logic method to tune PID gains. The structure of fuzzy logic controller is shown in the Fig. 2.

A fuzzy logic controller is based on a set of control rules called as the fuzzy rules among the linguistic variables. These rules are expressed in the form of conditional statements. Basic structure of the fuzzy logic controller consists of three important parts: fuzzification, knowledge base – decision making logic (inference system) and the defuzzification. The decision making unit uses the conditional rules of “if-then-else”. In the fuzzification process, the crisp variables, e. g., the speed error and the change in error are converted into fuzzy variables or the linguistics variables. The fuzzification maps the input variables to linguistic labels of the fuzzy sets. The fuzzy controller uses the linguistic labels as: NL (negative large), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), and PL (positive large). Each fuzzy label has an associated membership function.

The hardware in the loop (HIL) simulation is a recognized simulation method in different engineering areas, e. g., control of induction motor drive. HIL applications are used by design and test engineers to evaluate and validate components during development of new systems. Rather than testing these components in complete system simulations, HIL allows the testing of new components and prototypes while communicating with software models that simulate the remainder of the system. Replacing the remainder of the system with computer models running software simulations greatly reduces the size and complexity of applications and increases the flexibility and rate of running many different tests and test scenarios.

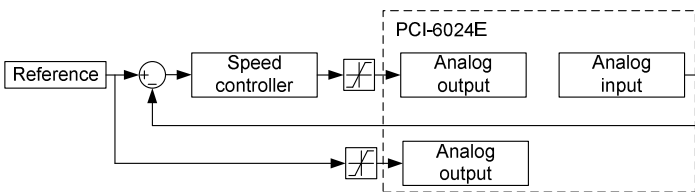


Fig. 3. Simulink model of used hardware in the loop simulation

As the name implies, in HIL simulation, a part of the system is modeled and simulated in real-time, while the remainder is the actual hardware, connected in closed loop by various I/O interfaces such as analog to digital (A/D) and digital to analog (D/A) converters, and signal conditioning equipment. *Matlab*[®] *Simulink*[®] model of HIL simulation is presented in Fig. 3.

3. Simulation and experimental research of sensorless frequency controlled induction motor drives

Frequency controlled induction motor drive is non-linear system and it is very difficult to calculate its parameters, because they are varying all the time. So, the conventional PID controller can work only in a certain point of all operating range. The self tuning fuzzy PID speed controller is created to solve this problem. Proposed controller can work in all of working speed range from 1 rad/s till synchronous speed. Model of induction motor with synthesis of fuzzy logic and PID controllers is presented in Fig. 4.

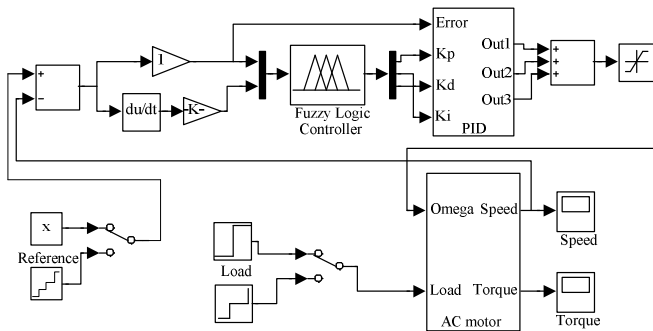


Fig. 4. *Simulink*[®] model of closed loop speed drive with self adjustable PID controller

Fig. 5 shows comparison of the induction motor speed reference and speed response signals.

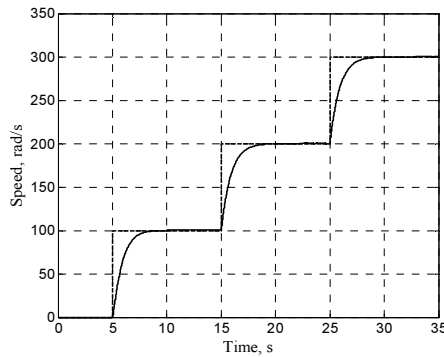


Fig. 5. Transients of the reference speed (dashed) and motor response signals (solid)

Obviously, the speed controller based on fuzzy logic with auto-tuning capability controls motor speed with a small time lag because of the motor inertia. It tooks 5 s to reach steady-state after the speed reference was changed 100 rad/s. As it is seen, there is no overshoot or oscillations.

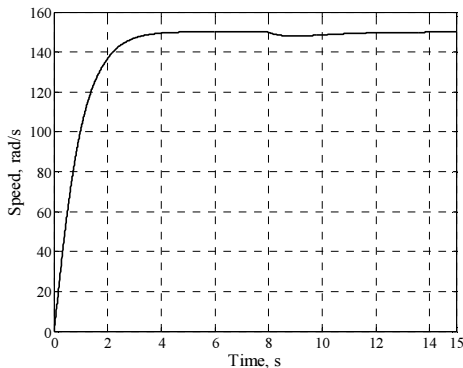


Fig. 6. Speed transient of induction motor

Fig. 6. shows speed transient of induction motor when reference signal is 150 rad/s. In Fig. 7 motor is loaded by 5 N·m at time 8 s. It is seen, that speed transient of fuzzy PID controlled system reaches steady-state value in 5 s with no overshoot and oscillations. After the 5 N·m load is on, motor speed decreases, but it took less than 5 s to restore it to reference signal. The transients shows, that proposed controller works smoothly.

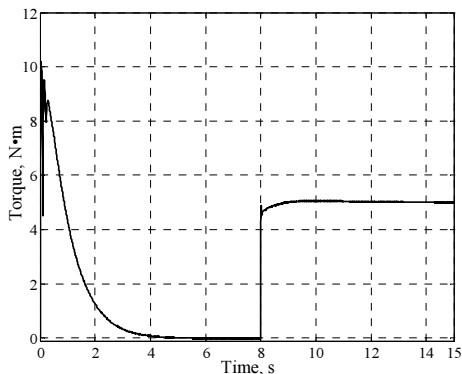


Fig. 7. Torque response of induction motor

Developed *Matlab*[®] *Simulink*[®] model of induction motor drive with speed observer is presented in Fig. 8. Motor model is elaborated in synchronous speed rotating reference frame.

Usually to measure feedback signal sensors are required. These sensors have moving parts and cables for data transferring so over the time likelihood, that they will fail or will continue to increase their margin of error. Also, these transducers are not reliable to use in the aggressive condition, as the dirt can have influence on the clear work of the transducer. In addition, connection of these transducers with the system requires cables, which can sometimes be the reason of failure, also, the cable system increases the price of the system.

Therefore the problem to have reliable speed sensor requires looking for solutions eliminating discussed shortcomings. As an alternative to transducer could be a speed observer. Observer is a program or model, which allows the calculation of motor parameters, for example, speed, torque, measuring only voltages and currents of the motors.

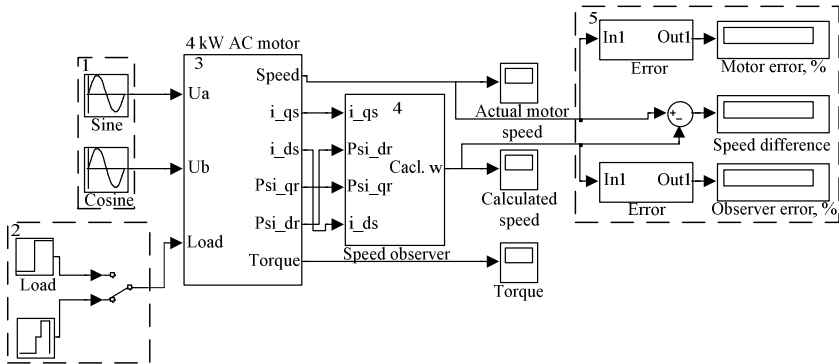


Fig. 8. *Simulink*[®] model of the induction motor drive with speed observer

Model consists of (Fig. 8): 1 – power supply, 2 – load control block, 3 – induction motor, 4 – speed observer, 5 – error measuring block. Transformed induction motor reference frame from phase to stationary, measured stator currents and calculated fields motor speed can be calculated. According to (10) equation computer model of speed observer is created and presented in Fig. 9.

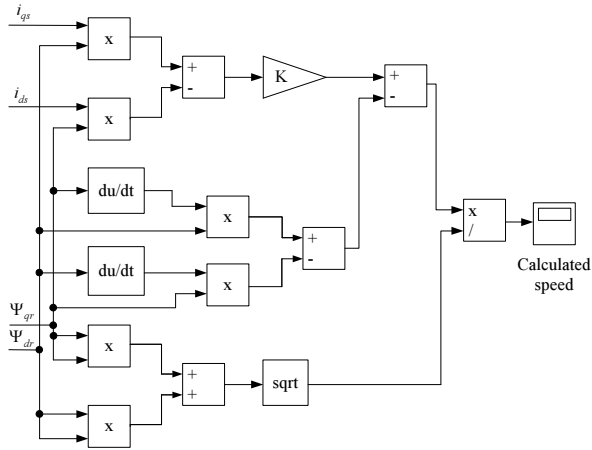


Fig. 9. Simulink[®] model of speed estimation from state equations

Fig. 10 and Fig. 11 shows induction motor real and estimated speed and torque transients. The speed reference signal is 150 rad/s. Investigating the response of induction motor and speed observer to variable load at time $t = 0.5$ s motor is loaded by nominal 13.2 N·m load. Motor steady-state error after loading is 3.2 % while speed observer calculated speed error is 5.7 % compared with the reference signal. Hence, speed error calculated by observer is 2.5 % compared with motor speed.

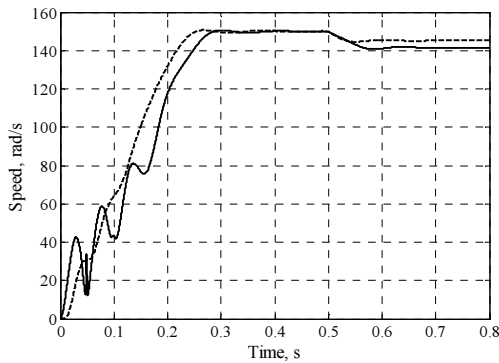


Fig. 10. Real (dashed line) and estimated (solid line) speed, when reference speed 150 rad/s

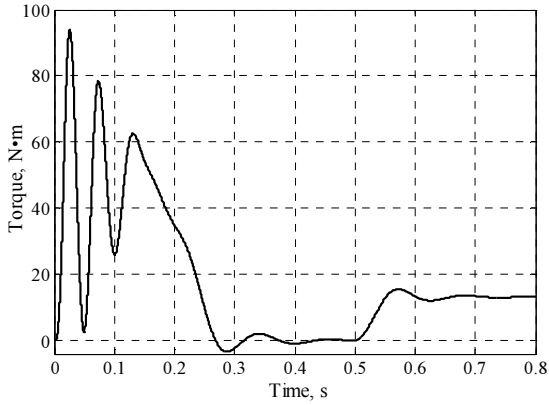


Fig. 11. Torque transient at load 13.2 N·m and reference speed 150 rad/s

The hardware in the loop control model of 4 kW electric drive system with speed feedback signal is elaborated. Required speed value is maintained by PI and PID controllers. Controlled system includes speed and torque reference signals, both those can be changed. The model of proposed system is shown in Fig. 12 and view of the examined system is presented in Fig. 13.

Analyzed obtained results established that speed observer precisely tracks motor speed and reacts to applied load.

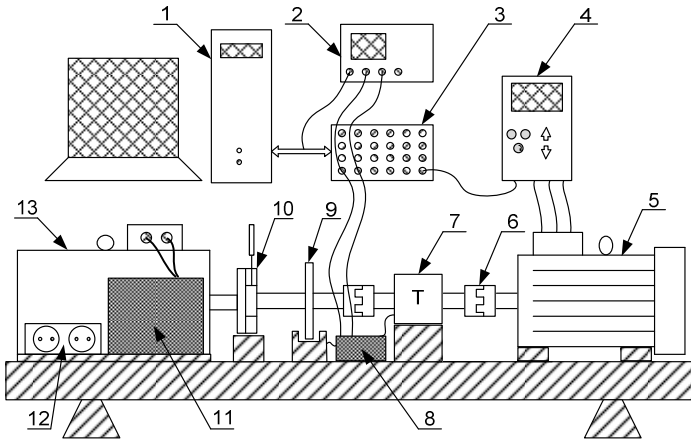


Fig. 12. Structure of experimental stand of frequency controlled drive

Here 1 is personal computer; 2 – oscilloscope; 3 – multifunction data acquisition card; 4 – frequency converter; 5 – induction motor; 6 – clutch; 7 – torque sensor; 8 – signal measuring card; 9 – speed sensor; 10 – mechanical brake; 11 – generator load control block; 12 – sockets; 13 – DC generator.

Analog reference signal can be changed from 0 to 10 V. 10 V corresponds to nominal drive speed which is 2890 rpm. Analog reference signal is sent to frequency converter where 10 V corresponds to 50 Hz. In order the *Simulink*[®] and frequency converter could communicate the digital signal processing (DSP) NI (National instruments) 6024E card is used. Also this analog to digital conversion card needs to read the feedback signal. DSP NI 6024E card has 15 analog inputs and 2 analog outputs. The power of used frequency converter is 7.5 kW. Torque is measured using *Lorens Messsetechnik GmbH DR-2212-R* type contactless rotary torque sensor. To load the AC motor is used 6x1 kW lamps. All measurements are recorded using *Tektronix TDS 2024B* oscilloscope.

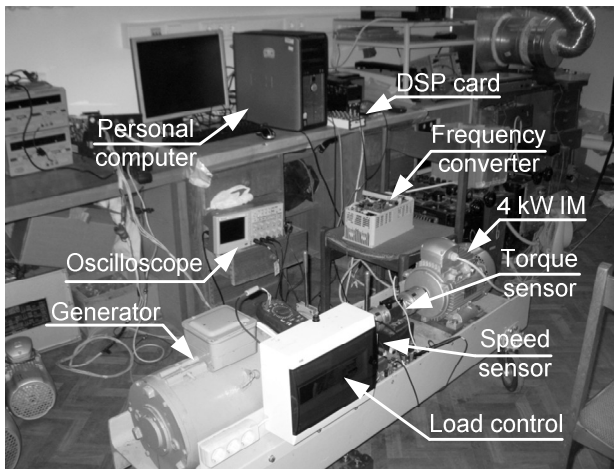


Fig. 13. View of the experimental stand

Experimental and simulation results of 4 kW induction motor in HIL controlled system results are presented and discussed.

Fig. 14 shows experimental and simulation speed and torque transients when speed reference 4 V or 121 rad/s and load is 0.4 mV or 13.2 N·m. The PID regulator was used.

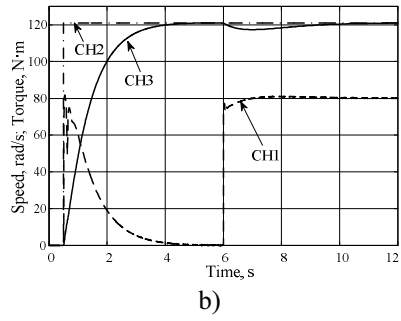
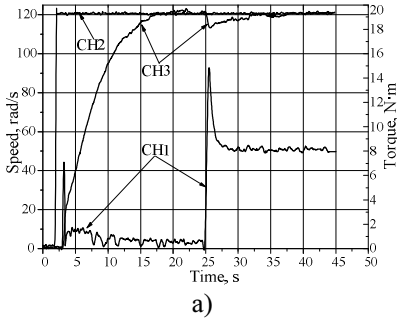


Fig. 14. Speed and torque experimental (a) and simulation (b) transients (CH1 – torque, CH2 – speed reference signal, CH3 – motor speed)

Fig. 15 shows motor speed and torque transients in HIL controlled system when motor works at steady-state and is loaded/unloaded.

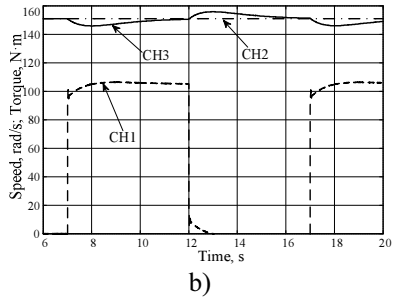
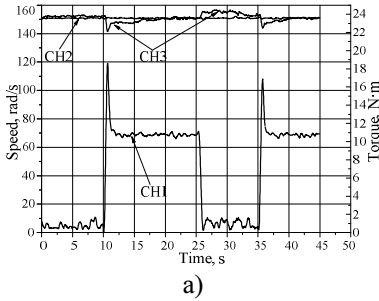


Fig. 15. Speed and torque experimental (a) and simulation (b) transients at steady-state (CH1 – torque, CH2 – speed reference signal, CH3 – motor speed)

Here speed reference is 5 V or 151 rad/s and torque is 10.6 N·m. After motor is loaded the speed drops down, but it took less than 5 s to return it to reference speed. It is clear, that torque oscillates less after the motor is loaded. The PID controller was used.

General conclusions

1. Proposed model of speed observer measures steady-state speed and tracks motor speed changes with 1.4 % steady-state error at high operating speed range and loads close to nominal values while at medium speed range static error is 2.5 %. Operating at no load static error is 0.03 % when speed

reference is close to nominal speed and up to 3 % at low speed reference. Consequently sensorless speed observer models are suitable to measure speed of induction motors and are able to replace usual electro mechanical sensors and encoders which reduce system reliability, increases system size and cost.

2. Frequency controlled electric drive system is non-linear system. When PID controller is used to control non-linear system it is applicable fuzzy logic method to tune each gain coefficient separately, such synthesis of controllers is composite controller which allows to control motor speed in all of operating speed range till synchronous speed with static error ± 0.05 – ± 5 %.

3. After the controller synthesis found that tuned up PID gains in the way, that start up transient are smooth and without overshoot the control quality is lost after static load is applied, so additional gain tuning is necessary. System transients quality indices meet the requirements for automation control systems without additional gain tuning when composite controller is used.

4. Developed scalar controlled induction motor drive system simulation model is verified experimentally using real-time controlled experimental test bench with 4 kW induction motor drive. Simulation transients time is smaller than experimental because model does not evaluate limited frequency converter start up time. According to obtained results developed system model can be applied to the new frequency controlled induction motor drives models development.

List of published works on the topic of the dissertation In the reviewed scientific journals

Juraitis, S.; Rinkevičienė, R.; Kriauciūnas, J. 2011. Fuzzy Controller of Two-mass System. *Electronics and electrical engineering*. No. 10(116): 3–6. Kaunas: Technologija. ISSN 1392-1215 (Thomson Reuters Web of Science).

Rinkevičienė, R.; Kriauciūnas, J. 2012. Fuzzy logic controller of the ventilation system. *Przegląd elektrotechniczny*. Vol. 88, iss. 7b. 192–194. ISSN 0033-2097. (Thomson Reuters Web of Science).

Rinkevičienė, R.; Kriauciūnas, J. 2013. An investigation and simulation of frequency controlled electric drive system. *Elektronics and electrical engineering*. No. 2: 17–20. Kaunas: Technologija. ISSN 1392-1215. (Thomson Reuters Web of Science).

Kriauciūnas, J.; Juraitis, S. 2012. Dvimasė elektromechaninė sistema su neraiškiosios logikos reguliatoriumi. *Mokslas – Lietuvos ateitis*. T. 4, Nr. 1: 43–46. Vilnius: Technika. ISSN 2029-2341.

In the other editions

Rinkevičienė, R.; Kriauciūnas, J. 2010. Modelling of the variable speed drive with speed observer. *In Proceedings of the 5th International Conference on Electrical and Control Technologies ECT-2010*. Kaunas: Technologija. 215–218. ISSN 1822-5934.

Kriauciūnas, J.; Rinkevičienė, R.; Juraitis, S. 2011. Simulation of Two-mass System with Fuzzy Controller. *In Proceedings of the 6th International Conference on Electrical and Control Technologies ECT-2011*. Kaunas: Technologija. 105–108. ISSN 1822-5934.

Kriauciūnas, J.; Rinkevičienė, R. 2012. Investigation into frequency controlled electric drive. *In Proceedings of the 7th International Conference on Electrical and Control Technologies ECT-2012*. Kaunas: Technologija. 117–120. ISSN 1822-5934.

Rinkevičienė, R.; Kriauciūnas, J. 2011. Fuzzy logic controller of the ventilation system. *In Proceedings of XXI International Conference on Electromagnetic Disturbances EMD'2011*. Bialystok, Poland. 222–252. ISBN 978-836-2582-075.

Kriauciūnas, J.; Rinkevičienė, R. 2012. Disturbances in the controlled variable speed drive. *In Proceedings of the 22nd International Conference on Electromagnetic Disturbances EMD'2012*. Vilnius, Lithuania. 56–59. ISBN 978-609-4572-609.

Rinkevičienė, R.; Kriauciūnas, J. 2010. Modeling of speed observer of the induction motor. *In Proceedings of Doctoral School of Energy and Geotechnology*. Pärnu, Estonia. 14–18. ISBN 978-998-5690-499.

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BEJUTIKLIŲ ASINCHRONINIŲ DAŽNINIŲ PAVARŲ TYRIMAS

Mokslø problemos aktualumas. Trifaziai narveliniai asinchroniniai varikliai dėl konstrukcijos paprastumo, palyginti mažų eksploatacinių kaštų, patikimumo ir gana didelio efektyvumo yra plačiausiai pavarose naudojami energijos keitikliai ir sudaro 90 % visų pramonėje naudojamų elektros variklių.

Šiuolaikinės literatūros analizė įrodo, kad modeliavimas ir imitavimas naudojami suprasti ir tinkamai valdyti dinaminių sistemų vyksmus.

Asinchroninė pavana yra netiesinė sistema, kuri aprašoma sudėtingomis ir sunkiai išsprendžiamomis diferencialinėmis lygtimis, todėl šių sistemų tyrimui tikslinga taikyti kompiuterinių modelių sudarymo ir imitacinių vyksmų tyrimo metodiką. Sudarius tokios sistemos modelį galima saugiai tirti jos veikimą esant skirtingo pobūdžio apkrovų charakteristikoms arba išorinių trikdžių poveikiui.

Dažniausiai grįžtamojo ryšio signalui gauti naudojami jutikliai, kurie turi judančias mechanines dalis ir jų prijungimui prie stebėjimo sistemos reikalingi kabeliai. Minėti trūkumai mažina sistemos patikimumą, nes bėgant laikui mechaninės dalys dyla ir didėja matavimo paklaidos, o duomenų perdavimas kabeliais gali būti sutrikdytas jų pažeidus. Kartais stebimas įrenginys gali būti pakankamai toli nuo operatoriaus pulto, todėl reikalingi papildomi kabeliai, kurie didina sistemos kaštus. Tokiu atveju tikslinga naudoti bejutikles elektros pavaras. Bejutiklė asinchroninė pavana arba stebiklis, tai kompiuterinis modelis, kuris matematiškai apskaičiuoja norimą sistemos parametą, pavyzdžiui, kampinį sukimosi greitį, matuojant tik statoriaus srovės ir įtampas.

Dažniausiai automatinio valdymo sistemose sutinkamas proporcinio integralinio diferencialinio (PID) tipo greičio reguliatorius. Toks *Matlab*[®] *Simulink*[®] pakete pateikiamas reguliatorius yra pritaikytas tiesinių sistemų modeliavimui, o nagrinėjama bejutiklė asinchroninė pavana yra netiesinė sistema. Šiai problemai spręsti pritaikytas neraiškosios logikos metodas, kurio pagalba kiekvienas PID reguliatoriaus koeficientas derinamas atskirai. Šio sprendimo nauda – netiesinės elektromechaninės sistemos greitis reguliuojamas visame darbinių greičių diapazone atitinka sistemos kokybės rodiklius.

Prototipų kūrimas yra priemonė, kuri leidžia realioju laiku patikrinti sistemos veikimą, kai dalis sistemos yra jos kompiuterinis modelis.

Tyrimų objektas. Dažninės asinchroninės pavaros ir jų pereinamieji vyksmai.

Darbo tikslas. Ištirti asinchroninės bejutiklės pavaros su netiesiniu PID reguliatoriumi, kurio kiekvienas koeficientas yra derinamas neraiškosios logikos metodu, pereinamuosius vyksmus.

Darbo uždaviniai. Darbo tikslui pasiekti keliama tokie uždaviniai:

1. Sudaryti asinchroninio variklio sukimosi greičio stebiklio kompiuterinį modelį, analiziškai palyginti išmatuoto ir apskaičiuoto greičio charakteristikas.

2. Sudaryti ir ištirti skaliariniu būdu valdomos bejutiklės asinchroninės pavaros modelius su PID ir neraiškiosios logikos reguliatoriais. Palyginti ir išanalizuoti imitacinius pereinamuosius vyksmus.
3. Atlikti realiuoju laiku valdomos pavaros eksperimentinius tyrimus ir patikrinti sukurtų modelių adekvatumą.

Tyrimų metodika. Darbe naudojami analiziniai, skaitmeniniai, eksperimentinio tyrimo ir neraiškiosios logikos metodai, objektinis kompiuterinių modelių sudarymas ir imitacijos. Imitaciniai modeliai sudaryti *Matlab*[®] *Simulink*[®] aplinkoje. Eksperimentiniai tyrimai atlikti Valstybinio mokslinių tyrimų instituto Fizinių ir technologijos mokslų centro Elektroninių sistemų laboratorijoje.

Mokslinis naujumas. Sprendžiant darbo uždavinius gauti šie elektros ir elektronikos inžinerijos mokslui nauji rezultatai:

1. Sudarytas naujas bejutiklės asinchroninės dažninės pavaros imitacinis modelis su kombinuotu PID ir neraiškiosios logikos reguliatoriumi, kuris leidžia valdyti pavaros greitį visame darbinų greičių diapazone.
2. Sudarytas naujas bejutiklės asinchroninės dažninės pavaros valdomos skaliariniu metodu imitacinis modelis su greičio stebikliu, leidžiantis apskaičiuoti faktinį pavaros sukimosi greitį nenaudojant specializuotų greičio jutiklių, o matuojant tik statoriaus srovės ir įtampas.
3. Panaudojant specialiąją techninę įrangą, sudaryta realiuoju laiku veikianti uždaroji automatinio valdymo sistema, kurioje bet kuri sistemos dalis gali būti pakeista sudarytu jos kompiuteriniu modeliu.

Praktinė vertė. Remiantis tyrimų metodika ir gautais rezultatais gali būti projektuojamos bejutiklės bejutiklės asinchroninės dažninės pavaros. Sudarytus kompiuterinius modelius galima pritaikyti automatinio valdymo problemoms spręsti. Sukurtos ir imitacijų būdu patikrintos sistemos gali būti pritaikomos realiose sistemose, pavyzdžiui, elektromechaniniai greičio jutikliai gali būti pakeisti kompaktiškais greičio stebikliais. Tokiu būdu galima sumažinti sistemos gabaritais, nes, pavyzdžiui, ne kiekvienas elektros variklio gamintojas numato galimybę sumontuoti enkoderį ant jų gaminamo variklio veleno. Taip pat sumažinami kaštai kabeliams, o tuo pačiu padidinamas sistemos patikimumas.

Šio mokslinio darbo rezultatai yra naudingi projektuojant bejutiklės asinchronines elektros pavaras ir tiriant jų pereinamuosius vyksmus. Disertacijos tema pateiktų darbų aktualumą taip pat rodo dalyvavimas aukštųjų

technologijų plėtros programos projekte, kurį vykdant gauti svarbūs disertacijai rezultatai.

Ginamieji teiginiai

1. Sukurti greičio stebiklių modeliai tinka apskaičiuoti nusistovėjusį asinchroninio variklio greitį ir sekti greičio pokyčius esant 1,4 % nusistovėjusio režimo nuokrypiui nuo užduotos vertės, kai variklio nuostatas ir apkrova yra artimi vardiniams dydžiams, o varikliui veikiant tuščiosios veikos režimu, stebiklio nusistovėjusio režimo nuokrypis nuo užduotos vertės – 0,03 %.
2. Asinchroninio variklio valdymo sistemos modelis su kombinuotu neraiškiosios logikos ir PID reguliatoriumi tinka reguliuoti variklio greitį darbinių greičių diapazone esant $\pm 0,05$ – ± 5 % nusistovėjusio režimo nuokrypiui nuo užduotos vertės.
3. Sudaryta ir eksperimentiškai patikrinta realiuoju laiku veikianti asinchroninės dažninės pavaros sistema tinka atlikti sistemos atskirų elementų sintezę ir analizę, kai dalis tiriamosios sistemos yra pakeista sudarytu jos kompiuteriniu modeliu.

Darbo apimtis. Disertaciją sudaro įvadas, trys skyriai, rezultatų apibendrinimas, literatūros ir publikacijų disertacijos tema sąrašas. Disertacijoje yra 111 puslapių teksto, 60 paveikslų, 3 lentelės ir 65 numeruotos formulės. Rašant disertaciją panaudoti 78 literatūros šaltiniai. Pirmame disertacijos skyriuje apžvelgiami asinchroninių variklių matematiniai modeliai ir valdymo metodai. Antrame skyriuje aprašoma bejutiklių asinchroninių pavarų kompiuterinių modelių sudarymo metodika ir priemonės. Asinchroninės pavaros imitacinių ir eksperimentinių tyrimų rezultatai pristatomi trečiajame skyriuje

Bendrosios išvados

1. Pasiūlytas greičio stebiklio modelis matuoja nusistovėjusio režimo greitį ir seka greičio pokyčius esant 1,4 % greičio nuokrypiui nuo realios variklio greičio vertės didelių darbinių greičių diapazone ir esant apkrovai artimai nominaliajai, o vidutinių greičių diapazone nuokrypis nuo realaus variklio greičio siekia 2,5 %. Nusistovėjusio režimo greičio nuokrypis nuo užduotos vertės siekia iki 0,03 % vardinių greičių diapazone ir iki 3% mažų bei vidutinių greičių diapazone. Todėl bejutikliai greičio stebiklio modeliai yra tinkami asinchroninio variklio greičiui matuoti ir gali pakeisti įprastus

- elektromechaninius greičio stebiklius ir enkoderius, kurie mažina sistemos patikimumą, didina sistemos gabaritus bei kainą.
2. Dažninė asinchroninė pavarą yra netiesinė sistema, kurią valdant PID reguliatoriumi, kiekvienam PID reguliatoriaus koeficientui derinti tikslinga taikyti neraiškosios logikos metodą, tokios reguliatorių sintezės rezultatas yra susiderinantis reguliatorius, kuris leidžia reguliuoti variklio greitį darbinių greičių diapazone iki sinchroninio greičio esant $\pm 0,05$ – ± 5 % nuokrypiui nuo užduotos vertės.
 3. Atlikus reguliatorių sintezę nustatyta, kad suderinus PID reguliatoriaus parametrus taip, kad paleidimo pereinamasis vyksmas būtų sklandus ir be perreguliuojimo yra prarandama proceso valdymo kokybė įjungus statinę apkrovą, todėl būtinas papildomas koeficientų koregavimas. Naudojant susiderinantį reguliatorių sistemos pereinamųjų vyksmų kokybės rodikliai tenkina automatinio valdymo sistemoms keliamus reikalavimus be papildomo derinimo.
 4. Sukurto skaliariniu metodu valdomo modelio adekvatumas ištirtas eksperimentiškai, naudojant realiuoju laiku valdomą bandymų standą su 4 kW asinchroniniu varikliu. Gautų imitacinių pereinamųjų vyksmų trukmė yra mažesnė, negu eksperimentinių dėl realios sistemos inercijos momento ir dažnio keitiklio įgreičio apribojimų. Tyrimo rezultatai rodo, kad sudarytas sistemos modelis gali būti taikomas naujų asinchroninių dažninių pavarų modelių kūrimui.

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INVESTIGATION OF FREQUENCY CONTROLLED
SENSORLESS INDUCTION MOTOR DRIVES

Summary of Doctoral Dissertation
Technological Sciences,
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Jonas KRIAUCIŪNAS

BEJUTIKLIŲ ASINCHRONINIŲ DAŽNINIŲ
PAVARŲ TYRIMAS

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