Introductory Chapter: Introduction to the Design and the Control of Electrical Machines

Abdel Ghani Aissaoui

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.78772

1. Introduction

In the last century, electrical machines have been the subject of a huge development. New concepts in design and control allow expanding their applications in different fields. They are considered important components in many industrial applications as: power systems, manufactories, power plants, electrical vehicles, and home appliances.

There are several types of electrical machines; we can find synchronous machines, induction machines, direct current (DC) machines, reluctance synchronous machines, transformers, etc. (**Figure 1**).

The electrical machines are incorporated into the process of energy conversion in the generation, transmission, and consumption of electric power. In a power station, turbine generator converts the energy coming from the combustion of coal, natural gas, etc. into electric energy

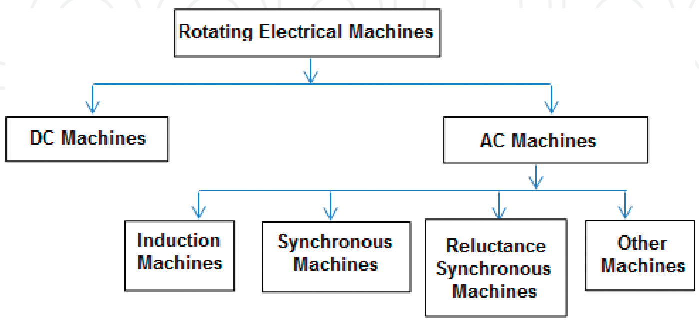

Figure 1. Different types of electrical machines.

that is transmitted to consumers: motors whose mechanical energy drive machines in industry, homes, traffics, etc.

Most applications are interested in rotating electrical machines. The rotating electrical machine can operate, without constructional changes, as a motor or generator, since the energy direction of an electrical machine is reversible (**Figure 2**).

Electrical machines can be classified according to the torque producing mechanism and their magnetic interactions. The first class based on the torque producing mechanism machines is classified into two types, one is alignment torque producing machines such as DC machines, induction, and synchronous machines and the second is the reluctance torque producing machine, for example, switched reluctance machines. The second class based on the magnetic interactions machines is classified as inductive-interactive type machines, for example, induction machines, synchronous machines, and DC machines, and variable reluctance type machines, for example, switched reluctance machines [1].

The electrical drive systems were developed based on the use of electrical machines. The majority of all drive systems are electrical drives with growing tendency. Electrical drive systems do not have a power density as high as pneumatic or hydraulic systems. Electrical motors are bulky and heavy in comparison to these competitors.

Electrical drives are considered for three reasons superior to other drive systems, such as pneumatic and hydraulic systems:

- Cleanliness of the energy supply
- Dynamics of control
- High efficiency of electromechanical power conversion

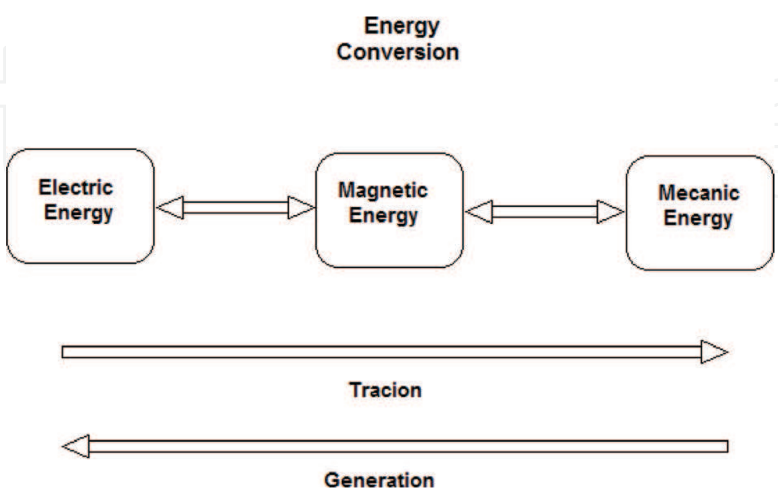

Figure 2. Conversion energy in electrical machines.

http://dx.doi.org/10.5772/intechopen.78772

The main part of these systems is electrical rotating machine. With the advent of power electronics, new possibilities appear for electrical machines with variable speed. Their technical performance and economical design opened a new philosophy of drive applications.

The control of electrical power today is possible within short time for megawatts. It can be controlled so fast than any other form of energy.

The energy conversion between electrical and mechanical power is performed by the electrical machine in both directions.

Electrical machines can be used for different ranges of speed. It can be used as motor particularly in traction, electrical vehicles, etc. or as generators in power station, wind turbines, etc.

2. Design

The electrical machines are usually manufactured through mass-production techniques; their performances can be affected by manufacturing processes and different operational conditions (e.g., temperature). As a requirement of quality control, a robust design process is often applied to minimize the influence of uncertainties on the machine performance.

However, the conventional computer simulation cannot reflect the influences of the environmental uncertainties directly. The input data of the numerical model are usually the geometries of the modeled device, the material properties, and the uncertainties in both must be taken into account. While most of the works in the robust design of electromagnetic devices focus on the uncertainties in the geometries [2–4], only a few efforts have been conducted on the influences of the material uncertainties. In electromagnetic field computing, the nonlinear behavior of the constitutive laws of ferromagnetic materials is usually obtained by B-H curves. For ferromagnetic materials, [5] constructed a stochastic material model using the uncertainties of the measured points to characterize a nonlinear B-H curve. In [6], a global sensitivity analysis was applied to study the variance of the predicted behavior of a turbo-alternator with respect to material uncertainties.

All the above stochastic material models have formed a solid foundation for the study of material uncertainties in the electromagnetic design. A robust design system can then be implemented for the analysis and design of electrical machines in order to minimize the effects of manufacturing errors in both iron and permanent magnets [7].

There are some general design methods, which can be applied in terms of different disciplines/domains: electromagnetic design, thermal design, structural design, multi-physics design, material design, and manufacturing process design.

Electromagnetic design: The principle of operation of electrical machines is based on the electromagnetic theory. Electromagnetic design is based on the calculation of magnetic field and its distribution in the electrical machines, which allowed to compute some basic electromagnetic parameters including winding inductance and the evaluation of some performances, such as electromagnetic force, power loss, and efficiency. To obtain the magnetic field, there are three main kinds of analysis methods, analytical method, magnetic circuit method, and finite element method (FEM) [8–10, 14, 15]. Meanwhile, power losses and efficiency are two important performance indexes for electrical machines.

Thermal design and structural design: these methods can be applied after the accomplishment of the electromagnetic design. The thermal design method aim is to compute the temperature distribution in the machine based on the heat obtained from the electromagnetic analysis. There are popular methods for the thermal analysis of electrical machines. They are computational fluid dynamics (CFD), FEM, and nodal method. Structural design aims to consider the stress and deformation of the machine under the electromagnetic and thermal analyses. Structural design can be conducted based on FEM as well [12, 13].

Multi-physics design: It aims to calculate the electromagnetic characteristics, temperature distribution, structural stress, vibration noise, and coupled performances of electrical machines based on a uniform model [8, 9, 10, 11]. The FEM has been widely employed as a powerful tool for the multi-physics design and analysis of electrical machines. It can be used to analyze the coupled field in machines, such as electromagnetic structure and thermal structure.

Material design: The type of material is important for the electromagnetic, thermal, and structural designs of electrical machines. Nowadays, new developed magnetic materials like soft magnetic composite (SMC), amorphous and grain-oriented silicon steel show better characteristics, such as high saturation flux density, low specific losses, and low manufacturing cost. They can be employed to design motors with new topologies, higher efficiency, and/or low manufacturing cost [16, 17].

Manufacturing process design: Manufacturing method design is also important in the design stage of electrical machines, which will influence their manufacturing quality and actual performances in operation. To obtain the best performances, some designs have complex structures which can be difficult for manufacturing.

With a good knowledge of the magnetic characteristics and manufacturing methods, we can fully exploit all the performances of the designed motors. A good motor design should be done in terms of both output performances and manufacturing abilities [18].

3. Optimization

Optimization is a very popular term in modern design of electrical machines and devices due to the competition in the world markets, increased cost of electrical energy, and pressures for its conservation.

Optimization helps designers to push the existing invisible design boundaries while using available materials and technology. The objective of the optimization process is usually to minimize either the initial cost of the machine or its lifetime cost including the cost of lost energy. Other objectives such as mass minimization or efficiency maximization may also be appropriate in some situations [19, 20].

http://dx.doi.org/10.5772/intechopen.78772

This can be explained and understood through the words of Miller [21]: "To a WISE engineer, optimal design means a compromise between conflicting factors, often producing an imperfect result from optimistic aspirations."

Most of the metaheuristic techniques can be used to solve global optimization problems with nonlinear constraint by using metaheuristic algorithms; there is a high possibility to determine a near optimal solution, which can be considered by designer and engineering as a global optimum [22].

One of the most promising algorithms from the class of evolutionary algorithms widely used in the field of electric machines is Differential Evolution (DE) [22–24] first introduced by Price and Storn [25] in 1995. The algorithm was later improved and named Generalized Differential Evolution (GDE) (extended DE for constrained multi-objective optimization) by Lampinen and Zelinka [25, 26].

Variety of other algorithms is used in electric machine design optimization: Genetic Algorithm (GA) [27, 28], Particle Swarm Optimization (PSO) [29, 30], Simulated Annealing (SA) [31], etc. Authors in [32] compared GA, SA, and DE on the design optimization of permanent magnet motor and authors in [32] compared DE, GA, and PSO on the design optimization of microstrip antennas. Both groups agree that the DE performance is the best. In [33, 34], PSO and GA were compared and PSO was found computationally more effective with slightly better objective function value reached. In [35], it is shown how PSO performs better than GA so some authors decided to use hybrid GA-PSO method [36, 37].

4. Control of electrical machines

The control of electrical machines has been the subject of great progress, due to the development and advancement in the field of power electronic devices, digital signal processing, the informatics tools, and advanced control techniques.

The energy conversion between electrical and mechanical power is performed by the electrical machine in both directions. The control of this energy is very important. In the case of motors, we control the electric power consumed, and in the case of generator, we control the electric power generated. The control of electrical machines can be expanded to other variables as speed, voltages, currents, flux, torque, etc. **Figure 3** shows the control structure of electrical machines.

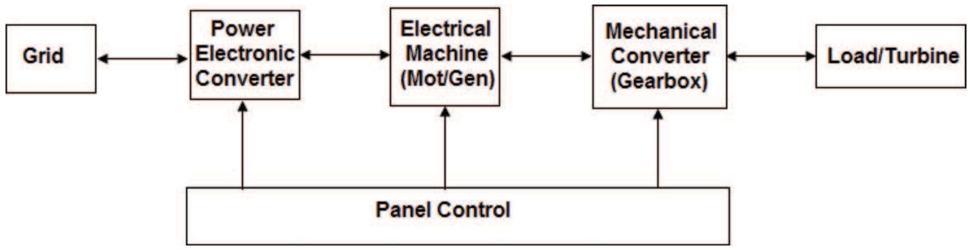

Figure 3. Control structure of electrical machines.

The electrical drive systems are based mostly on electrical machines. These machines can be designed to operate at different speeds: high, medium, and low speed. According to these benefits, the use of electrical machines with variable speed is very important in the field of power station, wind turbine, electrical vehicles, etc.

The electrical machines with high speed is in continuous evolution for a number of applications, including aero engine spools, electrical turbo-compounding systems, electrical spindles for milling cutters and grinding, helicopter and racing engines, turbochargers, fuel pumps, etc. These applications have typical operational speeds of over 10,000 r/min.

In the control design, we follow the next steps:

- Modeling: The plant can be described in the form of some mathematical equations. These equations constitute the mathematical model of the plant. A plant model should produce the same output response as the plant for the same inputs.
- Controller design: The controller is designed to meet the performance requirements for the plant model.
- Implementation: The implementation can be done using a digital computer. Its efficiency depends on the type of computer available, the type of interface devices between the computer and the plant, software tools, etc.

Figure 4 shows different steps of control design.

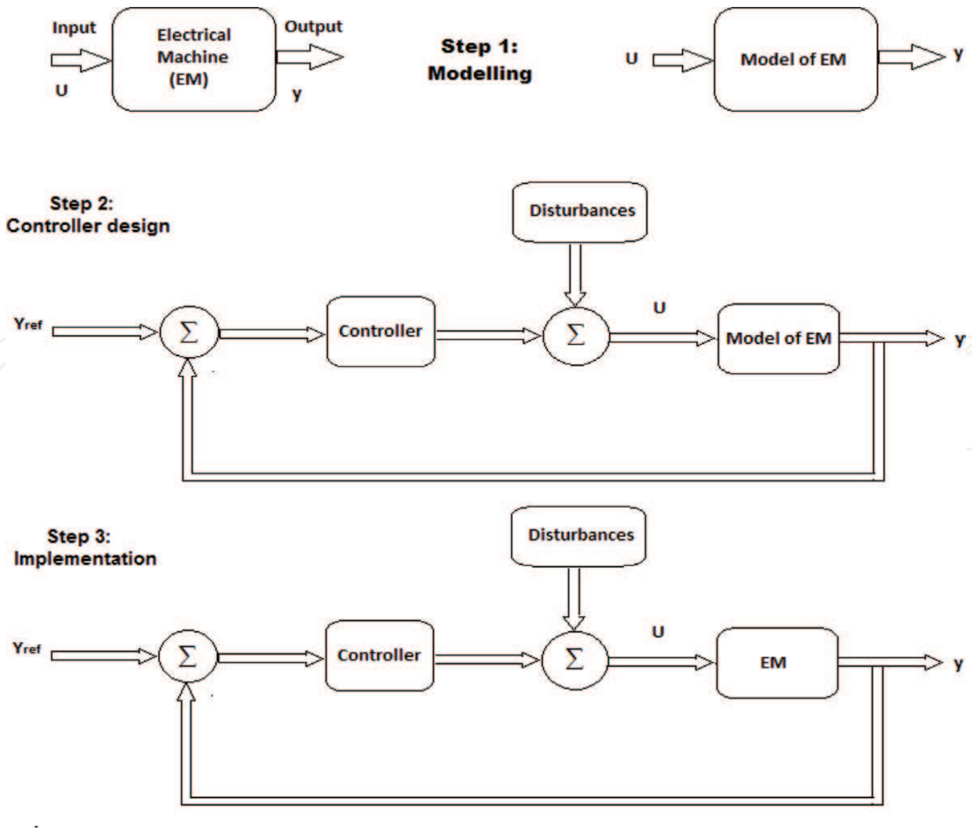

Figure 4. The steps of control design.

The control of these machines is very complicated. We need to represent them by mathematical models. Their models are defined by coupled and nonlinear equation systems.

Some mathematical transformations can be used to simplify the form of these models as Park transformation, Clark transformation, etc. The analytic approach of these equations is very complicated. To solve these systems of equations, the numerical methods are recommended.

Following the obtained models many strategies of controls were developed such as vector control, direct torque control, direct power control, etc., and these strategies aim to give more flexibility to the control systems.

New techniques of control were developed based on the powerful control theory and artificial intelligence tools. Many control techniques were studied and applied to electrical machine, which we can find variable structure control, model reference adaptive control, adaptive pole placement control, predictive control, backstepping control, etc. The use of artificial intelligence techniques has been the subject of many recent researches. The most famous are the fuzzy logic control, the neuronal control, the neuro fuzzy control, etc. In the literature, we can find many researches on these topics.

In [38], a model reference adaptive control-based estimated algorithm was proposed for online multi-parameter identification. In [39], MRAS observer was designed for the field oriented control of DFIG. Authors in [40] give an overview of model predictive control for induction motor drives. In [41], cascaded nonlinear predictive control was proposed for the control of induction motor. Backstepping controller was proposed in [42] for induction machine. An adaptive backstepping sliding mode controller was presented in [43]. A fuzzy logic controller was developed for a switched reluctance motor in [44].

Author details

Abdel Ghani Aissaoui

Address all correspondence to: irecom_aissaoui@yahoo.fr

Electrical Department, Faculty of Technology, University of Tahri Mohamed of Bechar, Algeria

References

[1] Rajendran N. A survey on electrical machines for variable speed applications. Indian Journal of Science and Technology. 2015;**8**(31). DOI: 10.17485/ijst/2015/v8i31/84306

[2] Yoon S-B, Jung I-S, Hyun D-S, Hong J-P, Kim Y-J. Robust shape optimization of electromechanical devices. IEEE Transactions on Magnetics. 1999;**35**:1710-1713

[3] Alotto P, Magele C, Renhart W, Weber A, Steiner G. Robust target functions in electromagnetic design. COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering. 2003;**22**:549-560

[4] Steiner G, Weber A, Magele C. Managing uncertainties in electromagnetic design problems with robust optimization. IEEE Transactions on Magnetics. 2004;**40**:1094-1099

[5] Bartel A, de Gersem H, Hulsmann T, Romer U, Schops S, Weiland T. Quantification of uncertainty in the field quality of magnets originating from material measurements. IEEE Transactions on Magnetics. 2013;**49**:2367-2370

[6] Mac D, Clenet S, Beddek K, Chevallier L, Korecki J, Moreau O, Thomas P. Influence of uncertainties on the B (H) curves on the flux linkage of a turboalternator. International Journal of Numerical Modelling: Electronic Networks, Devices and Fields. 2014;**27**:385-399

[7] Li M, Mohammadi MH, Rahman T, Lowther D. Analysis and design of electrical machines with material uncertainties in iron and permanent magnet. COMPEL–The International Journal for Computation and Mathematics in Electrical and Electronic Engineering. 2017;**36**(5):1326-1337

[8] Lei G, Zhu JG, Guo YG. Multidisciplinary Design Optimization Methods for Electrical Machines and Drive Systems. Berlin/Heidelberg, Germany: Springer-Verlag; 2016. ISBN 978-3-662-49269-7

[9] Lei G, Liu CC, Guo YG, Zhu JG. Multidisciplinary design analysis and optimization for a PM transverse flux machine with soft magnetic composite core. IEEE Transactions on Magnetics. 2015;**51**(11)

[10] Lei G, Liu CC, Zhu JG, Guo YG. Robust multidisciplinary design optimization of PM machines with soft magnetic composite cores for batch production. IEEE Transactions on Magnetics. 2016;**52**(3)

[11] Kreuawan S, Gillon F, Brochet P. Optimal design of permanent magnet motor using multidisciplinary design optimization. In: Proceedings of the 18th International Conference on Electrical Machines; Pattaya, Thailand; 25-28 October, 2015. pp. 1-6

[12] Lin F, Zuo S, Wu X. Electromagnetic vibration and noise analysis of permanent magnet synchronous motor with different slot-pole combinations. IET Electric Power Applications. 2016;**10**:900-908

[13] Li Y, Chai F, Song Z, Li Z. Analysis of vibrations in interior permanent magnet synchronous motors considering air-gap deformation. Energies. 2017;**10**:1259

[14] Pfister P-D, Perriard Y. Very-high-speed slotless permanent-magnet motors: Analytical modeling, optimization, design, and torque measurement methods. IEEE Transactions on Industrial Electronics. 2010;**57**(1):296-303

[15] Luise F, Tessarolo A, Agnolet F, Pieri S, Scalabrin M, di Chiara M, de Martin M. Design optimization and testing of high-performance motors: Evaluating a compromise between quality design development and production costs of a Halbach-Array PM slotless motor. IEEE Industry Applications Magazine. 2016;**22**(6):19-32

[16] Krings A, Boglietti A, Cavagnino A, Sprague S. Soft magnetic material status and trends in electric machines. IEEE Transactions on Industrial Electronics. 2017;**64**(3):2405-2414

[17] Fan T, Li Q, Wen X. Development of a high power density motor made of amorphous alloy cores. IEEE Transactions on Industrial Electronics. 2014;**61**(9):4510-4518

[18] Okamoto S, Denis N, Kato Y, Ieki M, Fujisaki K. Core loss reduction of an interior permanent-magnet synchronous motor using amorphous stator core. IEEE Transactions on Industrial Applications. 2016;**52**(3):2261-2268

[19] Lei G, Zhu J, Guo Y, Liu C, Ma B. A review of design optimization methods for electrical machines. Energies. 2017;**10**(12):1962. DOI: 10.3390/en10121962

[20] Liu X, Slemon G. An improved method of optimization for electrical machines. IEEE Transactions on Energy Conversion. 1991;**6**(3):492-496

[21] Miller T. Optimal design of switched reluctance motors. IEEE Transactions on Industrial Electronics. 2002;**49**(1):15-27

[22] Andersen SB, Santos IF. Evolution strategies and multiobjective optimization of permanent magnet motor. Applied Soft Computing. 2012;**12**(2):778-792

[23] Zarko D, Ban D, Lipo T. Design optimization of interior permanent magnet (IPM) motors with maximized torque output in the entire speed range. In: European Conference on Power Electronics and Applications; 2005. 10pp

[24] Zhang P, Sizov G, Ionel D, Demerdash N. Establishing the relative merits of interior and spoke-type permanent magnet machines with ferrite or NdFeB through systematic design optimization. IEEE Transactions on Industry Applications. 2015;**99**:1

[25] Storn R, Price K. Differential Evolution—A simple and efficient adaptive scheme for global optimization over continuous spaces. Technical Report TR-95-012. ICSI; March 1995

[26] Lampinen J, Zelinka I. Mixed integer-discrete-continuous optimization by differential evolution—Part 1: The optimization method. In: 5th International Mendel Conference on Soft Computing; 1999. pp. 71-76

[27] Kukkonen S, Lampinen J. Performance assessment of generalized differential evolution 3 with a given set of constrained multi-objective test problems. In: IEEE Congress on Evolutionary Computation, CEC 09; 2009. pp. 1943-1950

[28] Lukaniszyn M, JagieLa M, Wrobel R. Optimization of permanent magnet shape for minimum cogging torque using a genetic algorithm. IEEE Transactions on Magnetics. 2004;**40**(2):1228-1231

[29] Bianchi N, Durello D, Fornasiero E. Multi-objective optimization of a PM assisted synchronous reluctance machine, including torque and sensorless detection capability. In: 6th IET International Conference on Power Electronics, Machines and Drives (PEMD 2012); March 2012. pp. 1-6

[30] Duan Y, Harley R, Habetler T. Multi-objective design optimization of surface mount permanent magnet machine with particle swarm intelligence. In: IEEE Swarm Intelligence Symposium; September 2008. pp. 1-5

[31] Ma C, Qu L. Multiobjective optimization of switched reluctance motors based on design of experiments and particle swarm optimization. IEEE Transactions on Energy Conversion. 2015;**99**:1-10

[32] Mutluer M, Bilgin O. Comparison of stochastic optimization methods for design optimization of permanent magnet synchronous motor. Neural Computing and Applications. 2012;**21**(8):2049-2056

[33] Deb A, Gupta B, Roy J. Performance comparison of differential evolution, genetic algorithm and particle swarm optimization in impedance matching of aperture coupled microstrip antennas. In: 11th Mediterranean Microwave Symposium (MMS); September 2011. pp. 17-20

[34] Duan Y, Harley R, Habetler T. Comparison of particle swarm optimization and genetic algorithm in the design of permanent magnet motors. In: IEEE 6th International Power Electronics and Motion Control Conference, IPEMC; 2009. pp. 822-825

[35] Mutluer M, Bilgin O. Design optimization of PMSM by particle swarm optimization and genetic algorithm. In: International Symposium on Innovations in Intelligent Systems and Applications (INISTA), 2012; July 2012. pp. 1-4

[36] Sarikhani A, Mohammed O. Hybrid GA-PSO multi-objective design optimization of coupled PM synchronous motor-drive using physics-based modeling approach. In: 14th Biennial IEEE Conference on Electromagnetic Field Computation (CEFC); 2010. pp. 1-1

[37] Stipetic S, Miebach W, Zarko D. Optimization in design of electric machines: Methodology and workflow. In: International Aegean Conference on Electrical Machines & Power Electronics (ACEMP); Side, Turkey. 2-4 September 2015. pp. 441-448

[38] Zhong C, Lin Y. Model reference adaptive control (MRAC)-based parameter identification applied to surface-mounted permanent magnet synchronous motor. International Journal of Electronics. 2017;**104**(11):1854-1873

[39] Esmaeeli MR, Kianinejad R, Razzaz M. Field oriented control of DFIG based on modified MRAS observer. In: Proceedings of 17th Conference on Electrical Power Distribution Networks (EPDC); Tehran, Iran. May 2012. pp. 2-3

[40] Zhang Y, Xia B, Yang H, Rodriguez J. Overview of model predictive control for induction motor drives. Chinese Journal of Electrical Engineering. 2016;**2**(1):62-76

[41] Hedjar R, Toumi R, Boucher P, Dumur D. Cascaded nonlinear predictive control of induction motor. European Journal of Control. 2004;**10**(1):65-80

[42] Moutchou M, Moahmoudi H, Abbou A. Backstepping control of the induction machine, based on flux sliding mode observer, with rotor and stator resistances adaptation. International Review of Automatic Control (IREACO). 2014;**7**(4):394-402

[43] Lin F-J, Shen P-H, Hsu S-P. Adaptive backstepping sliding mode control for linear induction motor drive. IEE Proceedings–Electric Power Applications. 2002;**149**(3):184-194

[44] Bolognani S, Zigliotto M. Fuzzy logic control of a switched reluctance motor drive. IEEE Transactions on Industry Applications. 1996;**32**(5):1063-1068