New structural approach to reducing doubly salient variable reluctance motor's torque undulations

Abdelmajid Berdai,Abdelhamid Hmidat, Abdelaziz Belfqih, Jamal Boukherouaa, Faissal El Mariami,
Valery Titjuk, Vladimir Vlasenko

Abstract— The Switched Reluctance Motor (SRM) is widely applied for high-speed applications, because of its simple mechanical structure and development of power electronics. But a major disadvantage of SRM is the undulations of the electromagnetic torque witch constitute one of the major problems encountered in using variable reluctance machines. SRM torque undulations are caused by motor design and the way in which its phase windings are supplied. Each phase's level of electromagnetic torque largely depends on the rotor's angular position in relation to the phase, as well as current values of the phase, which, in its turn, is appreciably nonlinear. Research carried out in this field has had two main focuses:The first concerns finding and implementing the optimal control law by motor phase currents [1-4]. The second aims to come up with more efficient motor designs [5-8], of the magnetic system in particular, through determination of the basic magnetic relationship: number of poles, angles of stator pole and rotor teeth, shape of teeth, etc. This work focuses on finding optimal geometric relations in order to minimise electromagnetic torque undulations.

Index Terms— Torque Ripple Minimization, Switched Reluctance Machine (SRM),

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1. Introduction

Switched reluctance motor (SRM) drives are simpler in construction compared to induction and synchronous motors. Their combination with power electronic controllers may yield an economical solution. The structure of the motor is simple with concentrated coils on the stator and neither windings nor brushes on the rotor. This apparent simplicity of its construction is deceptive. SRM drives present several advantages as high efficiency, maximum operating speed, good performance of the motor in terms of torque/inertia ratio together with four-quadrant operation, making it an attractive solution for variable speed applications. The torque pulsations in switched reluctance motors are relatively higher compared to sinusoidal machines, due to the doubly salient structure of the motor .

In the Analysis of earlier studies, the authors propose in [1], a method for optimal control of phase current in order to minimise electromagnetic torque undulations. Rotation and flux-leakage torque characteristics are used to this end. The principle of optimal current generation is explained by the fact that, for a determined phase current value, the corresponding torque value is defined, which is compared with the value of the predefined torque, following which phase current is regulated. If phase current reaches a predetermined limit and, at the same time, the torque does not adjust its predefined value, the next phase's current is regulated, and it is then assumed that only two of the motor's phases are operating at the same time. This task is resolved discretely through the digital method, and consequently computation time must satisfy the motor's predefined speed. Therefore, during

computation, mutual inductance between phase and the active resistance of the motor's stator windings is ignored. In implementing this approach, we observed an 18% to 3% decrease in the torque undulation rate. Study [2] shows a method for using the neuro-fuzzy regulator to generate an optimal form of current. Here, the neuro-fuzzy signal from the compensator is added to the output value of the classic PI control loop in the of the closed loop current control system's regulation contour. Based on mathematical modelling, the proposed method's potential effectiveness is clearly demonstrated.

Analysing the approach taken by the method presented for solving this problem, a number of difficulties hampering its implementation may be remarked, including determination of the optimal phase current form for each of the motor's running speeds, the need to compute the synchronisation current in relation to rotor position, and supply of a high-speed, high-precision control system during implementation of a determined form of current. In addition, in the case of machines already built, methods for optimising the motor's control system are pertinent, so it is impossible to modify such machines' design. However, optimisation of the motor's design parameters is required when designing the SRM's electric drive system, and also facilitates their control

One of the methods of influencing the motor torque's form as regards its supply side is changing the phases' ignition and extinction angles and, by doing so, the commutation interval. The study presented in [3] shows the results of studies made of this means of influence. It was observed that increasing the phase ignition angle at constant commutation interval results in an increase in amplitude of motor torque undulations. This study also

shows how much influence the number of sections in each of the machine's phases has on undulation levels. Results confirm that any increase in the number of a phase's sections or number of phases leads to a reduction in torque undulation. It was observed that increasing numbers of sections from 3 to 6 led to an almost sixfold reduction in the undulation rate.

In order to find optimal parameters for SRM machines' magnetic system, researchers usually determine dimensions of the stator's and rotor's opening angles. In [4], the study proposes using a genetic algorithm and, as the result of the search for optimal solutions, gave recommended values for angles of polar arcs. In this respect, therefore, conclusions drawn on the basis of the torque's static characteristics depending on rotor position were well drawn, giving an idea on torque modification under constant current conditions. This same real current of the motor's phase varies depending on time, and possesses increasing and decreasing zones. Therefore, in this work, results could not be confirmed on a dynamic model enabling estimation of total torque undulation when working with w determined charge.

2. Position of the problem

analysis of a number of research works in this field leads to thought being given to the appreciable influence the geometric parameters of the motor's active zone's magnetic system have on electromagnetic torque wave form [7, 8]. Little research has been done on the special form of teeth and influence on the dynamic characteristics of the electromagnetic torque. In this work, we propose changing the geometric parameters of the SRM's magnetic system by addition of size b supplementary projections on rotor teeth (figure 1), so increasing the angle of the arc of rotor tooth α_r. The width of the rotor tooth's base, however, remains the same. This study, then, will bear on the influence the projecting part of the tooth has on the motor's torque's electromagnetic

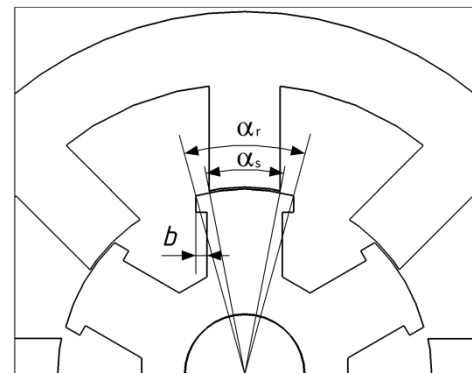undulations in order to determine the tooth's optimal shape.

Fig.1 SRM magnetic system

3. Theoretical approach and summary

In this research work, study of the SRM's basic electric drive system was carried out by modelling the system's electromagnetic field using the integral equation method [9]. This particular method was chosen because, unlike the finite element method, it only requires discretisation of the magnetic structure zone, which considerably simplifies calculations.

Starting out from the mathematical model produced from field theory, we computed stator inductance depending on variations in the rotor's angular position. According to the experimental model described in [10], we chose a 4-phase, 8/6 configuration SRM, as also described in reference [10]. Simulation of the motor's magnetic field was carried out with a steep of 2° throughout the period of the phase's inductance variation. Position 0 of angle θ corresponds to the stator and rotor poles' position of opposition.

Digital simulation of the SRM's electromagnetic field was carried out for a number of different widths of the rotor tooth's projecting part. Figure 2 shows the images of magnetic fields with poles' opposition position, for a series of values for the rotor tooth's arc angle.

a)   b)

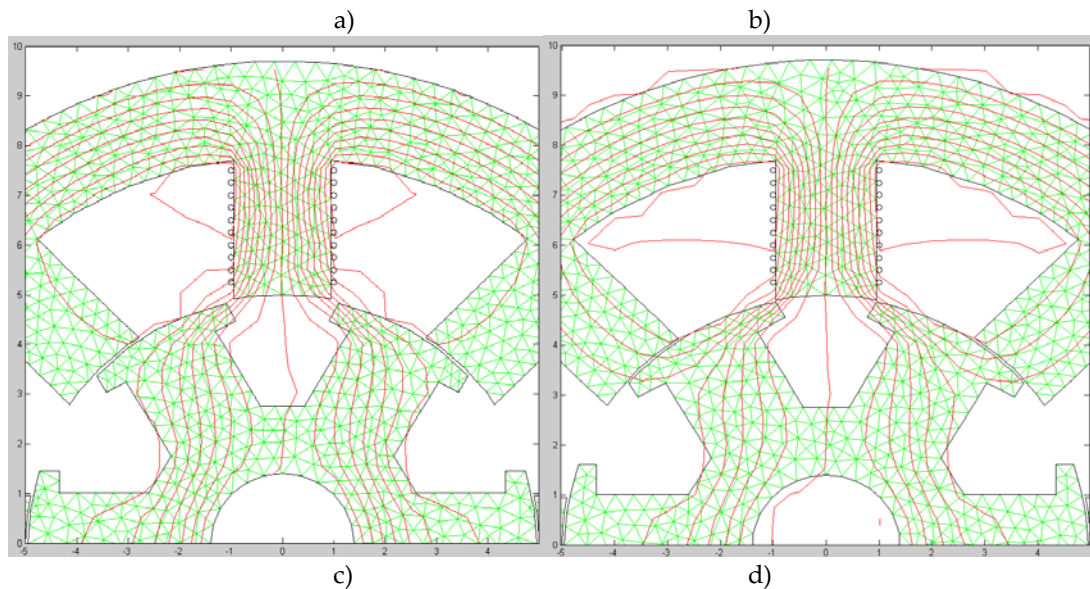c)   d)
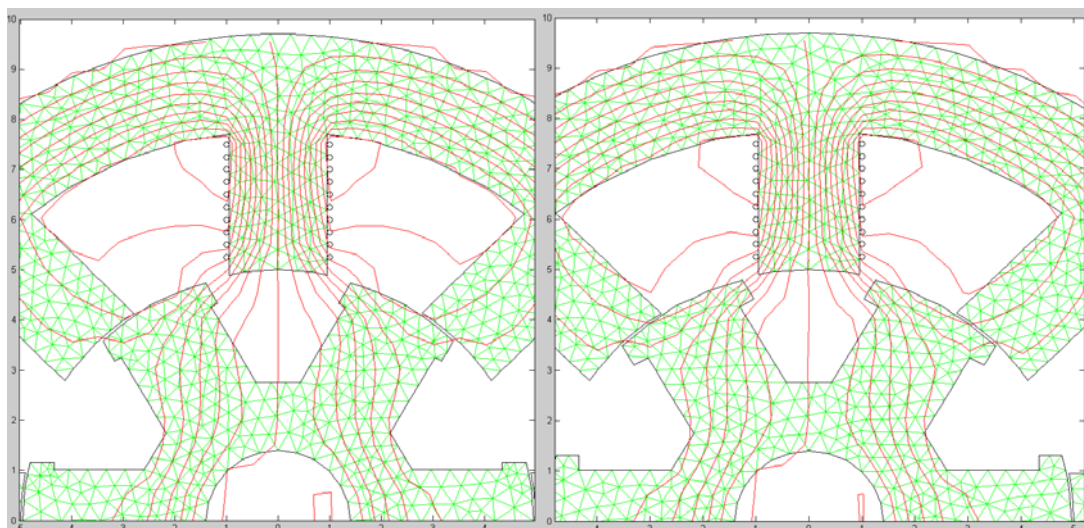
Fig.2 Images of the electromagnetic field for different rotor-tooth shapes
a) 27°; b) 30.5°; c) 34°; d) 38°.

On the basis of the results obtained from computation of the mathematical model of the motor's magnetic field, we were able to define the characteristics of the stator's inductance depending on rotor angle position L(θ) for various angles of rotor-tooth arcs, which are shown in Figure 3.

As almost all the magnetic flux passes through the stator's active pole, computation of phase inductance is carried out in the following way:

$$L = \frac{\Psi}{I} = \frac{2\Phi w}{I} \qquad (1)$$

Where $\Phi = \int B dl$ - The magnetic flux passing

through the stator pole's transversal section; B - induction of a transversal section on the stator pole; w - the number of spires per phase; I – current in a phase bobbin.
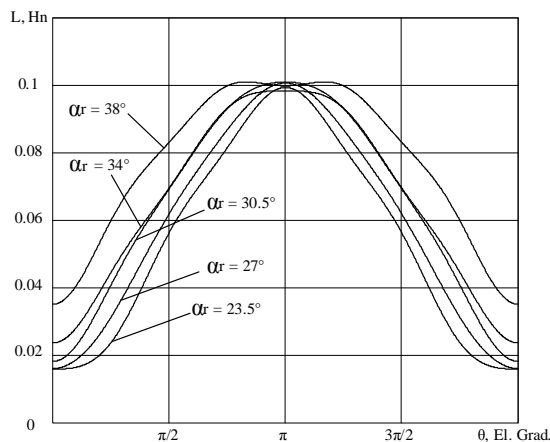

Fig. 3 - The function of L (θ) for the various rotor tooth arc angles

4. Mathematical Approach and simulation

The next step in simulating the SRM's dynamic processes was to establish the system of differential equations, on a basis taking the previously determined function $L(\theta)$ into full consideration.

Taking account of the complexity of electromagnetic phenomena in a SRM with a passive rotor, it is desirable to adopt the following hypotheses:

- Absence of mutual inductance between phase bobbins;
- Inverter switches are perfect – commutation is produced immediately without loss of energy;
- Infinite power supply with energy recuperation;
- No losses due to hysteresis or Foucault currents.

The above hypotheses enable simplification of the system of differential equations by rejecting insignificant factors and processes.

Data obtained through digital simulation was approximated by Fourier series, and is therefore presented by the analytical function of L (θ), with the function obtained used in the SRM's mathematical model [11,12], which may be presented by the following system of differential equations:

$$\begin{cases} u_k = Ri_k + L(\theta_k)\dfrac{di_k}{dt} + \omega\dfrac{\partial L(\theta_k)}{\partial \theta}i_k \\[2mm] M_e = \dfrac{\partial L(\theta_k)}{\partial \theta_k} \cdot \dfrac{i_k^2}{2} \\[2mm] \dfrac{d\omega}{dt} = \dfrac{1}{J} \cdot (M_e - M_c) \\[2mm] \dfrac{d\theta_k}{dt} = \omega \end{cases}$$

$$(2)$$

Where k = 1... m – phase number; u_k and i_k – designate voltage and current of phase k respectively.

θ_k: Angle of rotor position in relation to phase k

R: Active resistance of the stator winding

M_e: Electromagnetic torque

M_c – Resistant torque opposed by the load

J: Moment of inertia

ω: Rotor's angle speed.

By using the function of the phase inductance determined by equation (2), total electromagnetic torque may be simulated by block diagrams. Simulation was carried out in the Matlab Simulink environment. The diagram of the principle of the model so developed, which is the subject of this study, is shown in Figure 4.
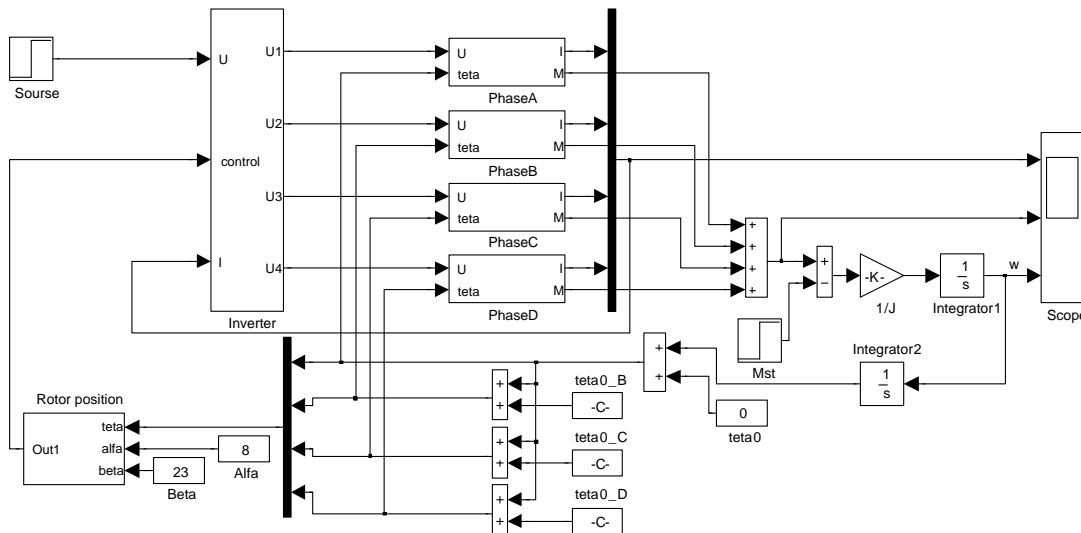

Fig. 4. Functional diagram of the model for SRM simulation

The power source is presented in the *source* block with voltage U supplying the transistorised *inverter* simulation block. The order of commutation of phases is defined depending on the rotor's angle of rotation by the *rotor position* block, which, by imitating the operation of the position captor, generates control pulses by power switches within the limits of specified phase commutation angles. These pulses are generated by blocks *alpha* and *beta* respectively. From the *inverter* block, voltage is supplied at entrance U of one of the *Phase A-D* subsystems, so simulating phase operation. With release of phase switches, the supply block is polarised under inverse voltage, and current circulates through the back-off diodes. When the current in the phase cancels out, the diodes are blocked and the current in the phase is extinguished. For specified torque values of the various phases, the *sum* block generates the resulting electromagnetic torque. The *Mst* block simulates the static torque opposed by the motor charge. Block *1/J* represents the moment of the motor's inertia.

Initial value of the rotor's angle of rotation is determined from the *teta0* block. Monitoring of variation of the different parameters is carried out by the bloc representing the scope.

Figure 5 presents the structure diagram of the model of a phase (bloc phase A). For certain laws of instantaneous variance of supply voltage and the rotation angle of rotor θ, this block calculates the value of the current and the electromagnetic moment. It is composed of blocks *L(teta)* and *dL_dteta*, forming the liaison between $L(\theta)$ and $dL(\theta)/d\theta$ respectively and their proposed approximate functions.
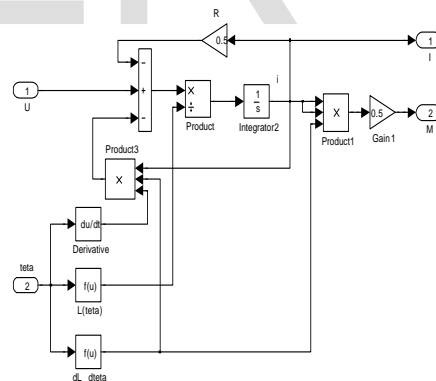

Fig.5. Model of simulation of an SRM phase

The process for starting the motor under nominal load was calculated on the basis of the above-mentioned model. Graphs obtained from such computation clearly show variations depending on time and main basic parameters. The form of the electromagnetic torque developed by the motor for various rotor tooth shapes is shown in Figure 6. Simulation was carried out under the same conditions: angles of commutations, supply voltage, static load torque, etc.
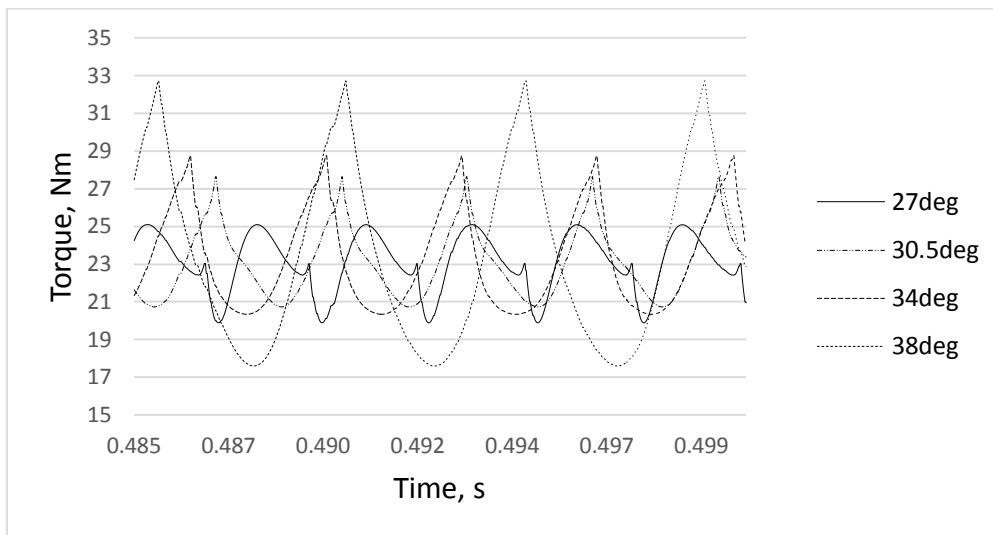
Fig. 6 – Motor's electromagnetic torque for various angles of the rotor tooth with projecting part

The main criterion for analysing the effectiveness of the proposed modifications to the motor's magnetic systems is use of the torque's undulation factor, which is defined as follows:
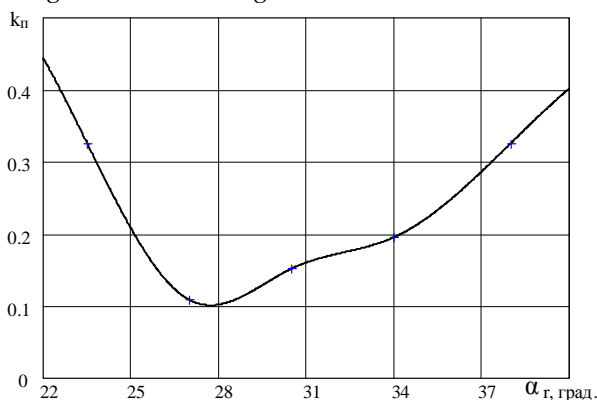
$$k_\Pi = \frac{M_{max} - M_{min}}{2 \cdot M_e} \qquad (4)$$

Where M_{max}, M_{min} - maximum and minimum torque exercised on the motor shaft.

M_e - effective value of the electromagnetic torque, which is equal to the static torque of the load applied to the motor shaft in steady state.

In the digital simulation, the torque undulation's coefficient was determined for a series of values of rotor tooth arc angles.

After obtaining results of spline interpolation of the data collected, we constructed the variation curve for the torque's undulation factor depending on the rotor tooth arc angle, as shown in Figure 7.

Fig. 7. Variations in the torque undulation factor depending on rotor tooth arc angle α_r

By analysing function $k_\Pi(\alpha_r)$, one may conclude that the optimal angle for the rotor tooth arc is in the region of α_r = 28°. This means that the optimal shape for the rotor tooth with projections corresponds to Fig. 2a, differing from the standard 23.5° shape of the tooth arc.

5. Conclusion

The study shows that in order to reduce electromagnetic torque undulations in an SRM motor, a special shape of rotor tooth has to be designed with a projecting part that increases the tooth's arc angle to a defined value. It was observed that the electromagnetic torque's undulation factor has a minimum of its own, which enables quantification of the size of the tooth's projecting part and optimisation of SRM motor design in line with the criterion of minimisation of electromagnetic torque undulation

REFERENCES

[1] L. Venkatesha , V.Ramanarayanan. Torque ripple minimisation in switched reluctance motor with optimal control of phase currents. 1998 IEEE, p. 529-534.

[2] Luís O. A. P. Henriques, Luís G. B. Rolim, Walter I.Suemitsu, Paulo J. C. Branco, Joaquim A. Dente. Torque Ripple Minimization in a Switched Reluctance

Drive by Neuro-Fuzzy Compensation // IEEE TRANSACTIONS ON MAGNETICS, VOL. 36, NO. 5, SEPTEMBER 2000, p. 3592-3594.

[3] Tkachuk V.I., Kasha L.V. Les Voies de réduction des ondulations du couple électromagnétique avec énergie de tampon // Електротехніка і Електромеханіка, 2008-№1, с. 53-56.

[4] M.Balaji,V.Kamaraj. Design of High Torque Density and Low Torque Ripple Switched Reluctance Machine using Genetic Algorithm // European Journal of Scientific Research ISSN 1450-216X Vol.47 No.2 (2010), pp.187-196.

[5] Joseph Peter. Modeling & Torque Ripple Minimization of Switched Reluctance Motor for High Speed Applications // International Journal of Science and Modern Engineering (IJISME), Volume-1, Issue-10, September 2013, p. 15-20.

[6] Iqbal Husain. Minimization of Torque Ripple in SRM drives // IEEE Transactions on Industrial Electronics. Vol.49 (2002), pp. 28-39.

[7] Sahin,F., Erta,H.B., and Leblebicioglu,L. Optimum geometry for torque ripple minimization of switched reluctance motors // IEEE Transactions on Energy Conversion. Vol. 15 (2000) pp. 30–39.

[8] Arumugam R., Lindsay J.F., Krishnan R. Sensitivity of pole arc/pole pitch ratio on switched reluctance motor performance // Proc, IEEE Industry Applications Society Annual Meeting Vol.1 (1988.), pp. 50-54.

[9] S.T. Tolmachev, Ilchenko E.V., Vlasenko V.A. Analyse du champ magnétique des machines à reluctance variable. //Revue de l'Université technique de Krivoyrog, 2010 – Edition 26, p. 189-192.

[10] Krishnan Ramu. Switched reluctance motor drives: modeling, simulation, analysis, design, and applications. – Boca Raton London New York Washington, D.C., 2001. – 416 p.

[11] A. Berdai, V.Vlasenko , V.Titjuk. , A.El Moudden. Analysis of reliability of the mathematical model of the SRM // Journal of Theoretical and Applied Information Technology. – Vol. 41. No. 1 – 2012. – pp 060 – 067.

[12] Abdelmajid Berdai, Abdelaziz Belfqih, Jamal Boukherouaa, Faissal El Mariami, Abdel-hamid Hmidat, Vladimir Vlasenko, Valery Titjuk. Similarity and Comparison of the Electrodynamics Characteristics of Switched Reluctance Motors SRM with Those of Series DC Motors Scientific Research Publishing, Engineering Vol.7 No.1, Pub. Date: January 21, 2015

[13] Vinogradov A.B. Commande vectorielle des entrainements électriques à courant alternatives. – IVANOVO, 2008. – p. 298 .