

## Development of methods of calculation and optimization of electromechanical characteristics of SRM

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**Abstract:** 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 [1]. 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 very wide size, power and speed range together with the economic aspects of its construction, will give the SRM place in the drives family. In this paper, we propose the novel method, which brings together the field-theoretical method approach used for calculation of the magnetic systems of switched reluctance motors (SRMs) and analysis of electromagnetic processes in electric drive systems using the electrical circuit's theoretical method. We then present a few results of simulation with a type 8/6 SRM using MATLAB / Simulink software package in order to prove the exactness of the model.

**Keywords:** Switched reluctance motor, powersys, simulink, simulation steady state and dynamic regime

### I. Introduction

SRM is an electric motor that converts the reluctance torque into mechanical power. In the SRM, both the stator and rotor have a structure of salient pole, which contributes to produce a high output torque. The torque is produced by the alignment tendency of poles. The number and the position of the poles both for the rotor and the stator have a determinant role in the optimization of the performance of the machine. It is necessary to obtain a motor torque in the desired direction by activating one phase, irrespective of the position of the rotor to the stator. Figure 1 shows a SRM with three phases, six stator poles and four rotor poles. Due to the lack of coils and rotor magnets, the speed of the SRM touches higher values, being limited both by the bearings and by the losses in the rotor iron. The domain of reduced speeds at higher torque can be covered, for this type of motors, by the elimination of mechanical gears. Due to both the higher values of the torque and the reduced inertia moment, higher values of accelerations can be obtained with the SRM. Also through a proper control different values of the torque in real time can be obtained. In conclusion, the dynamical behaviour of this motor is different, which leads to the large-scale use of the SRM in the electrical drives with variable speed.

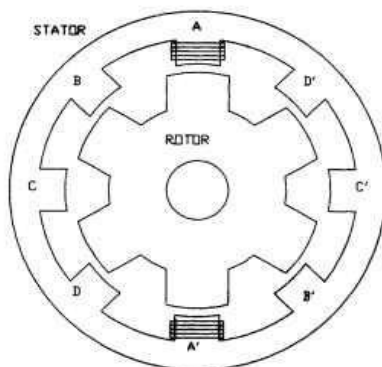


Fig. 1: 8/6 Switched Reluctance Motor

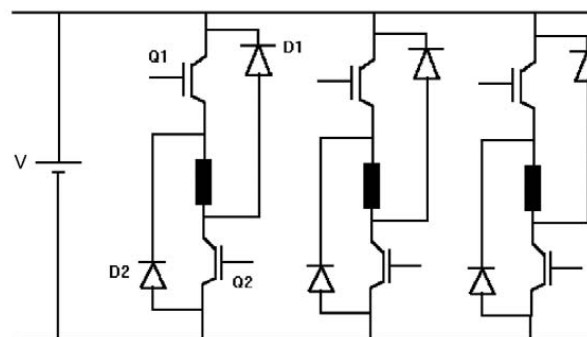


Fig. 2. H-bridge asymmetric converter

In this study we propose the novel method, bringing together the simplicity of electric circuit methods and the accuracy and polyvalence of electromagnetic field methods, which are regarded as the most perspective methods. In the case of switched reluctance motors, the novel method model enables static calculation of the electromagnetic field with use of other results obtained in the form of differential equations describing the dynamics of the electrical drive system[2].

The structure diagram of the SRM's mathematical model created using the novel method is shown in Figure 3.

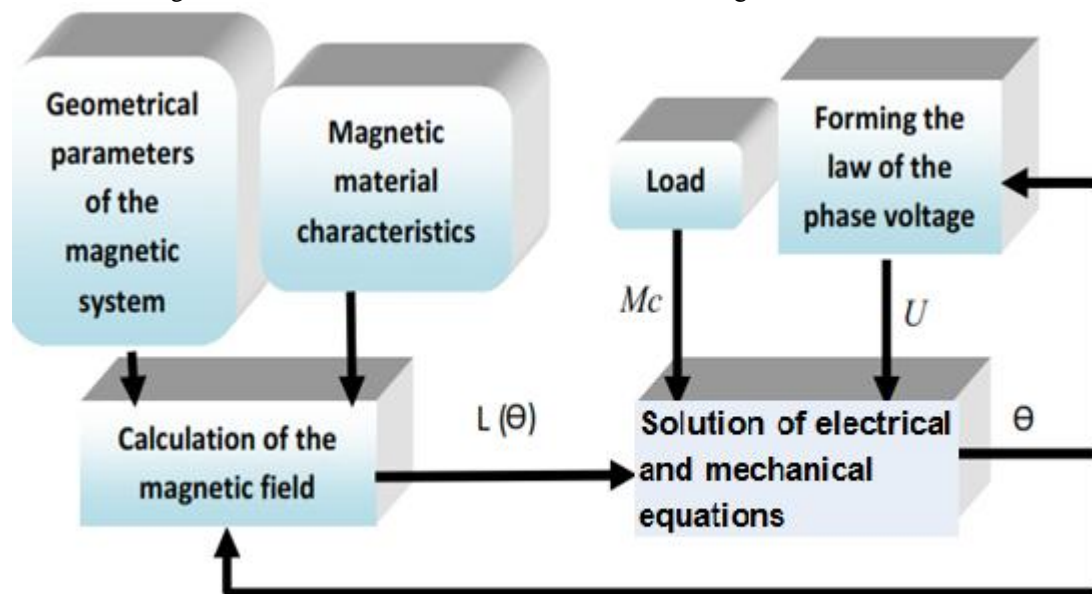


Fig. 3: structure diagram of the SRM's mathematical model created using the novel method

The new modelling approach's main problem results from the need for simultaneous calculation of the variation of the magnetic field's characteristics and those of the corresponding electrical circuits. Solving the problem in such a context greatly complicates the simulation process.

Use of the dynamic characteristics method is regarded as one of the possibilities for achievement of the new modelling method enabling design of the circuit of the field mathematical model of SRM.

## II. Theoretical Approaches And Syntheses

Use of the dynamic characteristics method is regarded as one of the possibilities for achievement of the combined method enabling design of the circuit of the field mathematical model of SRM[3]. The essentials of this method, in the case of its application for SRM simulation, consist of establishing a connection between the stator coil's inductance and the rotor's angle of rotation  $L(\theta)$ , and its introduction into the system of differential equations describing the electromechanical process in switched reluctance motors[4,5].

As the simulation subject, we have used an SRM with the following performances and characteristics:

Magnetic circuit material: 3405-quality steel; Magnetic circuit prototype: 8/6 (classic configuration); Stator exterior diameter: 62 mm; Stator interior diameter: 32.5 mm ;Length of active steel: 36 mm; Stator base thickness: 5.8 mm; Stator height: 9 mm; Rotor tooth height: 4.5 mm; Air gap: 0.25 mm; Polar angle of stator: 18°; Angle of rotor grooves: 19°; Shaft diameter: 9 mm; Number of spires per phase: 80; Nominal power: 1.5 kW; Nominal rotation frequency: 1500 rev/minute; Power supply voltage: 480V; Nominal current of stator: 12.4 A; Active coil resistance: 3 ohms.

On the basis of results obtained in studying the magnetic circuit, we were able to define the characteristic of the stators' inductance depending on the angle of the rotor  $L(\theta)$ . The characteristic was determined under the value of the stator coil's nominal current.

In real-life conditions, inductance coil stator also depends on the value of current  $L=L(\theta, i)$  due to the non-linearity of the steel's magnetisation curve.

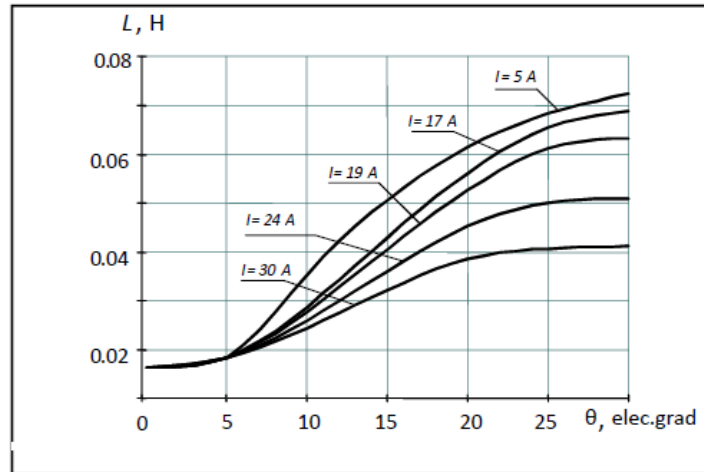


Fig. 4. Phase inductance depending on angle  $\theta$  for a stator current series

Variation of phase inductance depending on the rotor's angle of rotation may be approximated by the simple expression (20) - (fig. 5)

$$L(\theta, i) = L_0(i) - L_1(i) \cdot \cos\theta. \quad (1)$$

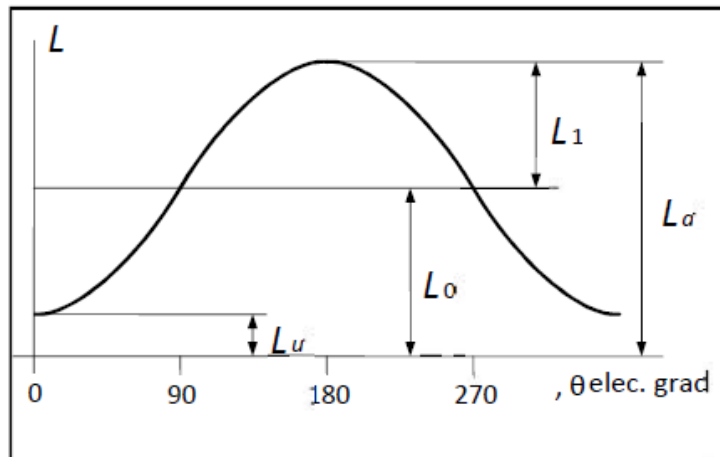


Fig. 5. Variation of phase inductance depending on angle  $\theta$

It is makes it easier if we operate with coherent values for inductance  $L_a$  and incoherent for  $L_u$ , the positions of the rotor poles and the stator, so:

$$L_0(i) = \frac{L_a(i) + L_u}{2}, \quad L_1(i) = \frac{L_a(i) - L_u}{2} \quad (2)$$

As calculation of the field shows, the value of inductance  $L_u$  does not really depend on phase current value, so  $L_u = \text{const} = 0,0163$  H. At the same time, the coherent value of phase  $L_a$  inductance decreases with increase in current, limited to the value of  $L_u$ .

Inductance  $L_a$  depends on current value due to saturation of the magnetic system (Figure 1) and may be represented by the function:

$$L_a(i) = a + \frac{b}{i + c} \quad (3)$$

Where  $a = 0.0163$ ,  $b = 1.72$ ,  $c = 14.35$  – coefficients obtained by calculation of the magnetic field. Therefore, equation (20) takes the form:

$$L(\theta, i) = \frac{1}{2} [L_a(i) + L_u - (L_a(i) - L_u) \cos(\theta)] \quad (4)$$

Graphing of  $L(\theta, i)$  is shown in Figure 6:

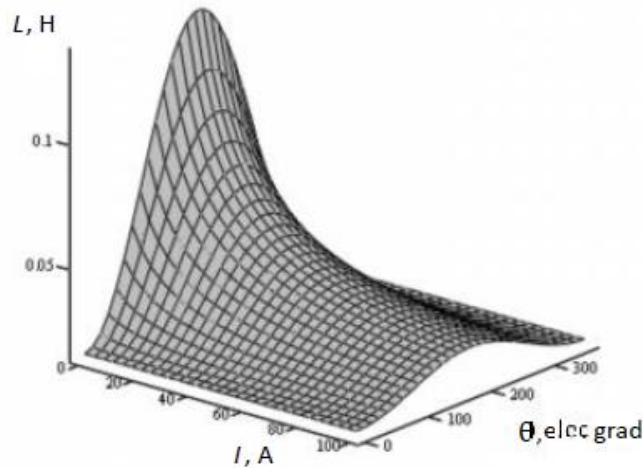


Fig.6. Approximate function of the  $L(\theta, i)$

### III. Modeling Of The Switched Reluctance Motor

As with all types of electric machines, an SRM's control system is composed of equations of electrical balance for each of the electric machine's stator phases, and equations for rotor movement.

The electrical relationship of the SRM stator coil's balance position is defined as follows:

$$U = iR + \frac{\partial \Psi}{\partial t} \quad (5)$$

Where U is the supply voltage.

Generally speaking, the magnetic flow through coil k in an electric machine with several coils is equal to:

$$\Psi_k = L_k i_k + \sum_{j=1, j \neq k}^N M_{jk} i_j \quad (6)$$

With:

$L_k$ : Inductance specific to a k phase;

$M_{jk}$ : Mutual inductance between phases j and k.

As, with symmetrical control in full step, currents overlap slightly depending on time, the equation's second term (2) may be ignored for a certain relationship between the motor's load and the number of stator coils. In this case, a coil's magnetic flow may be entirely determined by its own inductance.

As the inductance of an SRM coil depends on rotor angle in relation to the latter  $L_s=L_s(\theta, i)$ , equation (1) may be written as follows:

$$u = Ri + \frac{\partial \Psi}{\partial i} \frac{di}{dt} + \frac{\partial \Psi}{\partial \theta} \frac{d\theta}{dt} = Ri + L_\theta(\theta, i) \frac{di}{dt} + \omega \frac{\partial L_s(\theta, i)}{\partial \theta} i \quad (7)$$

Or

$$u = Ri + \frac{\partial L_s(\theta, i)}{\partial \theta} \omega i + \left( \frac{\partial L_s(\theta, i)}{\partial i} i + L_s(\theta, i) \right) \frac{di}{dt} \quad (8)$$

Where

$$L_\theta(\theta, i) = \frac{\partial \Psi(\theta, i)}{\partial i}, \quad L_s(\theta, i) = \frac{\Psi(\theta, i)}{i}, \quad \omega = \frac{d\theta}{dt} \quad (9)$$

Respectively designating dynamic inductance, static inductance and angular rotor speed.

The influence of dynamic inductance will be the subject of a separate analysis and will not be taken into consideration in this article

The electrical relationship of the voltage at an SRM phase's terminals in balance position may therefore be expressed as follows:

$$u = iR + L(\theta, i) \frac{di}{dt} + \frac{\partial L(\theta, i)}{\partial \theta} i \omega \quad (10)$$

Ignoring the difference between static and dynamic inductance, it may be noted that this hypothesis is valid in the absence of magnetic saturation of the system. Consequently, in order to better describe the electrical processes, we can use equation (6).

The electromagnetic torque that develops under the influence of phase i current

$$M_e = \frac{\partial L(\theta)}{\partial \theta} \cdot \frac{i^2}{2} \quad (11)$$

Therefore, the generalised system of differential equations for the SRM is :

$$\left. \begin{aligned} u_k &= Ri_k + L(\theta_k) \frac{di_k}{dt} + \omega \frac{\partial L(\theta_k)}{\partial \theta} i_k \\ M_e &= \frac{\partial L(\theta_k)}{\partial \theta_k} \cdot \frac{i_k^2}{2} \\ \frac{d\omega}{dt} &= \frac{1}{J} \cdot (M_e - M_c) \\ \frac{d\theta_k}{dt} &= \omega \end{aligned} \right\} \quad (12)$$

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

#### IV. Voltage Switching

There are several possible configurations to energize an SRM from a converter. The different energizing structures distinguish themselves by their number of semiconductors and passive components. They also depend on the number of phases and the way the stator coils are connected. The maximum control and flexibility is obtained, however, with the H-bridge asymmetric type converter shown in Figure 2. Each phase has two insulated gate bipolar transistors (IGBTs) and two diodes. The number of semiconductors is the same as for an inverter of a synchronous machine. However, the structure is completely different. One can also notice that it is not possible to short-circuit the source because the resistance of the coils limits the current [6,7].

The conditions for voltage switching are:

- When  $0^\circ < \text{Rotor angle } (\theta) < \text{Turn-on angle } (\theta_{on})$ , then Voltage = 0;
- When  $\text{Turn-on angle } (\theta_{on}) \leq \text{Rotor angle } (\theta) < \text{Turn-off angle } (\theta_{off})$ , then Voltage = +V;
- When  $\text{Turn-off angle } (\theta_{off}) \leq \text{Rotor angle } (\theta) < \text{commutation angle } (\theta_d)$  then voltage = -V

The control takes place applying the voltage source to a phase coil at turn-on angle  $\theta_{on}$  until a turnoff angle  $\theta_{off}$ . After that, the applied voltage is reversed until a certain demagnetizing angle  $\theta_d$ , which allows the return of the magnetic flux toward zero. To apply voltage V in one phase, the two IGBTs Q1 and Q2 in Figure 5 must be ON. On the contrary, to apply the -V voltage and assure the current continuity, the two diodes D1 and D2 are used.

Thus, the voltage at a phase's terminals varies according to the following division: :

$$u = \begin{cases} +V, & \theta_{ON} \leq \theta < \theta_{OFF}; \\ -V_s, & \theta \geq \theta_{ON}, i \neq 0; \\ 0, & \theta_{OFF} < \theta < 2\pi \cup \theta < \theta_{ON}, i = 0. \end{cases} \quad (9)$$

Where  $\theta_{ON}, \theta_{OFF}$  – designate the angles of commutation.

V. Functional Diagram Of The Model For Srm Simulation

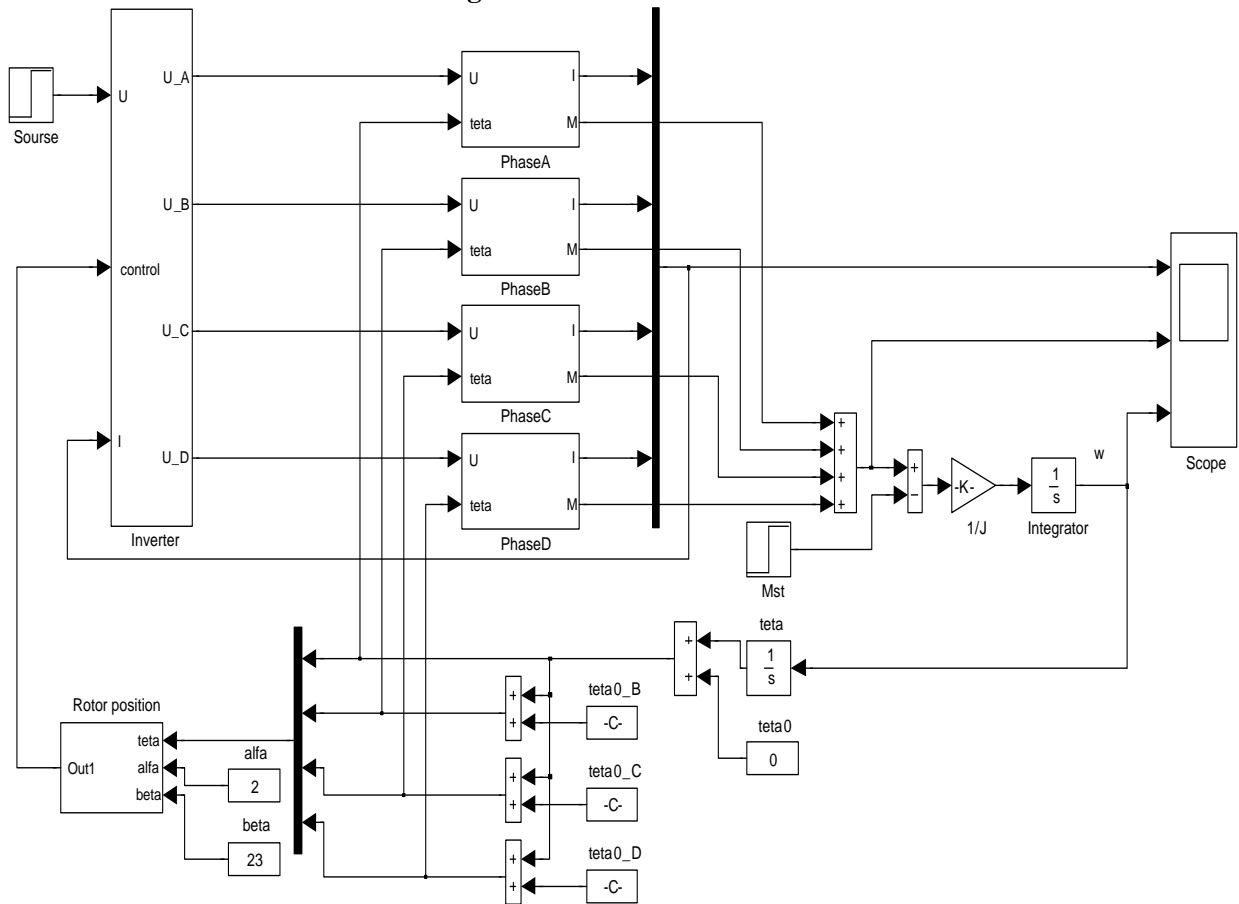


Fig. 7. Functional diagram of the model for SRM simulation

The model for simulation is developed from the above SRM equations. A structure diagram of the electrical-drive model based on the SRM, created with Matlab Simulink software [8-9-10], is presented in Figure 7.

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 *alfa* 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 8 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  $\theta$ , 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.

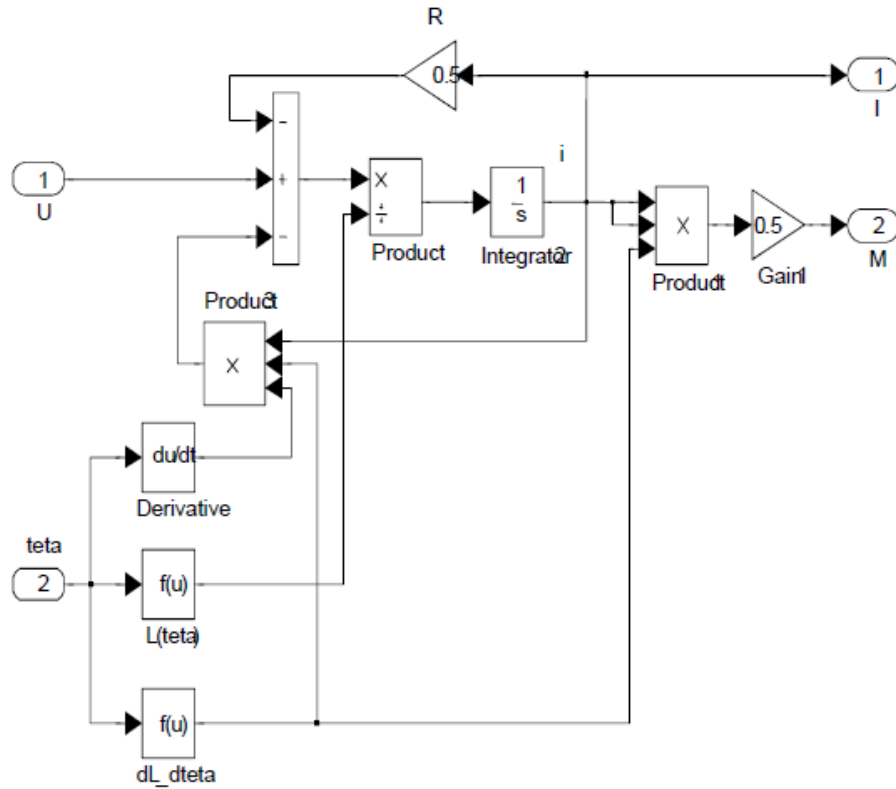


Fig. 8. Model of simulation of an SRM phase

### VI. SRM Simulation Results

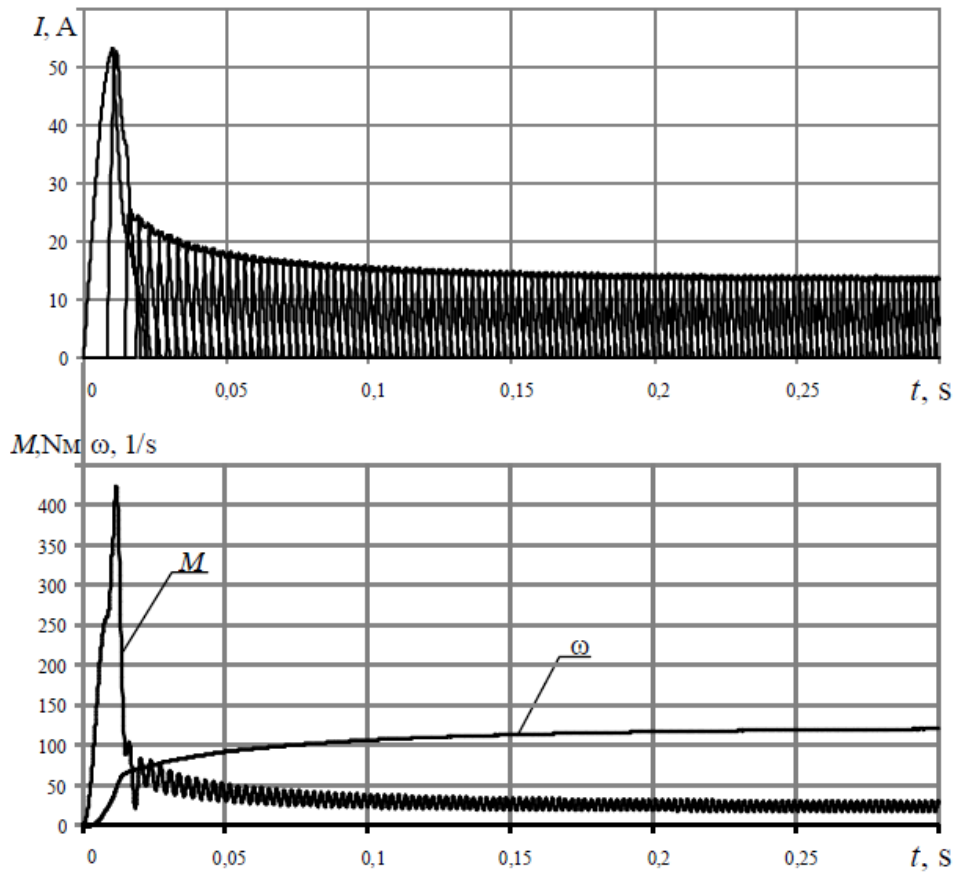


Fig.9 . Transition process of SRM at start-up

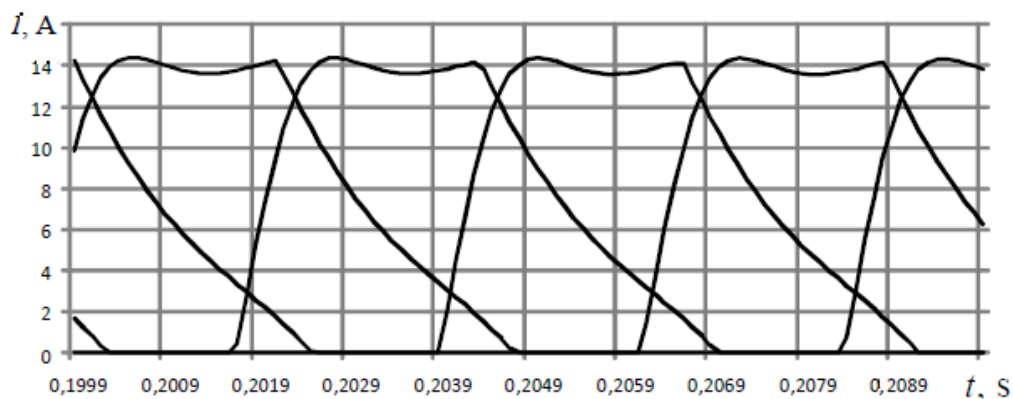


Fig.10. Forms of phase currents

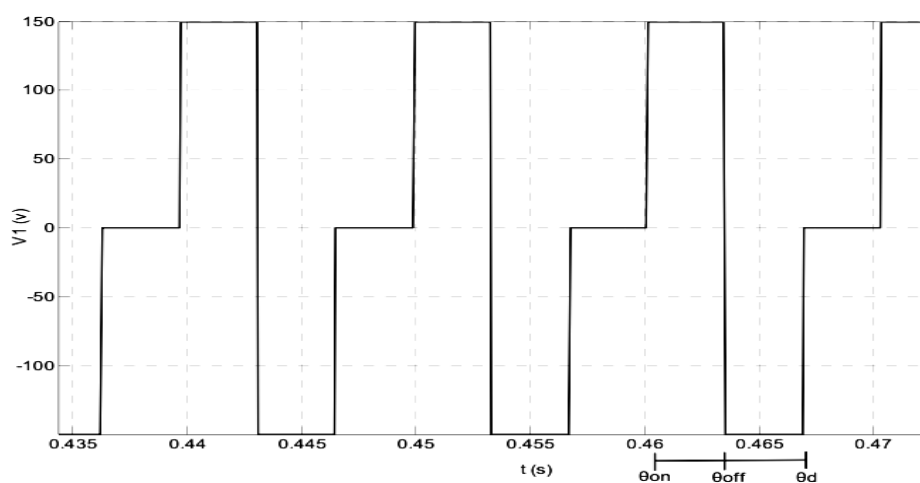


Fig. 11. Forms of one phase voltage

The results of simulating the start-up process for the electrical drive based on the SRM model with a resistive charge are presented in Figure 8 in the form of chronograms of phase currents, the resulting electromagnetic torque and the rotor's angular rotation speed. Forms of phase currents and of one phase voltage at  $\theta_{on}=0^\circ$  and  $\theta_{off}=30^\circ$  with open loop control during stationary motor operation are represented in Figure 10 and 11.

On the basis of the graphs in Figures 9, 10 and 11 obtained from the results of calculations carried out by the SRM's mathematical model, and considering the quality of the models' concordance and convergence towards the basic principle of electromechanical engineering [11], we may conclude that the new mathematical model developed is a consistent one.

## VII. Conclusion

Based on analysis of the SRM's magnetic system field method and analysis of the mathematical model of the SRM, we have established the results of calculation of the parameters of the motor's magnetic field and the characteristics of electro-dynamic processes with the simulated curves of the proposed model. We may therefore conclude that the simulation model proposed describes a switched reluctance motor's electrodynamic process. The model developed may be used for study of the SRM's electromechanical and energy properties. The universal nature of the mathematical methods and software tools used for development of the novel method creates the right conditions required for future improvements. Also it can be seen that Simulink environment will significantly impact the simulation results. The reason can be detailed studies for the future. For the future studies, how to control this motor more precisely can be considered.



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