PLATFORM FOR EXPERIMENTAL STUDY OF A SWITCHED RELUCTANCE MOTOR

Yassen Gorbounov[1], Romeo Alexandrov[2]

[1]*University of Mining and Geology "St. Ivan Rilski", 1700 Sofia; y.gorbounov@mgu.bg*
[2] *University of Mining and Geology "St. Ivan Rilski", 1700 Sofia; romeo.alexandrov@mgu.bg*

ABSTRACT. Switched reluctance motors (SRM) are among the first rotating electric machines, but they are little known in Bulgaria and are rarely mentioned, mainly in the courses on electric machines and special electric motors. However, they have great potential because they are environmentally friendly, highly efficient and can work in harsh environments. Although they have a simple construction, there are difficulties in their control due to the highly nonlinear nature of the magnetic circuit resulting from their salient pole structure. In this article, a laboratory model for studying low-power SR motors is presented. The key problems related to their principle of operation and control are discussed and a method for identifying the non-linear inductance is introduced which allows for implementing sensorless control algorithms. A small modification of the motor winding is made, which makes the simulation of phase winding faults possible.

Keywords: Switched Reluctance Motors, Electrical Drives, Nonlinear Magnetic Circuit

ПЛАТФОРМА ЗА ЕКСПЕРИМЕНТАЛНО ИЗСЛЕДВАНЕ НА ПРЕВКЛЮЧВАЕМ РЕАКТИВЕН ДВИГАТЕЛ

Ясен Горбунов, Ромео Александров
Минно-геоложки университет „Св. Иван Рилски", 1700 София

РЕЗЮМЕ. Превключваемите реактивни двигатели (ПРД) са сред първите въртящи се електрически машини, но са слабо познати в България като за тях се споменава рядко, предимно в курсовете по електрически машини и специални електрозадвижвания. Те крият обаче, голям потенциал, тъй като са екологични, с висок коефициент на полезно действие и могат да работят в тежки условия. Макар че имат просто устройство, съществуват трудности при тяхното управление, свързани със силно нелинейния характер на магнитната верига, произтичащ от явнополюсната им конструкция. В настоящата статия е представен лабораторен макет за изследване на ПРД с малка мощност. Дискутирани са основните проблеми, свързани с техния принцип на работа и управление и е представен метод за идентификация на нелинейната индуктивност, с чиято помощ може да бъде реализирано безсензорно управление. Извършена е малка модификация на фазната намотката, която позволява да бъдат симулирани аварийни режими на работа.

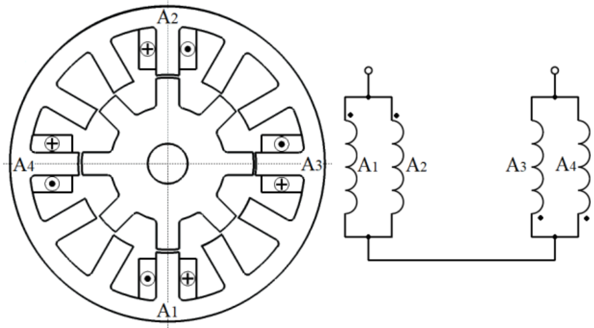
Ключови думи: Превключваеми реактивни двигатели, Електрозадвижване, Нелинейна магнитна верига

Introduction

The Switched Reluctance Motors (SRM) are synchronous machines that have salient poles and simple construction with a rotor made of laminated steel (Krishnan 2001). They are easy to be manufactured and are ecological due to the reduced amount of copper in the windings and the absence of impregnating resins. They feature high power and also a very high level of safety and reliability due to the complete lack of arcing which is a result of their brushless operation and their inherent ability to work with one, and in some cases with even more disconnected phases. Although the broad majority of SRM applications range in the field of household appliances as well as in automotive and industrial machinery, the advantages just mentioned above make the electrical drives built with SR motors extremely suitable for use in mining. There are specific requirements for the electrical drives used in the mining sector such as smooth adjustable speed control, high torque, operation in harsh and explosive environments, high degree of protection and high reliability.

In the mining industry there are known few cases of application of SRM mainly for locomotives and drives of belt conveyors (Gorbounov 2019; Ptakh 2015) but in Bulgaria their usage is still very limited and is virtually absent. The main reason for their relatively small distribution are the increased requirements for the power and control electronics, especially in terms of computing speed. To be able to realize continuous movement of the rotor it is necessary to continuously monitor its position and just before reaching the so called aligned position it is necessary to switch off the phase of the motor. The precise control of the advance angle of phase switching is crucial for the efficient motor control and is heavily dependent on the quite non-linear shape of the stator inductance which is a function of three variables namely the angle of rotation of the rotor, the current through the winding and the temperature. With the lack of control of the SRM, which takes into account the position of the rotor, the motor efficiency falls below 50%. In the same time with proper electronic control the real efficiency can reach 90% and above. This makes all developments related to increasing the power and control efficiency of SRM drives highly relevant and significant in view of the upgrading of mining machinery. The development of new algorithms and tools for energy management can lead to improved power efficiency, which is crucial for the whole mining industry.

The basic structure of a typical rotating 3-phase SR motor of type 12-8 is depicted in Fig. 1. This type of motor is used in the current experimental platform. For clarity only a single phase is shown.



(a) (b)

Fig. 1. Basic configuration of a typical SRM of type 12-8: salient pole structure (a), and windings arrangement (b)

The torque is produced due to the tendency of the rotor to transition to the so called aligned position, i.e. a position with minimum reluctance (minimal magnetic resistance, respectively a maximum inductance). The windings are wound on the opposite poles of the yoke and they are coupled in pairs to form the phase sections of the inductor. They are connected so that the total magnetic flux is increased.

The motor is said to be of type 12-8 because it has 12 stator poles Zs and 8 rotor poles Zr. The phase count *m* is equal to the number of stator teeth divided by the number of poles 2p which for the SR motors with central axial symmetry is 2.p = Zs-Zr. Knowing that Zs=2.p.m, the angular distance between the closest stator and rotor poles (from the unaligned to the aligned position) can be expressed either using poles number or using pole pairs and the number of phases, and it is given by the expression (1). For the SRM12-8 it is ε=15°.

$$\varepsilon=2.\pi.\left(\frac{1}{Z_r}-\frac{1}{Z_S}\right)=\frac{\pi}{p}.\left(\frac{1}{m-1}-\frac{1}{m}\right) \quad (1)$$

The motor is being controlled by square wave pulses that energize each phase. The control voltage and current shape for single phase commutation is shown in Fig. 2.

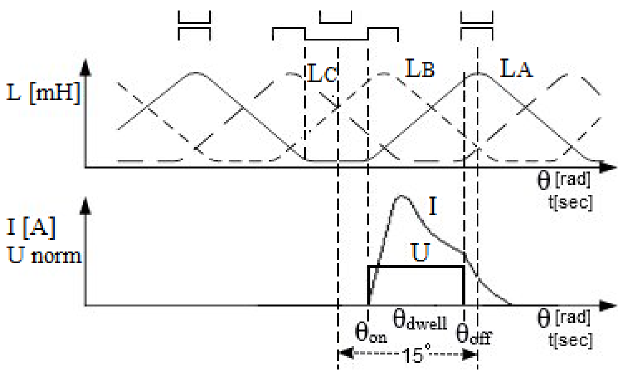


Fig. 2. Idealized inductance shape and control signal profile

As it has been already mentioned the inductance is a function of three variables of which the rotor position and the current flowing through the phase winding are the most important. This dependence is due to the saturation of the magnetic circuit and the air gap that changes during rotation and is the cause of the highly nonlinear inductance shape. In order to implement efficient control and to minimize torque ripples the most important parameters are the switching angles. The start of the commutation angle is *θon* which have to be slightly delayed from the ideal unaligned position (Kjaer 1997). Next it is the switch-off angle *θoff* which determines the instant of de-energizing the phase. In order to not produce a braking torque this angle must come with some advance before reaching maximum inductance. To achieve the goal of efficient control it is crucially important to obtain the correct rotor position information. This can be done either by using some position sensor such as an encoder or by identifying the inductance profile in real time thus implementing sensorless control algorithm.

The current paper aims to introduce an experimental platform built using a real SRM which can help for conducting research on the digital control algorithms and the identification of the stator inductance. Since the SRM is known for its high fault tolerance a modification of the phase winding is done which allows for introducing phase faults.

Mathematical description

The mathematical modeling of the SRM drive can be derived by taking into account the voltage equations, the motion equation and the equation of the torque. The phase voltage can be written by observing the equivalent circuit in Fig. 3 and is given in (2).

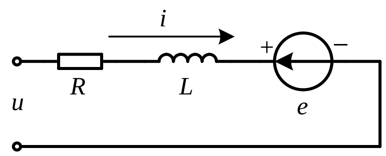


Fig. 3. Equivalent circuit of one phase

$$u=Ri+\frac{\partial\psi}{\partial i}\cdot\frac{di}{dt}+\frac{\partial\psi}{\partial\theta}\omega \quad (2)$$

In this expression *u* is the control voltage, *R* is the active phase resistance, *i* is the current through the winding, *θ* represents the angular position, ψ denotes the flux linkage and ω is the angular velocity (3).

$$\omega=\frac{d\theta}{dt} \quad (3)$$

Substituting (3) in (2) and taking into account that the derivative of the flux linkage with respect to the current is in fact the inductance (4) it can be obtained (5).

$$\frac{\partial\psi}{\partial i}=L(i,\theta) \quad (4)$$

$$u=Ri+L(i,\theta)\frac{di}{dt}+i\frac{\partial L(i,\theta)}{\partial\theta}\cdot\frac{d\theta}{dt} \quad (5)$$

The motion equation is given in (6) assuming the following conditions.

- the drive is presented for a single-mass system, without taking into account the elasticity of the elements of the mechanical system;
- the moment of inertia *J* of the system is constant and does not change during the movement;
- the equation refers to the motoring mode, the electromagnetic torque acts in the direction of motion, and the load counteracts.

$$J\frac{d\omega}{dt}=T_{em}-T_L \tag{6}$$

The torque equation is derived by the method for analysis of the magnetic energy and the co-energy of the SRM taking into account the effect of the saturation of the magnetic system. For the most of the motors, the saturation region of the magnetic circuit is reached. Usually the motors are not designed to work in the linear region of the dependence between the field strength H and the magnetization M, because the achievement of a certain torque will be at the expense of very large dimensions.

The magnetization curve profile as a function of the stator current is given in Fig. 4. In the figure *U* denotes the unaligned position and *A* is the aligned position of the rotor.

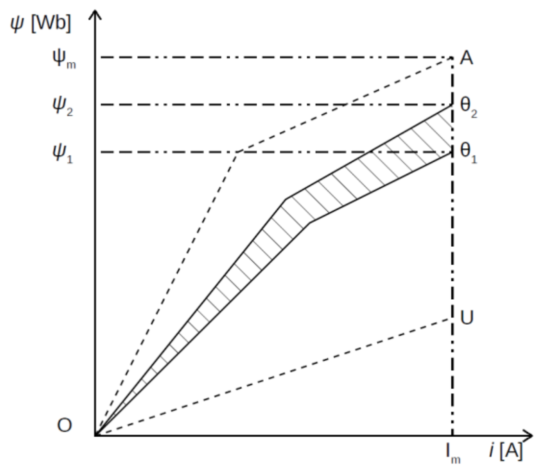


Fig. 4. A family of magnetization curves at particular rotor positions *θi*

The torque of the motor is determined by the magnetic field created by the motor windings. Under its pull, the rotor rotates from some angular position θ_1 to the next one $\theta_2=\theta_1+\Delta\theta$ for a time of Δt. The analysis is made on the basis of the characteristics of the total magnetic flux ψ as a function of the current *i* for different values of the angle θ, provided that during the movement, the current does not change its value. To simplify the analysis, heat losses are neglected. The energy of the electric source for time Δt is used to increase the magnetic energy and the energy of the system.

For the change in the electric field energy it can be written (7).

$$\Delta W_{el}=\Delta W_{mag}+\Delta W_{co}=I_m(\psi_2-\psi_1)=I_m\cdot\Delta\psi \tag{7}$$

The change in the electric field energy ΔW_{el} is in fact the area of the rectangle $\theta_1\theta_2\psi_2\psi_1$.

On the other hand, under the law of energy storage it turns out that the change in the electric field energy is equal to the change in the mechanical energy (8).

$$\Delta W_{el}=\Delta W_{mag}+\Delta W_{meh} \tag{8}$$

The change in the mechanical energy is the mechanical work done and it is given in (9).

$$\Delta W_{meh}=\Delta W_{co}=T_{em}(\theta_2-\theta_1)=T_{em}\cdot\Delta\theta \tag{9}$$

The change in the co-energy ΔW_{co} is (10). It corresponds to the shaded area in Fig. 4 which is the area of $O\theta_1\theta_2$.

$$\begin{aligned}\Delta W_{co} &= \int_0^{I_m}\psi(\theta_2,i)\,di-\int_0^{I_m}\psi(\theta_1,i)\,di = \\ &= \Delta\int_0^{I_m}\psi(\theta,i)\,di\end{aligned} \tag{10}$$

This way the motoring torque equates to (11).

$$T_{em}=\frac{\partial}{\partial\theta}\int_0^{I_m}\psi(\theta,i)\,di \tag{11}$$

Measurement of the magnetization curves

The magnetization curves measurement is important for implementing optimal control strategies for maximum energy efficiency and minimum torque ripples as well as for validating the simulation tools performance. There exist many methods for obtaining flux linkage curves (Shehata 2018) either in a direct or indirect fashion. Some of them include measuring and recording the transient current profile (Gobbi 2006, Radimov 2005), static torque measuring at an arbitrary position (Zhang 2006), applying alternating current source with auxiliary search coil and next recording the induced voltage in the auxiliary coil together with the excited stator instantaneous current (Szabo 2013).

In this paper the magnetization curves measurement is made using the technique described in (Cossar 2001) which is a direct method. For this purpose the SR motor is coupled with a dividing head which is capable of holding the motor shaft at a desired angle as shown in Fig. 5. For each angular position from the unaligned to the aligned position a square pulse of the nominal motor voltage is being applied to a single stator phase using the pulse generator PG. Measurement samples of the voltage and current are being taken with the aid of an oscilloscope and are stored into memory. After all the curves are collected they are processed offline using a mathematical software package such as Matlab or SciLab.

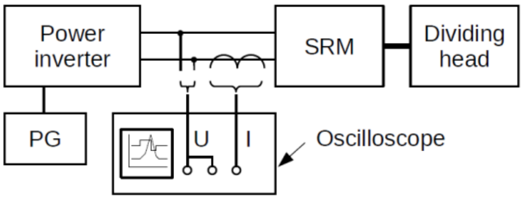


Fig. 5. Magnetization curves measurement direct method test setup

Using this setup the flux linkage calculation can be evaluated using equation (12).

$$\psi(t)=\int\left(u(t)-i(t).R\right).dt \qquad (12)$$

The magnetization curves family is shown in Fig. 6.

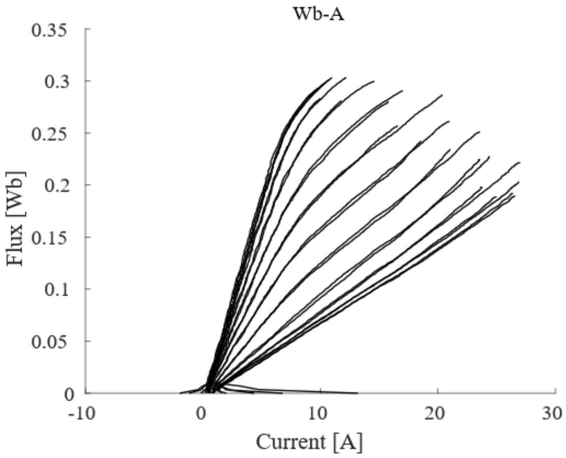


Fig. 6. Switched reluctance motor magnetization curves

The lowest curve in the figure corresponds to the unaligned position, i.e. the one where no saturation is observed because of the maximum air gap (minimum inductance). The top curve corresponds to the aligned position where the nonlinearity is obvious and is due to the maximum inductance value.

According the Faraday's Law it is known that the self-induced voltage across the inductor coil due to a current is proportional to the rate of change of the total magnetic flux. This means that if the above procedure is transformed to a continuous online measurement, the inductance as a function of the angular position and the current can be obtained by solving (13).

$$L=\frac{d\psi}{di} \qquad (13)$$

Being able to calculate the flux linkage and the inductance means that the angular position information can be obtained from the magnetic characteristics of the motor itself which is of great benefit especially for SR motors where the magnetic circuit is highly nonlinear. This way it can be synthesized a sensorless control algorithm which eliminates the external mechanical sensors.

The experimental platform

As stated in the previous chapter in order to measure the magnetization curves the motor shaft have to be fixed at desired angle. This is done by the aid of the dividing head shown in Fig. 7. The measurements are taken at a resolution of 1º although a significantly higher resolution is possible.

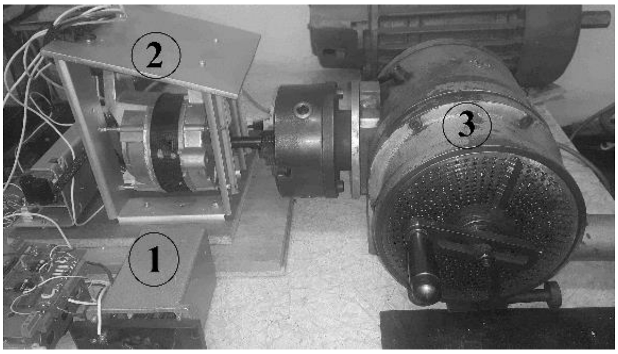


Fig. 7. The SR motor shaft coupled with a dividing head

In the figure (1) denotes the pulse generator, (2) is the switched reluctance motor and (3) is the dividing head.

After taking the measurements a loading machine is coupled in the place of the dividing head (not shown).

The salient pole construction of the motor can be visually observed by using the hole cut in the back side of the housing (Fig. 8).

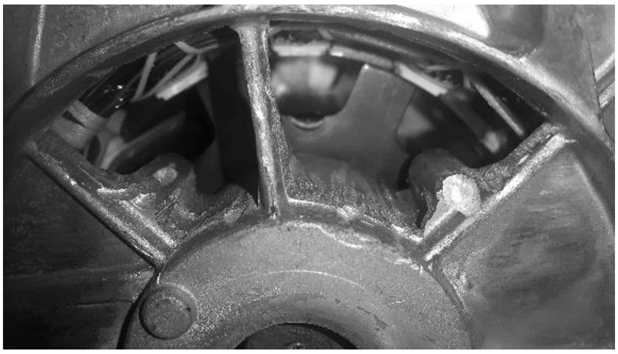


Fig. 8. An opening in the motor housing exposing the salient pole construction of the rotor

Although useless at high speeds of rotation this modification is very useful for educational purposes when explaining the working principle of the motor and in observing the degree of alignment during rotor positioning by the dividing head.

Fault injection capabilities

The SR motor is known as a robust and reliable machine in which faults can occur predominantly in its windings and bearing (Miller 1995; Nandi 1999; Szabo 2013). In the majority of the fault cases the motor remains operational, which is critical for some applications. Common winding faults include short circuit in an entire phase or between two different phases, short circuit from a coil to ground, an interrupted phase and open circuit in one coil of a phase.

In order to simulate some of the possible faults a small modification in a section of the winding is made which is shown in Fig. 9.

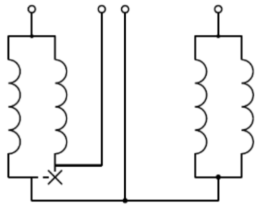


Fig. 9. Modification of a coil in a single phase winding

As it can be seen the coil is interrupted and its leads are exposed so they can be externally connected. A pole coil can be eliminated or connected in various configurations that allows to simulate different faults in the phase winding. Some of the possible connections are shown in the next figures.

In Fig. 10 (a) the broken coil is reconnected to its normal state by the aid of the bridge B while in Fig. 10 (b) the bridge is removed thus disconnecting the coil.

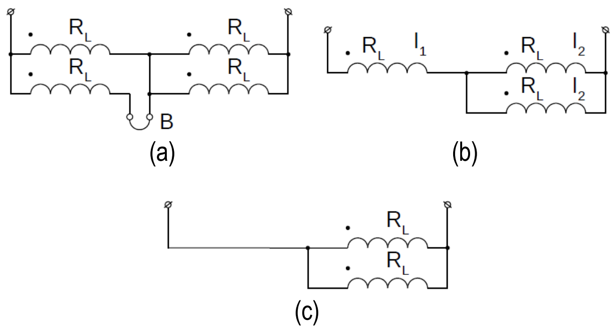


Fig. 10. Normal (healthy) connection (a), a disconnected coil (b) and a short in two opposite coils (c)

If all the coils are assumed to be equal and to have an active resistance R_L, the steady state current flowing through the phase winding according to Ohm's law is $I=U/R_L$. The nominal current trough each section is half that value because the sections are connected in pairs in parallel. If the bridge is removed (Fig. 10 (b)) that would mean an interrupted coil. In this case the nominal phase current will equal $I=2U/3R_L$. This in turn will lead to increase in the current I_1 with 1.33 times compared with the same current in healthy mode while the total current is slightly decreasing. It is also possible to short-circuit the left-hand coil (Fig. 10 (c)). In this case the current through the coils becomes equal to $I_2=U/R_L$ which is an increase by a factor of two comparing with the previous case.

The measurement of the magnetization curves family is repeated under the condition in Fig. 10 (b) and the new plot is shown in Fig. 11. Comparing the results with Fig. 6 it can be seen that the current is decreased and it becomes harder to reach saturation.

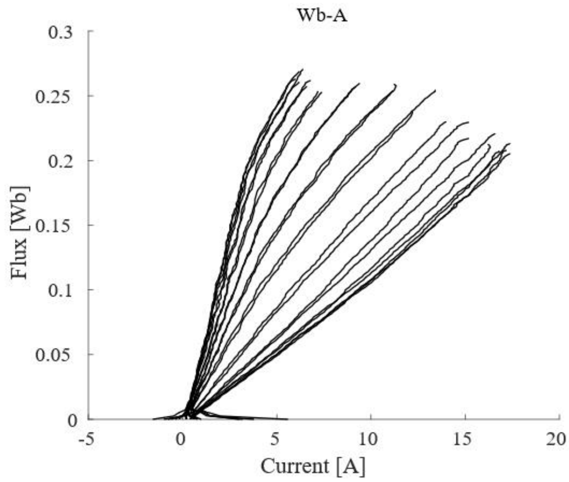


Fig. 11. Switched reluctance motor magnetization curves with an interrupter coil.

The proposed modification allows for few several faults to be injected and examined such as the ones shown in Fig. 12.

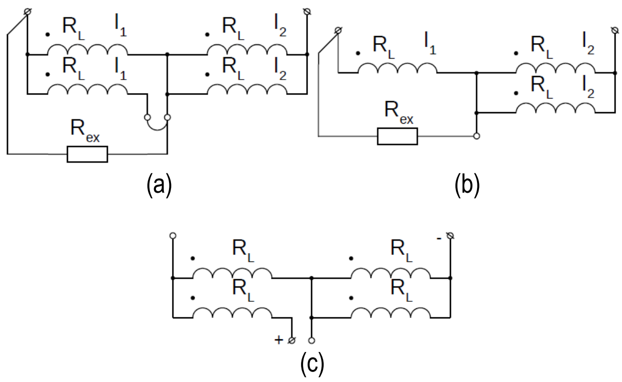


Fig. 12. Faulty situation with decreased coil resistance: case 1 (a) and case 2 (b), and simulation of a reversed coil (c)

A (variable) external resistance can be added either as shown in Fig. 12 (a) or in Fig. 12 (b) thus decreasing the equivalent active resistance of one or two opposite pole coils. This way a controllable value of the current can be achieved. The case shown in Fig. 12 (c) allows for increasing the equivalent active resistance or for applying external voltages of differing polarities and amplitudes to various sections of the circuit which provides additional flexibility to the proposed experimental platform.

Conclusions

The proposed experimental platform provides a multifunctional setup which allows to find the electromagnetic quantities which are involved in the mathematical model of the SRM, both under normal operating conditions and in the case of a damaged phase winding. It has the following capabilities:

- the salient pole structure can be visually observed, which is very important when teaching the basics and the principle of operation of the SRM;
- the magnetization curves measurements can be taken at fixed angles with a resolution exceeding 1/12 of the degree;

- the influence of the vibrations that occur in this type of experiments is greatly reduced by the construction of the setup;
- the parameters of the control pulses can be adjusted such as the voltage amplitude, the repetition period and the pulse duration. This allows for experimenting with the commutation strategy by varying the switching angles thus examining the properties of the control algorithms;
- the proposed experimental platform offers a non-destructive method for the introduction of various types of faults related with the exploitation of the SRM.

The capabilities listed above provide prerequisites for creating an adequate mathematical model of the motor, which existence is critical for the efficiency of the control. The implemented method for measuring the magnetization curves is very important for the creation of a sensorless control system, which is associated with solving the opposite task – the inductance can be calculated online during the movement which allows for estimating the rotor position. This leads to a reduction in the cost and size of the SRM drive, while increasing its reliability and fault tolerance.

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References

Cossar C., Kelly L., 2001. Drive development and test, in Electronic Control of Switched Reluctance Machines by T. J. E. Miller, Oxford Newnes, pp. 201-226, ISBN 978-0-7506-5073-1

Gobbi R., N. Sahoo, R. Rajandran, 2006. Rising and Falling Current Methods for Measurement of Flux-Linkage Characteristics of Switched Reluctance Motors: A Comparative Study, IEEE International Conference on Power and Energy (PECon), pp. 383 – 387, ISBN 1-4244-0273-5

Gorbounov Y., H. Chen, 2019. Technological Aspects And Applications Of Large Power Switched Reluctance Motors In Mining, Journal Of Mining And Geological Sciences, Vol. 62, Number 3, pp. 86-92, ISSN 2682-9525

Kjaer P., J. Gribble, 2001. Instantaneous torque control, 10.1016/B978-075065073-1/50008-0

Krishnan R., 2001. Switched Reluctance Motor Drives: Modeling, Simulation, Analysis, Design, and Applications, CRC Press LLC, ISBN 0-8493-0838-0

Miller T., 1995. Faults and unbalance forces in the switched reluctance machine, IEEE Transactions on Industry Applications, Vol. 31, pp. 319-328, ISSN 0093-9994

Nandi S., H. Toliyat, 1999. Condition monitoring and fault diagnosis of electrical machines - A review, Proceedings of the IEEE International Conference on Electric Machines and Drives, pp. 197-204, ISBN 0-7803-5589-X

Ptakh G., 2015. Switched Reluctance Drive Medium and High Power: Foreign and Domestic Experience (in Russian), Russian Internet Journal of Electrical Engineering, Vol. 2, No. 3, DOI 10.24892/RIJEE/20150305

Radimov N., N. Ben-Hail, R. Rabinovici, 2005. Inductance measurements in switched reluctance machines, IEEE Trans. on Magnetics, Vol. 41, pp. 1296 – 1299, ISSN 0018-9464

Shehata A., Y. Abdalla, A. Wakeel, R. Mostafa, 2018. Flux Linkage, and Inductance Measurement of a Fault Tolerant Switched Reluctance Motor Drive, 20th International Middle East Power Systems Conference (MEPCON), Cairo University, Egypt, ISBN 978-1-5386-6654-8

Szabo L., R. Terec, M. Ruba, P. Rafajdus, 2013. Detecting and Tolerating Faults in Switched Reluctance Motors, Universal Journal of Electrical and Electronic Engineering Vol. 1, Number 2, pp. 16-25, DOI: 10.13189/ujeee.2013.010202

Zhang J., A. Radun, 2006. A New Method to Measure the Switched Reluctance Motor's Flux, IEEE Transactions on Industry Applications, Vol. 42, pp. 1171 – 1176, ISSN 0093-9994