POWER ESTIMATION IN SENSORLESS CONTROL OF SWITCHED RELUCTANCE MOTORS

Yassen Gorbounov[1], Romeo Alexandrov[2], Hao Chen[3]

[1,2]University of Mining and Geology “St. Ivan Rilski”, 1700 Sofia; E-mail: y.gorbounov@mgu.bg, romeo.alexandrov@mgu.bg
[3]China University of Mining and Technology, E-mail: hchen@cumt.edu.cn

ABSTRACT. Switched reluctance motors (SRM) are among the first rotating electric machines. Due to the significant achievements in the development of power electronics and computing, they have become particularly prospective nowadays because of the numerous construction and energy advantages they have. The growing interest is prompted both by the challenges posed by the emerging electric vehicles, as well as by the increased ecological and production criteria in the field of large powers, namely in mining. The article discusses a method for sensorless estimation of the angular position of the rotor, whereby the shaft power can be simultaneously determined per step based on the information obtained for the flux linkage. This would allow the creation of an estimation function and an algorithm for searching for the optimum switching angle in real time so that the motor would run at minimum losses and minimum torque ripples regardless of the change in load within normal bounds. The unevenness of the torque is a typical drawback of the SRM and is a major problem to be solved in their control.

Keywords: Switched Reluctance Motors, Electrical Drives, Nonlinear Magnetic Circuit, Mining, Sensorless Control.

ОЦЕНКА НА МОЩНОСТТА ПРИ БЕЗСЕНЗОРНО УПРАВЛЕНИЕ НА ПРЕВКЛЮЧВАЕМИ РЕАКТИВНИ ДВИГАТЕЛИ

Ясен Горбунов[1], Ромео Александров[2], Хао Чен[3]
[1,2]Минно-геоложки университет „Св. Иван Рилски“, 1700 София
[3]Китайски университет по минно дело и технологии, Сюджоу, Китай

РЕЗЮМЕ. Превключваемите реактивни двигатели (ПРД) са сред първите въртящи се електрически машини. Благодарение на постиженията в силовата електроника и изчислителната техника те са особено перспективни в днешно време поради конструктивните и енергетични предимства, които притежават. Нарастващият интерес към тях се дължи както на предизвикателствата, поставени от страна на навлизащите електромобили, така и на повишаването на екологичните и производствени критерии в областта на големите мощности, а именно в минното дело. Статията разглежда метод за безсензорно определяне на ъгловата позиция на ротора, при който едновременно може да се определи мощността на вала за една стъпка на база получената информация за пълния магнитен поток. Това би позволило създаването на оценъчна функция и алгоритъм за търсене на оптимален ъгъл на комутация в реално време, така че двигателят да работи при минимални загуби и минимални пулсации на момента независимо от промяната на товара в допустими граници. Неравномерността на момента се явява характерен недостатък на ПРД и основен проблем за решаване при тяхното управление.

Ключови думи: Превключваеми реактивни двигатели, Електрозадвижване, Нелинейна магнитна верига, Минно дело, Безсензорно управление.

Introduction

Switched reluctance motor (SRM) based drives gain in popularity with the increasing capabilities of control and power electronics and the emerging hybrid and electric vehicles. This is due to the high torque density and low losses, respectively the very good power efficiency, which positions them in classes IE4 (super premium efficiency) and IE5 (ultra premium efficiency) after the IEC 60034-30-1 standard (IEC60034-30 2008, Horia 2017). They have very good environmental performance since they do not contain rare earth magnetic materials, such as neodymium (Nd) and dysprosium (Dy), whose production releases radioactive waste and carbon dioxide. Besides, in some cases, it is possible to replace the copper conductors with aluminum (AEM 2020). Due to the ability to work in highly polluted and heavy environments and high fault tolerance, they are increasingly used in the mining industry in cutting and digging machines, electric screw presses, oil pumping, belt conveyor systems, and many more.

In order to reach the optimum control parameters of the SRM, it is necessary to synchronise the commutation of the phase windings with respect to the position of the rotor, and this presumes the existence of a good mathematical model of the motor. Its description is strongly non-linear due to the salient pole construction of the machine. The generated electromagnetic torque is a function of current, rotor position and stator temperature, which, however, is lower than that of asynchronous and most other types of motor. The standard method for obtaining position feedback includes optical and mechanical (encoders) or magnetoelectric sensors (Hall sensors and resolvers), which leads to an increased cost of the entire drive system and limits the areas of its applications. Therefore, in recent years, the number of studies offering accurate methods for indirect identification of mechanical variables and elimination of mechanical sensors, which is well known as sensorless control, has greatly increased. Unfortunately, in SR motors, the determining factor for finding the proper phase switching angle is the value of the stator inductance, which is also strongly non-linear. Its measurement, when no current flows through the phase coil, is not particularly difficult. However, this is not the case when current flows through the stator winding as the change in inductance is a function of the current due to the saturation effect of the magnetic circuit.

The article discusses a method for sensorless estimation of the angular position of the rotor that allows the simultaneous calculation of the power of the shaft for one step with the aid of the obtained information about the flux linkage. The ultimate goal is the future creation of an estimation function and an algorithm for finding the optimum switching angle in real time, so that the motor operates with reduced losses and minimum torque ripples.

Sensorless control

A wide variety of sensorless control methods exist that are classified according different characteristics. In (Gallegos-Lopez 2001), the author describes in detail the methods divided into three major categories: open loop, energised phase, and unenergised phase methods. In (Siadatan 2019), a consideration is made based on the speed of rotation of the motor, namely standstill, low and high speed, since different methods have different response time and accuracy in the distinct speed ranges. In (Jae-Hoon 2019), sensorless control methods are classified according to the technique used: data-based, model-based, intelligent methods. In (Dinchev 2009), a method is presented for measuring inductance stator under load by injecting a radio frequency signal. In (Gorbounov 2020), a direct method is used, founded on the one proposed in (Cossar 2001), to obtain the flux linkage in real time by measuring the current and voltage as given in (1):

$$\psi(t)=\int\left(u(t)-i(t).R\right).dt \qquad (1)$$

This is done with the aid of a laboratory setup built with 120V 2.5A 3-phase SRM type 12-8, model H55PWBKS-1848.

The obtained magnetisation curve profile as a function of the stator current is given in Fig 1.

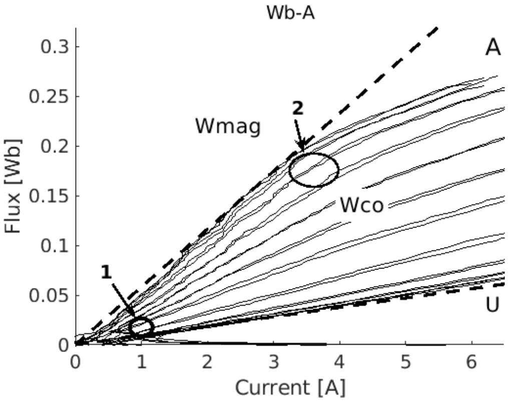

Fig. 1. Magnetisation curves family at rotor angles θ between the unaligned (U) and aligned (A) positions

In the figure, U denotes the unaligned position and A is the aligned position of the rotor teeth with respect to the stator teeth. The area enclosed by the flux linkage curves corresponds to the co-energy Wco, which is given by the non-linear power conversion, while Wmag is the stored magnetic energy. Due to the effect of saturation, Wmag < Wco. The straight dashed lines depict the margins in the case if there is no saturation, i.e. as if the model was linear. The two ellipses in the figure reflect the beginning of poles overlapping (point 1, at small rotor angle) and the approximate area where the saturation of the stator begins (point 2, at larger rotor angle) correspondingly. The difference between the linear and non-linear model is obvious. These two quintessential points are analysed by the finite element method (FEM) and are depicted in Fig. 2.

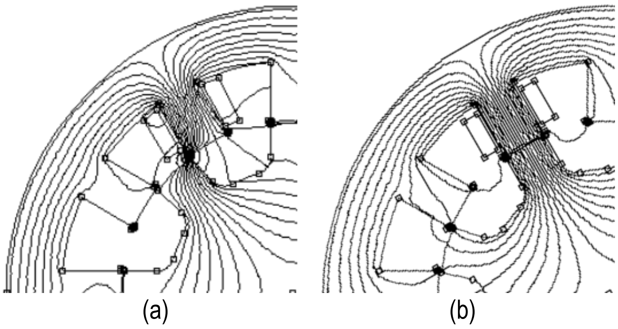
(a) (b)

Fig. 2. Cross-sectional view of a quarter of the SR motor (single pole of the active phase) and the corresponding magnetic field lines: (a) – beginning of poles overlapping in unaligned position and (b) – fully overlapped poles in aligned rotor position

The integral area of the co-energy Wco can be used to calculate the average value of the motoring torque for one full cycle between the unaligned and the aligned position of rotor teeth (Miller 2001). One cycle (of the execution of the loop for Wco) is called a stroke. The number of strokes per revolution is S and is given in (2):

$$S=m.Nr \qquad (2)$$

In this expression, m denotes the number of phases and Nr is the number of rotor poles.

For the average torque, equation (3) is valid:

$$T_{eAVG}=\frac{S.Wco}{2.\pi} \qquad (3)$$

From the data obtained by the magnetisation profile, the inductance can also be derived as a function of the current through the active phase and the angle of rotation as in (4):

$$L=\frac{\Delta\Psi(\theta,i)}{\Delta i} \qquad (4)$$

The three-dimensional relation of the inductance with respect to the current and the angular position, by neglecting the influence of the temperature, is given in Fig. 3.

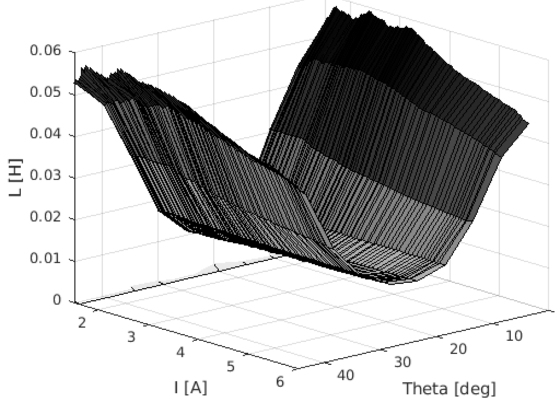

Fig. 3. A three-dimensional plot of the inductance as a function of the current through the active phase and the angle of rotation for aligned to unaligned and back to aligned teeth positions

Based on (1) and looking at the above figure, a sensorless position estimating device can be built as shown in Fig. 4.

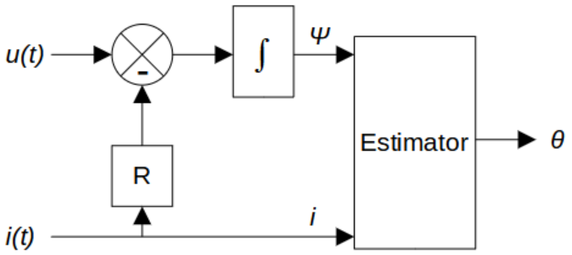

Fig. 4. Sensorless angular position estimator

The position estimator performs calculations based on the flux linkage equation to assess the angular position of the rotor. In the figure, the “Estimator” block can be implemented either by the lookup-table (LUT)-based method (Jae-Hoon 2019) or by an intelligent method, such as an artificial neural network (ANN) or fuzzy logic inference (Jae-Hoon 2019, Pavlitov 2013).

A sensorless approach for determining the proper time instance for switching-off the phase is depicted in Fig. 5:

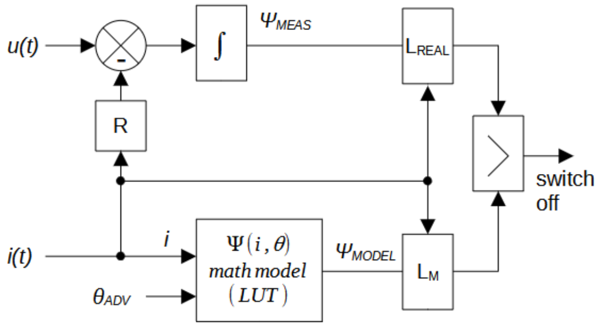

Fig. 5. Sensorless phase switching-off algorithm

In this algorithm, a LUT-based mathematical reference model of the flux linkage function is added. The flux linkages from the online measurement and the model are used to obtain instantaneous values for the inductance: L_M (model-derived) and L_{REAL} (measured). Next, the two calculated numbers are checked for equality by a comparator, and finally, the switching-off instant is decided. The advantage of the reference model method is that it could allow making adjustments of parameters that cannot be obtained by direct measurement.

Power estimation

Losses in SR motors are mainly of two types: losses in the stator windings and losses in the steel. The latter, in turn, are divided into hysteresis losses and eddy current losses. Power losses per unit mass in the stator windings are given in (5):

$$p_w = \frac{\rho}{\gamma_w . S_w^2} . I_{eff}^2 \qquad (5)$$

In this expression:
ρ – specific resistance of the conductor,
γ_w – density of the wire,
S_w – cross section of the conductor;
I_{eff} – effective value of current in one phase.

The magnetisation of magnetic materials with changing field is accompanied by energy losses. Losses per unit volume are given by the area of the hysteresis cycle (6):

$$W_H^{'} = \oint H.dB = \frac{1}{S.l}\oint i.d\psi \qquad (6)$$

In the equation:
H denotes the intensity of the magnetic field, *B* is the induction, *S* is the cross section of the magnetic circuit, l is the length of the magnetic field lines.

To find the power loss from hysteresis per unit mass of the magnetic circuit, equation (7) is used:

$$p_H = \frac{f}{\gamma} . W_H^{'} \qquad (7)$$

Here:
γ is the density of silicon steel, *f* is the number of hysteresis cycles per second.

Power losses in the steel per unit mass are divided into two components: hysteresis losses that are proportional to the frequency, and eddy current losses - proportional to the square of the frequency [Leites 1981]. They are given in (8):

$$p = a.f + b.f^2$$
(8)

To determine the coefficients *a* and *b*, data on the losses at several values of the frequency for sinusoidal varying induction are needed. In practice, the power losses per unit mass of the magnetic circuit can be determined by (9):

$$p = p_{fb}\left(\frac{p_h}{p}\right)_b\left(\frac{f_e}{f_b}\right) + p_{fb}\left[1-\left(\frac{p_h}{p}\right)_b\right]\left(\frac{f_e}{f_b}\right)^2 \qquad (9)$$

where:

p_{fb} – losses per unit mass at base frequency for a certain type of silicon steel (catalogue data),

$\left(\frac{p_h}{p}\right)_b$ – the ratio of the hysteresis losses to the total losses in the steel at the base frequency (it equals 0.5 to 0.8 for the different types of silicon steel),

f_b – base frequency at which the steel was tested,

f_e – equivalent frequency.

The equivalent frequency refers to sinusoidal induction and is such that the calculated losses for one period are equal to the losses in the real curve of change of induction, also for one period. This is given in (10):

$$f_e = f\left(\frac{K_{fU}}{K_{fU\sin}}\right) \qquad (10)$$

In this expression:

$K_{fU} = \frac{U_{eff}}{U_{av}}$ – form factor,

U_{eff}, U_{av} – effective and average value of the induced voltage when the induction changes.

The average value of the induced voltage can be obtained from (11) and the effective value from (12), respectively:

$$U_{av} = \frac{1}{T}\int_0^T \left[u(t) - R.i(t)\right] dt \qquad (11)$$

$$U_{eff} = \sqrt{\frac{1}{T}\int_0^T \left[u(t) - R.i(t)\right]^2 dt} \qquad (12)$$

T denotes the period of the real curve of induction change.

The power estimation analysis is a prerequisite for the creation of an estimation function that would allow the motor to operate at minimal losses regardless of the relative change of load within acceptable limits.

Conclusions

This paper discusses a method for sensorless estimation of the angular position of the rotor in which the shaft power can simultaneously be determined based on the information obtained for the flux linkage. This is done by conducting an experiment to determine the flux linkage in real time by measuring only the current and voltage. This makes it possible to obtain information on both the instantaneous value of the inductance and the power of the motor shaft, i.e. the actual useful power. The former can help decide the exact time for switching the phase winding on and off in a sensorless way, so that no braking torque is generated and the torque ripples are reduced. The latter allows the creation of an estimation function and an algorithm for finding the optimum switching angle in real time, so that the motor operates at minimum losses regardless of the change of load within acceptable limits. This would increase the efficiency of the machine and would expand the applications of SRM in the drive systems of various mechanisms.

Acknowledgements. The support for this work is provided by the bilateral Chinese-Bulgarian scientific project of the National Science Fund of the Ministry of Education and Science with contract № KP-06-China/2 D-83/2018 between the China University of Mining and Technology and the University of Mining and Geology “St. Ivan Rilski”, Sofia.

References

AEM (Advanced Electric Machines) Ltd. 2020. 10-11 Teal Farm Way, Washington, NE38 8BG, United Kingdom.

Cossar C., L. Kelly. 2001. Drive development and test, in Electronic Control of Switched Reluctance, Oxford Newnes, pp. 75-97, ISBN 978-0-7506-5073-1

Dinchev D., V. Velinov, I. Galinov, Y. Gorbunov, K. Pavlitov. 2009. Measurement and Modeling of the Stator Inductance of a Switched Reluctance Motor of Type 12-8 with the Aid of Artificial Neural Networks - *Proceedings of TU-Sofia*, 59, Book 1, pp. 27-34, ISSN 1311-0829. (in Bulgarian)

Gallegos-Lopez, G., J. Walters, K. Rajashekara. 2001. Switched Reluctance Machine Control Strategies for Automotive Applications, SAE Technical Paper, SAE 2001 World Congress, https://doi.org/10.4271/2001-01-0955, ISSN: 0148-7191

Gorbounov, Y., R. Alexandrov. 2020. Platform for experimental study of a switched reluctance motor. - *Journal of Mining and Geological Sciences*, 63, pp.146-151, University of Mining and Geology "St. Ivan Rilski", Sofia, ISSN 2682-9525.

IEC60034-30, 1st Ed. 2008. Rotating electrical machines - Part 30: Efficiency classes of single-speed, three-phase, cage-induction motors (IE-code)

Horia, G., V. Manescu, G. Paltanea, G. Scutaru, I. Peter. 2017. New Trends in Energy Efficient Electrical Machines. - *Procedia Engineering*, 181, pp. 568-574, ISSN 1877-7058, https://doi.org/10.1016/j.proeng.2017.02.435.

Jae-Hoon, K., K., Rae-Young. 2019. Online sensorless position estimation for switched reluctance motors using characteristics of overlap position based on inductance profile. - *IET Electric Power Applications*, 13, Issue 4, pp. 456-462, ISSN 1751-8660.

Leites, L. *Electromagnetic calculations of transformers and reactors*. 1981. Energia, Moscow, pp. 137-138, BBK 31.261.8. (in Russian)

Miller, T. 2001. *Electronic Control of Switched Reluctance Machines.* Reed Educational and Professional Publishing Ltd, ISBN 0 7506 50737.

Pavlitov C., Y. Gorbounov, R. Rusinov, X. Ma, W. Wang. 2013. Precise Model of a Class of Switched Reluctance Motors Based on Neural Network Descriptions. - *Journal of the Balkan Tribological Association*, IF 0.236, 19, No 3, pp. 377-390, ISSN 1310-4772.

Siadatan, A., H. Torkaman, M. Rafie. 2019. Design, modeling, prototyping, and comparison of a low-cost, small-size, and accurate sensorless driver for switched reluctance motor. - *Engineering Reports*, Wiley Online Library, 2, Issue 1, pp. 1-16, https://doi.org/10.1002/eng2.12072.