UDC 621.3 https://doi.org/10.20998/2074-272X.2023.3.05

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Sensorless control of switched reluctance motor based on a simple flux linkage model

Introduction. *The operation of switched reluctance motor requires prior knowledge of the rotor position, obtaining from either low resolution photocoupler based position sensor or high resolution shaft encoder, to control the on/off states of the power switches.* ***Problem***. *However, using physical position sensor in harsh environment will inevitably reduce the reliability of the motor drive, in which sensorless control comes into play.* ***Novelty***. *In this paper, a sensorless control scheme of switched reluctance motor is proposed.* ***Methodology***. *The method is based on a simple analytical model of the flux-linkage curves rather than the conventional approach that normally uses a look-up table to store all the data points of the flux-linkage curves. By measuring the phase current, rotor position can be deduced from the analytical model.* ***Practical value***. *Simulation results are given and the proposed sensorless scheme is verified to provide a moderate position estimation accuracy in a wide speed range in both unsaturated and saturated conditions.* References 9, figures 6.

Key words: **analytical model, switched reluctance motor, sensorless control.**

Вступ. *Для роботи вентильного реактивного двигуна потрібне попереднє знання положення ротора, отримане або від датчика положення на основі оптопари з низькою роздільною здатністю, або від енкодера з високою роздільною здатністю, щоб керувати станами вмикання/вимикання силових перемикачів.* ***Проблема***. *Однак використання датчика фізичного положення в суворих умовах неминуче знижує надійність моторного приводу, в якому набуває чинності бездатчикове управління.* ***Новизна***. *У цій роботі пропонується бездатчикова схема управління вентильним реактивним двигуном.* ***Методологія*** *Цей метод заснований на простій аналітичній моделі кривих потокозчеплення, а не на традиційному підході, який зазвичай використовує довідкову таблицю для зберігання всіх точок даних кривих потокозчеплення. Вимірявши фазний струм, положення ротора можна вивести з аналітичної моделі.* ***Практична цінність***. *Наведено результати моделювання та перевірено запропоновану бездатчикову схему для забезпечення помірної точності оцінки положення в широкому діапазоні швидкостей як у ненасичених, так і в насичених умовах.* Бібл. 9, рис. 6.

Ключові слова: **аналітична модель, вентильний реактивний двигун, бездатчикове керування.**

Introduction. Switched reluctance motor (SRM) is an electric motor that has gained a lot of attention in recent decades due to its unique features such as rugged structure and cost effective [1, 2]. It has been widely adopted in industrial and home applications and shows superior performance. Unlike the induction motor and the synchronous motor that are able to run by just plugging in the phase terminal to the power grid, the operation of SRM cannot be separated from the dedicated controller and rotor position sensor, which is one of the main disadvantages of SRM [3].

The control of SRM always involves acquiring the rotor position as crucial information to determining the firing of switches. Due to the principle of the torque production in SRM, the magnetization of phases should synchronize with the rotor poles in order to maximize the efficiency of the torque production. Miss firing of the switches may heavily impact the performance of the SRM drives or even threaten its stable operation. A high-resolution optical encoder or a low-cost Hall effect sensor is therefore normally embedded in the SR motor.

SRM is quite suitable in the applications under harsh environment, the rotor position sensor may be impacted and malfunctioned however. In the applications with limited budget, the expensive encoder is usually not an option. Therefore, sensorless control is favorable in many cases.

The sensorless operation of SRM generally requires two kinds of rotor position information, continuous or discrete. The former one needs to resolve the rotor position uninterrupted while the latter one is simpler and only requires few points during an entire electrical cycle and the intermediate points can be interpolated [4].

Different types of position sensorless scheme have been reported in literatures, they can be broadly classified as active phase methods or inactive phase methods [5]. In [6], a sensorless method based on an analytical self-inductance model of SRM is introduced, the inductance curves at three crucial rotor positions are picked out to construct a complete inductance profile at all positions. The rotor position is then resolved from the transformed voltage equation. The method only measures the phase current and does not require additional hardware. Instead of using analytical model, look-up table is used in [7] to look up the rotor position if knowing the value of the current and the flux in real-time. Despite the advantage of high accuracy, the main drawback of the method is that large storage space is required to store the offline look-up table, which will add to the cost of the motor controller. By analyzing the inductance profile of SRM, a simple sensorless method that observes the current gradient is proposed in [8]. The current slope will suddenly change the sign at a specific location where the rotor position can be detected.

In this paper, a sensorless control scheme of SRM is proposed. It is based on a simple analytical model of the magnetization curves developed in [9] rather than using the look-up table in the conventional approach. The model only requires few parameters that are normally available or easily obtained to form the SRM magnetization curves. The rotor position is inherently a part of the model due to the nonlinear relationship among the flux-linkage, current and rotor position, thus it can be estimated from the flux-linkage model. The proposed sensorless control only requires the measurement of the current of the active phase in real-time, thus the hardware will be simple. Besides, there is no need to store the look-up table, so the memory size of the controller needed is reduced. Simulations under multiple operating conditions are carried out in MATLAB/Simulink to verify the correctness and effectiveness of the proposed sensorless control method.

Proposed sensorless control method of SRM. A sensorless method normally relies on the magnetization characteristics of the motor. Due to the nonlinear characteristics of SRM, the flux-linkage is a nonlinear function of the current and the rotor position, which implies that if the current and the flux-linkage are known, it is possible to deduce the rotor position. Therefore, having an accurate model of the magnetization characteristics of SRM makes it convenient to develop the sensorless control scheme, and the accuracy of the estimated position relies on the accuracy of the model.

The phase voltage equation of SRM can be written as

$$u = R \cdot i + \frac{\mathrm{d}\psi(i,\theta)}{\mathrm{d}t}, \quad (1)$$

where u is the phase voltage; R is the phase resistance; i is the phase current; ψ is the flux-linkage; θ is the rotor position.

The flux-linkage can be rewritten in an integration manner as

$$\psi(i,\theta) = \int (u - R \cdot i)\mathrm{d}t. \quad (2)$$

If it is not in low voltage application, the phase voltage can be assumed to be equal to the U_{DC}, $-U_{DC}$, or 0 V, where U_{DC} is the DC link voltage, while only introducing minor error due to the comparatively small voltage drops across switches and diodes in the converter circuit. The phase resistance is measured one time when the motor stalls. The phase current is measured in real-time and by doing integration, the flux-linkage can be estimated.

Due to the doubly-salient structure of SRM, the flux-linkage characteristics vary with rotor position. Two typical positions are the unaligned position and aligned position. When the rotor pole is at unaligned position, the air gap dominates in the magnetic circuit, therefore the flux vs. current curve is a straight line, and the unaligned inductance is denoted as L_q, which is the slope of the flux-linkage curve. In aligned position, the flux-linkage curve is a straight line before knee point, and the inductance in this condition is L_d, which is notably larger than L_q. However, when the motor iron is saturated, the flux-linkage curves bends over and the slope is much smaller than unsaturated condition. The magnetization characteristics of the sample SRM is shown in Fig. 1. The results are obtained from FEM analysis. As can be seen from Fig. 1 that the flux-linkage is a nonlinear function of current and rotor position, which is a fundamental characteristic of any SR motor.

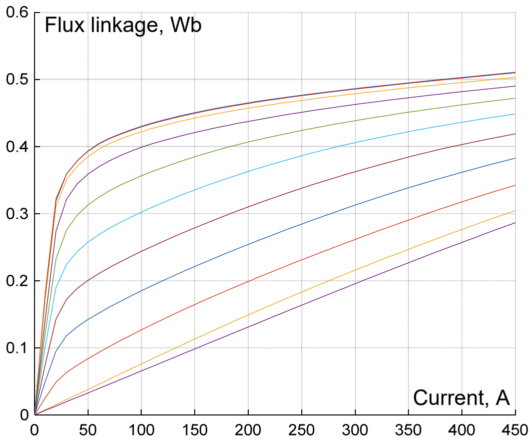

Fig. 1. Flux-linkage characteristics of the sample SRM obtained from FEM analysis

In order to model the nonlinear curves in Fig. 1, a simple analytical model is proposed in [1]. The curves at unaligned position can be simply represented by a straight line, and the slope is L_q in

$$\psi_q = L_q \cdot i, \quad (3)$$

where ψ_q is the unaligned flux-linkage.

The nonlinear curve at aligned position can be approximated by a function composed of exponential term, and written as

$$\psi_d = l_{dsat} \cdot i + A\left(1 - e^{-B \cdot i}\right), \quad (4)$$

where ψ_d is the aligned flux-linkage; l_{dsat} is the incremental inductance when the magnetic circuit is saturated at aligned position; A and B are the constant coefficients that can be determined in order the equation has a good approximation of the curve.

When the motor operates with maximum allowable current I_m, the motor is in deep saturation and the exponential term can be neglected, thus A can be deduced from (4) as

$$A = \psi_m - l_{dsat} \cdot I_m, \quad (5)$$

and B is calculated by

$$B = \frac{L_d - l_{dsat}}{\psi_m - l_{dsat} \cdot I_m}, \quad (6)$$

where ψ_m is the flux-linkage corresponds to I_m.

The magnetization curves of the intermediate positions between unaligned and aligned position can be deduced by using a nonlinear function as shown in (7), where N_r is the rotor pole number:

$$f(\theta) = \frac{2 \cdot N_r^3}{\pi^3} \cdot \theta^3 - \frac{2 \cdot N_r^2}{\pi^2} \cdot \theta^2 + 1. \quad (7)$$

Then the complete magnetization characteristics can be generalized as

$$\psi(i,\theta) = L_q \cdot i + \left[l_{dsat} \cdot i + A \cdot \left(1 - e^{-B \cdot i}\right) - L_q \cdot i\right] \cdot f(\theta). \quad (8)$$

The model in (8) makes it possible for the proposed sensorless scheme to preclude the use of the offline look-up table of the magnetization curves that takes up large amount of storage space in the controller.

Figure 2 shows the magnetization curves calculated from the aforementioned analytical model. As compared with the FEM result in Fig. 1, it can be said that the analytical model has good approximation. This is crucial in the sensorless control, otherwise the rotor position estimation will be erroneous due to a poor model.

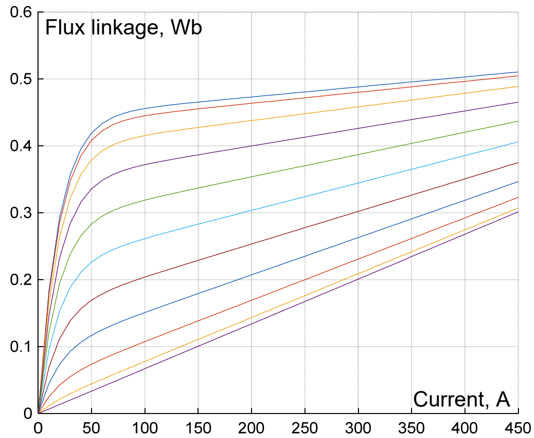

Fig. 2. Flux-linkage characteristics of the sample SRM calculated by the analytical model

From (8), the rotor position estimation can be deduced. The current i is measured in real-time, the flux-linkage ψ is then calculated by doing integration, L_q, l_{dsat}, A and B are also known constants. Therefore, the rotor position θ can be easily solved from (8), and sensorless operation is then possible by using this analytical model. In other words, if the current and the flux are known at the instant, the rotor position is solely determined in Fig. 1. This is the theoretical background of the rotor position estimation.

Simulation results and discussion. In order to verify the proposed sensorless control scheme, simulation is carried out in MATLAB/Simulink.

The simulation is at first evaluated at the speed of 1000 rpm. The speed is maintained constant by setting a high inertia value. The motor is operating under current chopping control. In Fig. 3, the reference current is kept at 20 A, and the hysteresis bandwidth of the phase current is 2 A. As can be seen from the magnetization curves in Fig. 1, the motor is running under unsaturated condition with low current. By comparing estimated rotor position and the real rotor position measured in mechanical angle, it can be found that the maximum error is around 2°, which is an acceptable accordance.

In Fig. 4, the motor is running under saturated condition, where the reference current is raised to 300 A and the hysteresis band is 60 A. In this case, the maximum deviation of the estimated angle from the real angle is also around 2°. It can be concluded that the proposed position estimation works well in both unsaturated and saturated conditions.

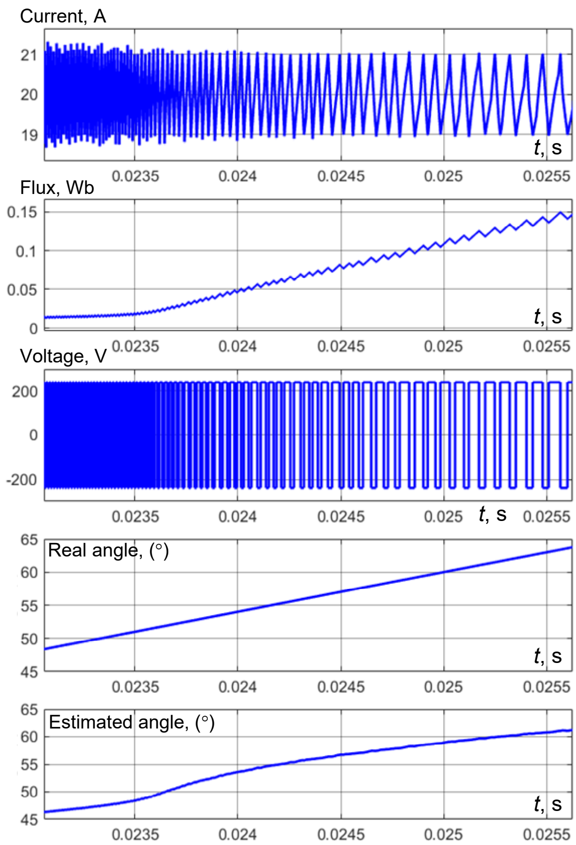

Fig. 3. Unsaturated operation at 1000 rpm

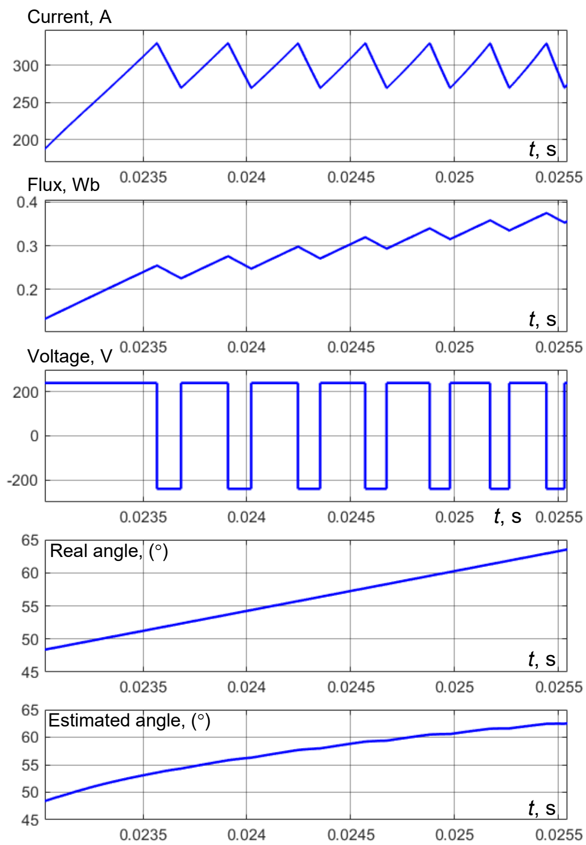

Fig. 4. Saturated operation at 1000 rpm

Then the simulation is carried out under different operation speeds in Fig. 5, 6. When operating in low speed, which is 50 rpm in Fig. 5, the current is kept in hysteresis manner at 200 A. It can be seen that the estimation error is below 2°. As in high speed operation in Fig. 6, the current can no longer maintained due to the significant back-EMF. Similar to the previous case, the maximum position estimation error is around 2°. Therefore, the proposed sensorless scheme is suitable in both low-speed and high-speed operation.

Conclusions.

In this paper, a new sensorless control method for the switched reluctance motor is proposed. The method uses an analytical flux-linkage model such that the large look-up table used in conventional approaches is not needed. The proposed idea only needs to measure the phase current in real-time, and the rotor position can be estimated continuously from solving a flux-linkage equation. The sensorless method has the merit of minimum data storage requirement since the large look-up table of the switched reluctance motor magnetization characteristics is replaced by the analytical model. Therefore, it is suitable to be used in low cost digital controllers. Simulation results have shown that the proposed sensorless control can acquire the rotor position continuously and the accuracy of the position estimation is small in low and high speed, unsaturated and saturated conditions.

Acknowledgement. This study was supported by Seoul National University of Science and Technology.

Conflict of interest. The authors declare that they have no conflicts of interest.

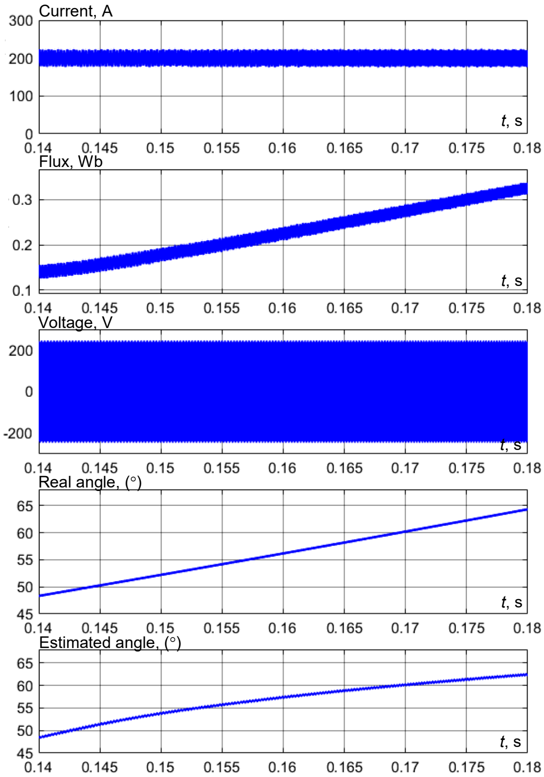

Fig. 5. Low-speed operation, 50 rpm

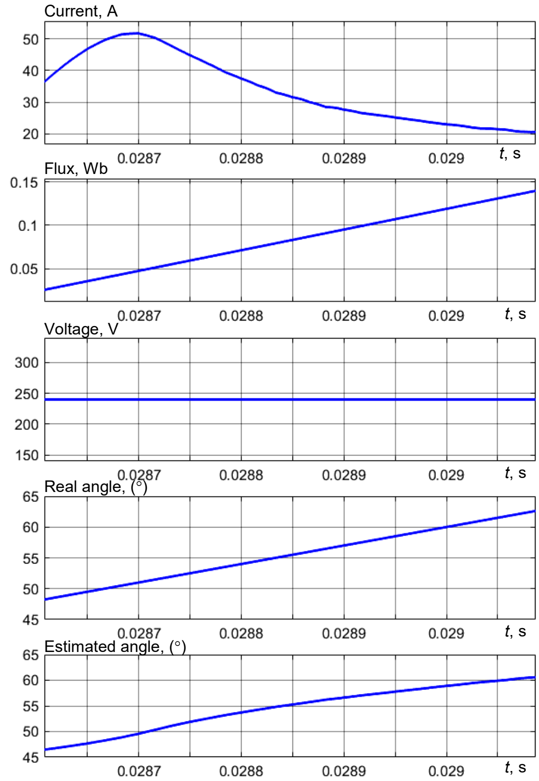

Fig. 6. High-speed operation, 5000 rpm

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Received 10.08.2022
Accepted 30.11.2022
Published 06.05.2023

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How to cite this article:
Fan J., Lee Y. Sensorless control of switched reluctance motor based on a simple flux linkage model. *Electrical Engineering & Electromechanics*, 2023, no. 3, pp. 36-39. doi: https://doi.org/10.20998/2074-272X.2023.3.05