Self-Tuning Control of SRM for Maximum Torque with Current and Shaft Position Feedback

Jong-yun Seo*, Hyong-yeol Yang*, Kwang-Heon Kim*, Young-Cheol Lim*, Hyun-Rok Cha**, Do-Hyun Jang***

*Dept. of Electrical Engineering and RRC/HECS, Chonnam National University
300 Yongbong-dong Buk-gu Gwangju, Korea

**SAMSUNG KWANGJU ELECTRONICS CO., LTD
Gwang-ju 2nd Factory 1119 O-Ryong-Dong Buk-Gu Gwangju, Korea

***Dept. of Electrical Engineering, Hoseo University
Sechul-ri Baebang-myun Asan-si chungnam Korea

Abstract- In this paper, we present self-tuning control of switched reluctance motor for maximum torque with phase current and shaft position sensor. Determination method of turn-on/off angle is realized by using self-tuning control method. During the sampling time, micro-controller checks the number of pulse from encoder and compare with the number of pre-checked pulse. After micro-controller calculates between two data, it moves forward or backward turn-off angle. When the turn-off angle is fixed optimal turn-off angle, the turn-on angle automatically moves forward or backward by a step using self-tuning control method. And then, optimal turn-off angle is searched once again. As such a repeating process, turn-on/off angle is moved automatically to obtain the maximum torque. The experimental results are presented to validate the self-tuning algorithm.

1. Introduction

A useful SRM (Switched Reluctance Motor) was developed in the beginning of 1980's. Until now, it has been primarily a research activity. The SRM has a simple structure with an easily modified topology. The SRM inverter control is independent of the polarity of the current, so it has low cost. And the SRM that has high torque density and high efficiency is compared with the BLDCM. New achievements in power semiconductor technology have been changed the view of the SRM from a theoretical subject to a practical drive. As a result, industry specialists began to consider it as a reliable variable drive.

Self-tuning method is one of the first efforts on this area of research. Shifting the problem from manufacturing of the drive to its control is the first step towards the solution. In other words, it can transform a hardware problem into a software task by strategy in accordance with the drive parameters. And the controller with the proposed adaptation technique is essentially universal and can be connected to any SRM. Artificial intelligence techniques have been used to implement the above approach and promising results have been obtained. [1]

2. Mathematical modeling for SRM

Although the operation of the SRM appears simple, an accurate analysis of the motor's behavior is required relatively complex mathematical approach. Fig. 1 is the equivalent circuit for SRM. The instantaneous voltage across the terminal of a phase winding is same as the time derivative of the flux linked in the winding as [3]

$$v = R\cdot i + \frac{d\lambda}{dt} \tag{1}$$

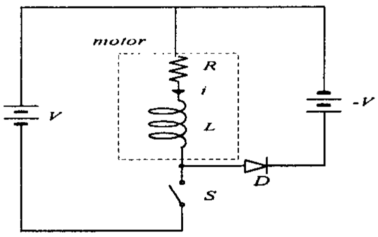


Fig. 1 Equivalent circuit of SRM

where, v, i, R, and λ are the terminal voltage, phase current, phase resistance, and the flux linked by the winding, respectively. The flux linkage is a function of rotor position and the phase current because of the saliency of the poles and the magnetic nonlinearity. Thus, Eq. (1) can be expanded as

$$v = R\cdot i + \frac{\partial\lambda}{\partial i}\frac{di}{dt} + \frac{\partial\lambda}{\partial\theta}\frac{d\theta}{dt} \tag{2}$$

where, $\frac{\partial\lambda}{\partial i}$ and $\frac{\partial\lambda}{\partial\theta}$ are defined as inductance $L(\theta,i)$, and the instantaneous back EMF coefficient, respectively.

Multiplying each side of Eq. (1) by the phase current i gives an expression for the instantaneous power as

$$vi = R\cdot i^2 + i\frac{d\lambda}{dt} \tag{3}$$

where, vi represents the instantaneous electrical power delivered to the SRM. $R\cdot i^2$ represents the ohm loss in the in the SRM winding. Then, the second term $i\frac{d\lambda}{dt}$ must represent the sum of the mechanical power output of the SRM and the power stored in the magnetic field from the conservation of the power.

Assuming that the motor remains magnetically unsaturated during operation, then the relationship from flux to current is given by

$$\lambda = L(\theta)\, i \tag{4}$$

And the motor inductance varies only as function of rotor angle. Substituting equation (4) into $W_c = \int_0^i i(\theta,i)d\lambda$ and evaluating the integral yields,

$$W_c = \frac{1}{2}L(\theta)i^2 \tag{5}$$

And then, substituting equation (5) into $T = \frac{dW_c}{d\theta}$ gives the familiar simplified relationship for SRM torque,

$$T = \frac{1}{2}\frac{dL(\theta)}{d\theta}i^2 \tag{6}$$

Therefore, the torque equation of 8/6 SRM gives

$$T_{out} = \frac{1}{2}i_a^2\frac{dL(\theta)}{d\theta} + \frac{1}{2}i_b^2\frac{dL(\theta-15^o)}{d\theta} + \frac{1}{2}i_c^2\frac{dL(\theta-30^o)}{d\theta} + \frac{1}{2}i_d^2\frac{dL(\theta-45^o)}{d\theta} \tag{7}$$

where i_a, i_b, i_c, and i_d are phase current, respectively.

The torque equation of general motor is given by

$$T_m = J_m\frac{d\omega_m(t)}{dt} + B_m\omega_m(t) + T_l + T_f \tag{8}$$

where J_m, B_m, T_l, T_f, ω_m are inertia, damping coefficient, load torque, static friction torque, and speed of the motor, respectively.

In the condition of the fixed input power, regular load torque, and a steady state, if SRM is driven, the torque is proportional to speed as

$$T_m \propto \omega_m(t) \tag{9}$$

As the Eq. (9), if SRM is driven at the maximum speed by using self-tuning control, we can know the maximum torque.

3. Optimal turn-on/off angle determination by using self-tuning control

Fig. 2 represents the instantaneous torque of SRM that the turn-off angle is changed when turn-on angle is fixed. Fig. 2(a) represents the instantaneous torque of SRM that the turn-off angle is moved near the turn-off point at the maximum torque, not having the negative torque and the total torque is not high enough. Fig. 2(b) represents instantaneous torque of the SRM that the turn-off angle is moved to the highest point of inductance profile. The high positive torque is generated, but the negative torque is generated in this mode. Therefore total torque is decreased. Fig. 2(c) represents instantaneous torque of the SRM that the turn-off angle is moved to the optimal point. As positive torque is increased, total torque is reached more high than any other turn-off angle even though some negative torque is generated. [2]

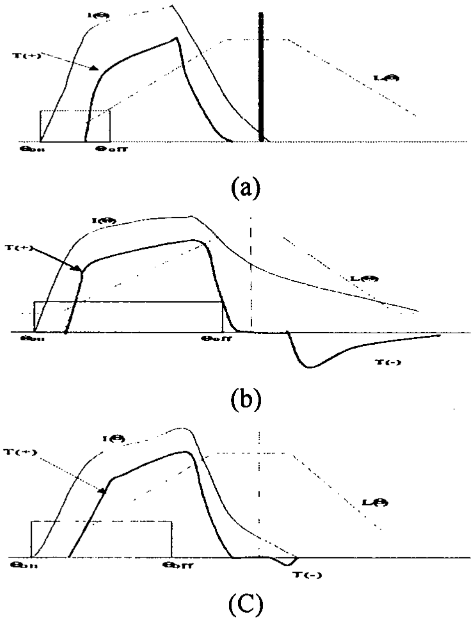
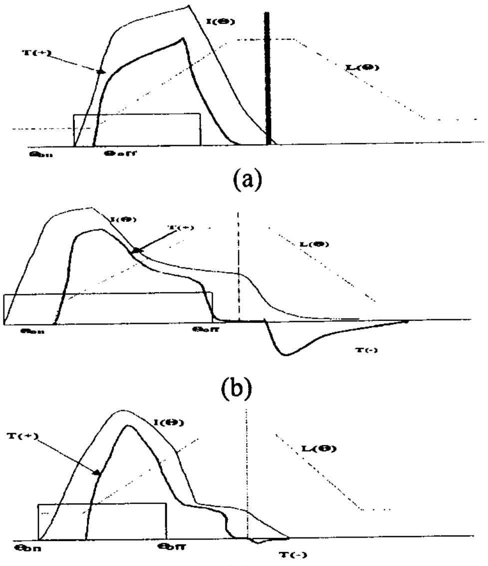


Fig. 2 Instantaneous torque of SRM at the fixed turn-on angle and variable turn-off angles; (a) moved to the turn-off point at maximum torque, (b) moved to the highest point of inductance profile, (c) moved to the optimal turn-off angle.

Fig. 3 represents the instantaneous torque of SRM that the optimal turn-on/off angles are found by using self-tuning control method. Fig. 3(a) represents the instantaneous torque of SRM that the turn-on angle is moved near the rising point of inductance profile; it doesn't have the negative torque and has high efficiency but total torque is not high enough. Fig. 3(b) represents instantaneous torque of the SRM that the turn-off angle is moved more forward than the optimal turn-on angle. The high positive torque and the negative torque are generated. Therefore total torque is decreased. Fig.3(c) represents instantaneous torque of the SRM that the turn-on angle is moved at the optimal turn-on/off angle. As positive torque is increased, total torque is reached the maximum torque even though some of the negative torque is generated.

The Fig. 4 shows the flowchart of subroutine to determine the turn-on/off angle by using self-tuning control of SRM for maximum torque with phase current and shaft position sensor. It is supposed that the turn-on angle θ_{on} is fixed at mechanical angle 0° and the turn-off angle θ_{off} starts at mechanical angle15° , which is located between minimum value and maximum value of inductance profile in the 8/6 SRM.

It is explained that the optimal turn-on/off angle is determined by self-tuning control when the fixed input power, regular load torque, and a steady state. Supposing that turn-off angle is fixed at a certain point of $\theta_{off,}$ a number of pulses, T (n-1) checked by encoder is stored in the register during the sampling time $[\theta_{n-1}, \theta_n]$. The number of pulse during next sampling time $[\theta_{n,} \theta_{n-1}]$ is compared with the number of pre-checked pulse. After microprocessor calculates difference between two data, the turn-off angle moves forward or backward. As of these repeating processes, the turn-on/off angle for the maximum torque and maximum efficiency are determined.



(a) (b) (c)

Fig. 3 Instantaneous torque of SRM at the fixed optimal turn-off angle and variable turn-on angles; (a) moved to the rising point of inductance profile, (b) moved forward angle than the optimal turn-on angle, (c) moved to the optimal turn-on/off angle.

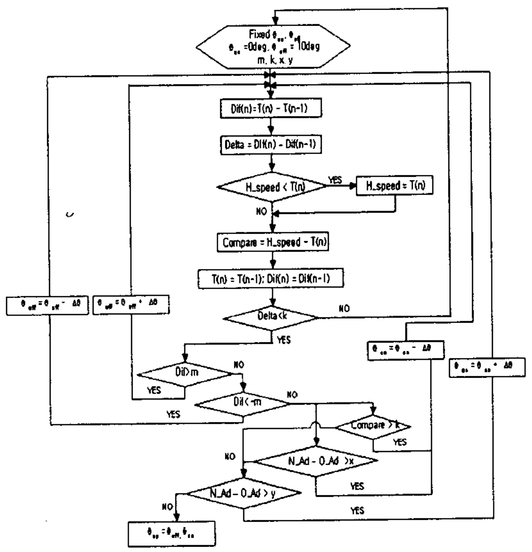


Fig. 4 Flowchart of subroutine for determination of optimal turn-on/off angle

Assuming that the number of pulse measured by encoder at present sampling time is T (n) and the number of pulse at previous sampling time re T (n-1), the deviation value Dif (n) is given by

$$\mathrm{Dif}(n) = T(n) - T(n-1) \qquad (10)$$

If the Dif (n) is on the given margin value m,

$$-m < \mathrm{Dif}(n) < m \qquad (11)$$

In the case of Dif (n) > m, first θ_{off} moves forward

$$\theta_{off}(n+1) = \theta_{off} - \Delta\theta \qquad (12)$$

Supposing that optimal turn-off angle is the middle line in the left region and the case of Dif (m)<-m, θ_{off} is increased as much as angle deviation $+\Delta\theta$ repeating process in the turn off angle, and θ_{off} is moved backward.

$$\theta_{off}(n+1) = \theta_{off} + \Delta\theta \qquad (13)$$

As such a repeating process, this turn-off angle is set into optimal switching angle

If optimal turn-off angle is found, optimal turn-off angle is fixed and turn-on angle is moved forward or backward in this algorism.

Assuming that optimal turn-off angle is fixed, a current value O_Ad (n-1) checked by current sensor is stored in the register. A current value N_Ad (n) during the next conversion time is compared with a pre-checked current value. After calculating difference between two data, the turn-on angle moves a step forward or backward. The optimal turn-off is searched once again. The optimal turn-on/off angle for the maximum torque and maximum efficiency is determined by repeating the processes.

4. Experimental results

The proposed method, self-tuning turn-on/off angle control, is compared with the existing method in the fixed input power, regular load torque, and steady state. It is observed that the output torque increases in the proposed method, because the speed is proportional to torque. Fig. 5 is the proposed speed control system driving SRM by using self-tuning control method. In the experimental equipment, an encoder and current sensor check speed and turn-on/off angle information. We can control turn-on/off angle from encoder and current sensor. The reason of setting two sensors (encoder and current) is as follow. In the case of using the only encoder, current waveforms can't maintain a constant waveform in the steady state. Whatever results follow, the speed traction can not be flatted. In the case of using the only current sensor, switching angle control is very difficulty in the transient state because current waveform are distorted.

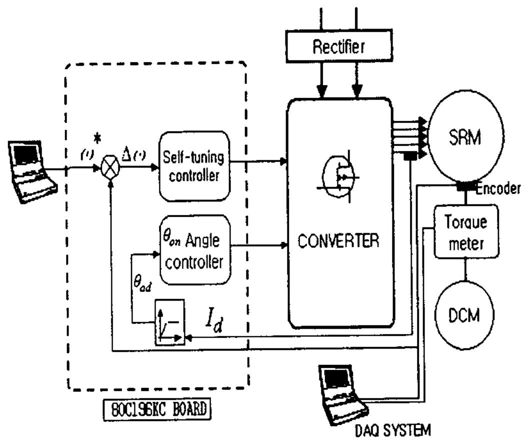


Fig. 5 ental system. Configuration of experim

Fig. 6 and Fig. 7 are compared with characteristics of current and voltage of proposed system by using self-tuning turn-on and turn-on/off angle control. Fig. 6 is the waveform when it is fixed at turn on angle 0° and turn-off angle is controlled by using self-tuning method.

Fig. 7 is the waveform when the turn-on/off angle is moved optimal turn-on/off angle by using self-tuning control method. It is shown that maximum current value is increased in comparison with Fig. 6. Fig. 8 is the waveform of speed traction. Fig. 8(a) is the waveform when it is fixed at turn on angle 0° and turn-off angle is controlled by using self-tuning method. Fig. 8(b) is the waveform when the turn-on/off angle is moved optimal turn-on/off angle by using self-tuning control method.

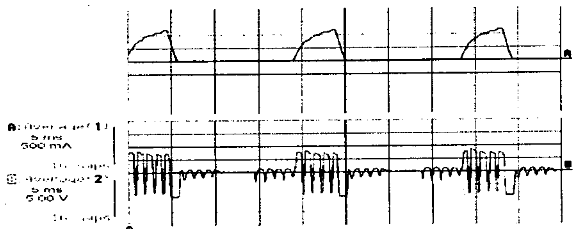


Fig. 6 Waveform of self-tuning turn-off angle control.

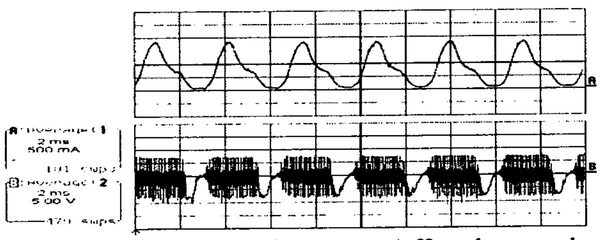
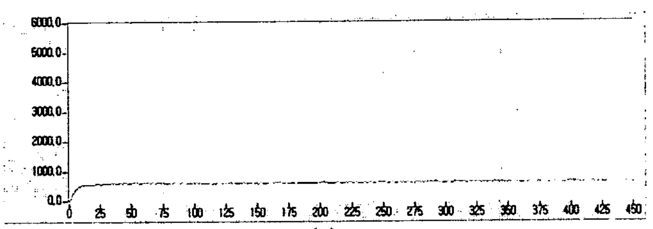
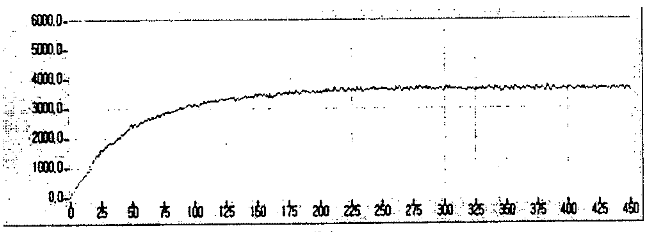


Fig. 7 Waveform of self-tuning turn-on/off angle control.



(a)



(b)

Fig. 8 Speed traction; (a) The speed waveform at fixed turn-on and optimal turn-off angle. (b) The speed waveform at optimal turn-on/off angle

5. Conclusion

It is difficult to find the optimal turn-on/off angle that produces maximum torque and maximum efficiency because turn-on/off angle is changed by magnetic saturation, converter topology and so on. This paper proposes the maximum torque control system of SRM drive by using self-tuning method that determines optimal turn-off angle. In experimental results, it is performed that the torque of SRM is higher when using self-tuning turn-on/off angles control than when using fixed turn-on angle and self-tuning controls. Also the speed control of the keeping maximum torque is available by using self-tuning control.

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