論 文
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SRM구동을 위한 새로운 제어방식

A Novel Control Scheme for SRM Drives

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Abstract - A novel control scheme for a Switched Reluctance Motor(SRM) drive is described. To increase torque, and to commutate easily, flat-topped phase current and fixed switching angle control is proposed. The conditions for flat-topped phase current are analyzed. It is achieved by voltage control with fixed switching angle. The proposed control system was tested to verify this suggestion.

Key Words : SRM, Voltage control, Fixed switching angle, Flat-topped current

1. Introduction

Recently, SRM draws much attentions due to the advantages such as simple and robust construction, high efficiency, excellent reliability, high speed capability and good thermal characteristics[1]. However, this machine has some disadvantages such as relative high torque ripple, high non-linearity and current commutation difficulty during high speed operation.

Thus, it is desirable to reduce torque ripple and develop high torque by using flat-topped phase current[2]. It is also important that the switching angle is predicted and/or calculated from the motor conditions for the easier commutation, .

In this paper, novel control scheme for the high torque drive is proposed. The conditions for high torque drive which includes flat-topped phase current control are analyzed and adopted. Flat-topped current can be achieved by the voltage control with fixed switching angle. This scheme has easy commutations characteristics in a wide speed range.

2. Suggestion of novel control scheme

In general, the torque-speed characteristics of SRM are similar to DC series motor, and are varied by control methods. To get high efficiency, high torque, low torque ripple and easy commutation, flat-topped phase current and appropriate switching angle calculation are essential[1~2].

To develope torque with low ripple, the current must be rectangular or pulse type. It can be easily achieved in current-source type(Fig. 1). However, it is difficult to realize that type of current and not cost effective. Thus, voltage-source type inverter is adopted more frequently because of its versatility and realizability. But, it is very difficult to regulate current shape which is very important to reduce torque ripple.

Rectangular or flat-topped phase current in a voltage-source driven SRM is possible. As the phase current changes by switching angles and applied voltage in a given motor parameters, appropriate conditions for the flat-topped phase current can be derived in a voltage source driven SRM system.

The 3 different types of current shape of SRM are shown in Fig. 2. Current type A is underexcited and C is overexcited condition. But type A and B would have more torque ripple than type B. Type A and C require more power to produce the same torque than type B. Therefore, type A and C are less effective to develop a torque[2~4].

The switching angle for the flat-topped phase current as B is derived as follows.

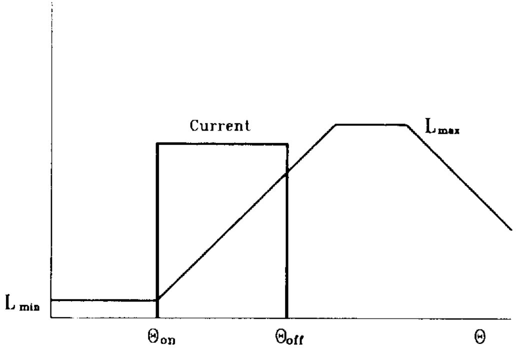

Fig. 1 Inductance profile and phase current in a current source driven SRM

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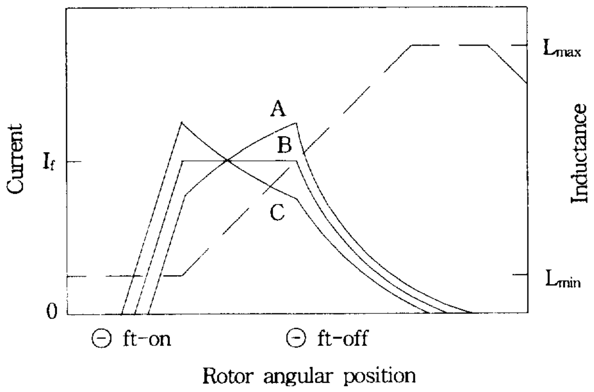


Fig. 2 Phase currents in a SRM

Voltage equation for a phase in a SRM can be described as eq.(1).

$$V = Ri + L(\theta, i)\frac{di}{dt} + i\frac{dL(\theta, i)}{d\theta}\frac{d\theta}{dt} \tag{1}$$

where R is winding resistance, L is inductance in a phase.

If the magnetic saturation is neglected for simple analysis and a flat-topped phase current could be achieved. In this case di/dt can be assumed to be zero in eq. (1). The phase current become eq. (2).

$$i_{ft} = \frac{V}{R + k\,\omega_r} \tag{2}$$

Where $k = \dfrac{dL(\theta, i)}{d\theta}$, $\omega_r = d\theta/dt$

And to build-up this current as much as the magnitude of flat-topped value at the end of the minimum of inductance profile, the switching-on angle, θ_{ft-on} is derived as follows. The change of inductance is zero, since it dose not occur during current build-up period.

Eq. (1) is to be rewritten as eq. (3).

$$V = Ri + L_{\min}\frac{di}{dt} \tag{3}$$

In this equation, the switching-on angle to form flat-topped phase current is derived as eq.(4) by solving this equation.

$$\theta_{ft-on} = -\omega_r \frac{L_{\min}}{R}\ln\left(1 - \frac{R}{R + k\,\omega_r}\right) \tag{4}$$

The current starts to decrease and to vanish within a maximum region of inductance profile not to generate negative torque. As the demagnetizing voltage, V_b is applied at the switching-off instant, eq. (1) is rewritten as eq. (5).

$$-V_b = Ri + L_{\max}\frac{di}{dt} \tag{5}$$

This maximum turn-off angle, θ_{ft-off} is derived as eq. (5) by solving this equation.

$$\theta_{ft-off} = -\omega_r \frac{L_{\max}}{R}\ln\frac{1}{1 - \dfrac{R\,V}{(R + k\,\omega_r)\,V_b}} \tag{6}$$

Where, V_b is applied voltage during demagnetization.

So, the torque developed by this flat-topped phase current is as eq. (7).

$$\begin{aligned} T(\theta) &= \frac{1}{2}\frac{dL(\theta, i)}{d\theta}\,i^2 \\ &= \frac{1}{2}\frac{dL(\theta, i)}{d\theta}\frac{V^2}{(R + k\,\omega_r)^2} \end{aligned} \tag{7}$$

From the above analysis and equations, the appropriate applied voltage and switching angles enable to drive a motor with the flat-topped phase current and the reduced torque ripple. Eq. (2) shows the similar characteristics to V/F=constant of speed control of ac motors.

3. Simulations

Fig. 3 shows the simulation results of the variation of switching angles when the resistance of motor winding or the demagnetizing/magnetizing voltage ratio change.

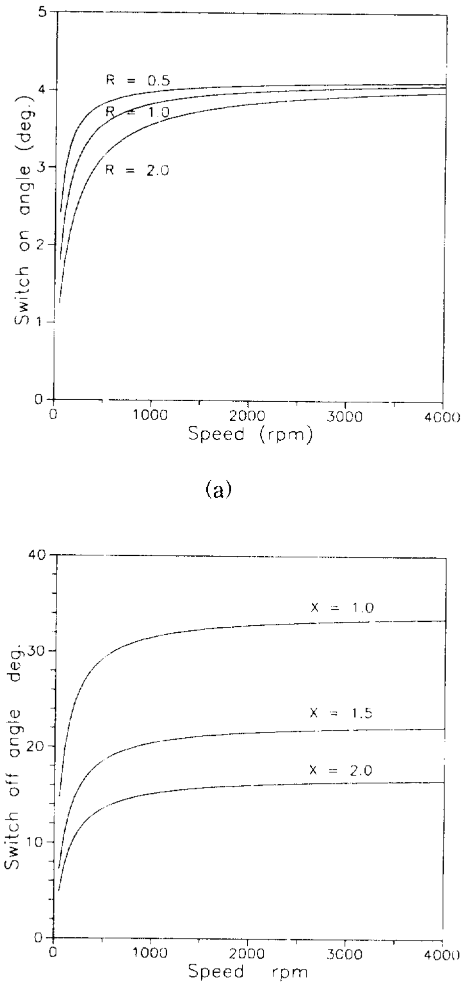
The results show that switching-on, -off angle is effected not so much as winding resistance variation except low speed range. This means that the switching-on angle could be fixed in an operating speed range. So, if the winding resistance is neglected, eq. (4) and (6) are simplified as eq. (8) and (9), respectively.

$$\theta_{ft-on} = \frac{L_{\min}}{k} \tag{8}$$

$$\theta_{ft-off} = \frac{L_{\max}\cdot V}{k\cdot V_b} \tag{9}$$

These equations show that switching-on angle could be fixed and switching-off angle is varied as the ratio of demagnetizing/magnetizing voltage, X varies. This means that the higher magnetizing voltage, X needs shorter switching-off interval. *i.e* if the demagnetizing voltage is 2 times as magnetizing voltage(X=2), it takes about one-half time to finish a phase current without producing negative torques. This ratios depend on the inverter topology and operating conditions. To simplify the control, the power converter uses classic type as shown in Fig. 4. In this topology, the demagnetizing voltage is equal to magnetizing voltage(X=1). In this case, eq. (9) become as eq. (10).

$$\theta_{ft-off} = \frac{L_{\max}}{k} \tag{10}$$



(a)

(b)

Fig. 3 Switching angles according to (a) the resistances (R) and (b) demagnetizing/magnetizing voltage ratio(X) variations

4. Experiments and Results

To verify this proposed control scheme, control system is constructed and tested.

The proposed power converter is classic inverter with chopper as shown in Fig. 4. The chopper is to control magnetizing voltage for the flat-topped phase current by equation(2). In this configuration, the free-wheeling paths are connected to regulated dc-link source. The switching angles are fixed as eq. (8) and (10) at a variable torque with variable speed control operation.

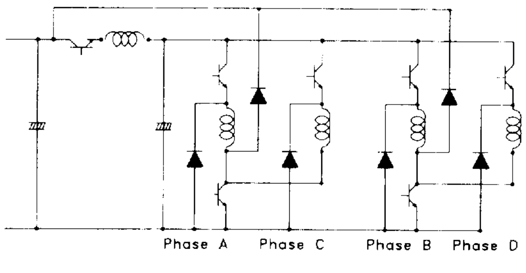
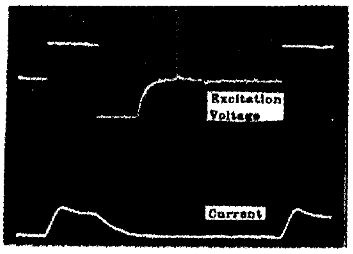


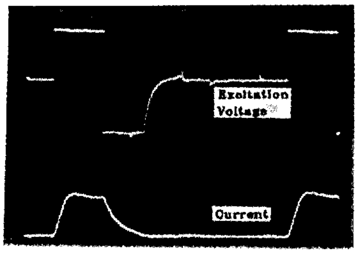
Fig. 4 Proposed power converter circuit

Fig. 5 and 6 shows that the phase current is flat-topped. In Fig. 5, dc-link voltage is regulated as the torque changes with fixed switching angle. This can be also shown in Fig. 6 when speed changes. Therefore, this scheme can be driven with the flat-topped phase current which means low torque ripple, and fixed switching angle control which means easy commutation.

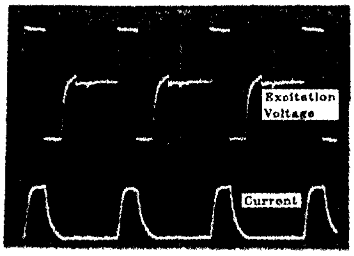
Torque is increased compare to the conventional current limit method(Fig. 7). At the low speed range, torques in two methods are same value. This is because that the current shape is similar to each other at the range. But at the high speed range, torque of proposed method is higher. It is due to the fact that torque ripple is reduced by this control scheme.



(a) torque 0.9[N·m], speed 1000[rpm]

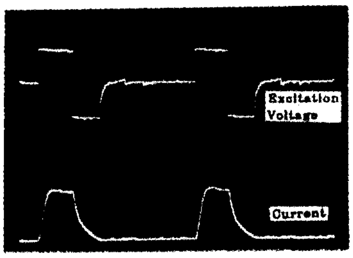


(b) torque 2.9[N·m], speed 1000[rpm]

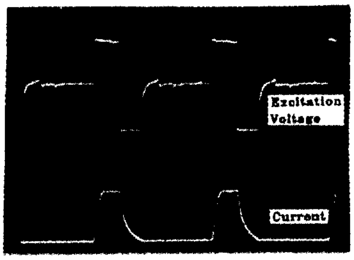


(c) torque 4.9[N·m], speed 1000[rpm]

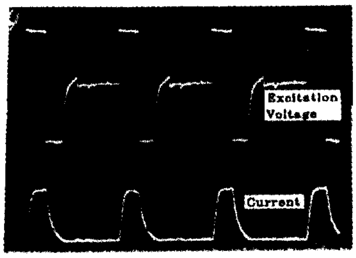
Fig. 5 Phase voltages and currents as torque changes with constant speed



(a) speed 800[rpm], torque 3.9[N·m]



(b) speed 1000[rpm], torque 3.9[N·m]



(c) speed 1400[rpm], torque 3.9[N·m]

Fig. 6 Phase voltages and currents as speed changes with constant torque

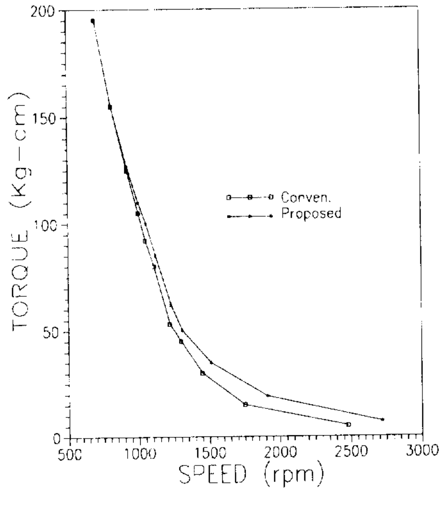


Fig. 7 Speed-torque characteristics of SRM drive system

5. Conclusion

This paper describes novel control scheme for a SRM drive. The control strategy is to form a phase current as flat-topped to increase torque with fixed switching angle. For this purpose, the voltage and switching angle conditions for the flat-topped shape of a current is derived. The test results show that this technique is advantageous to increase torque, to reduce torque ripple, and to commutate easily.

Appendix Table of motor ratings

Base Hp	2 Hp		
Number of stator poles	8	Number of rotor pole	6
Maximum Inductance, L_{max}	200 mH	Minimum Inductance, L_{min}	15 mH
Stator pole arc	20 °	Rotor pole arc	27 °

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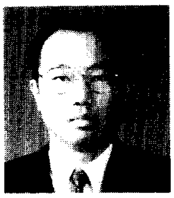

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