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분배용 선형 엔코더의 개발

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The study on the distribute type liner encoder

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Abstract - In SRM drive, the ON · OFF angles of each phase switch should be accurately controlled in order to control the torque and speed stably. The accuracy of the switching angles is dependent upon the resolution of the encoder and the sampling period of the microprocessor, that are used to provide the information of the rotor position and to control the SRM power circuit, respectively. However, as the speed increases, the amount of the switching angle deviation from the preset values is also increased. Therefore, the low cost encoder suitable for the practical and stable SRM drive is proposed and the control algorithm to provide the switching signals using the simple digital logic circuit is also presented in this paper. As a result, a stable high speed SRM drive can be achieved by the high resolution switching angle control and it is verified from the experiments that the proposed encoder and logic controller can be a powerful candidate for the practical low cost SRM drive.

Key words : SRM, Encoder, High precision switching angle control

1. Introduction

With the rapid development of the semiconductor technology, high-speed switching and high-capacity of device for the control of electric power become enabled. A multi-functional, high performance motor drive is needed by the development of mechatronics in the industry. SRM(Switched Reluctance Motor) is a single excited machine, which has a simple structure and a superior drive performance over wide speed range. The SRM has been researched spreading the application range to the industry such as household appliances, electric-car, aircraft, etc.[1][2] The rotor and stator of the SRM have both salient-pole type structure to maximize the reluctance torque and the winding is coiled to only the stator concentratively. As intermittent excition power is applied to each phase winding sequencially, it has the ability of low-switching frequency and high-speed operation.[3]

However, A position device to detect the information about the rotor position angle is essential for the proper switching operation.[4] An encoder or a resolver is generally used to detect position of the rotor. But the higher the resolution of position sensor, the higher the unit price increases. Therefore, in order to reduce the installation cost, a low-price encoder is to be used or a sensorless operation is to be adopted[5]. In order to turn on and off the switch of each phase, a microprocessor which is popularly used to calculate and generate position signal is used. But in the control of the SRM using a microprocessor, the resolution of the position signal is restricted by the sampling period of the microprocessor as well as the resolution of the encoder. Moreover, the higher the operating speed, the worse the resolution of position by the microprocessor becomes. It makes the steady state unstable. In this study, a low-cost linear encoder for the control of the SRM is proposed, in which the switch on-off angle is controlled with a simple circuit by using the proposed encoder. In the proposed switching method, the resolution of switch on-off angle, different from the general switching method, is not affected by the sampling period of a microprocessor and speed of the motor. The on-off angle can be always carried out at any desired position. Test results show that it gives a stable and high resolution drive with simple and low encoder.

2. Angle control of SRM

An SRM is an electric machine which converts the reluctance torque into mechanical power. Both the stator and rotor has a structure of salient-pole type to use the torque to the highest degree and the winding is coiled to only the stator concentratively. The torque is generated to the direction that the reluctance is to be minimized. The magnitude of torque generated in each phase is proportional to the square of the phase current and the gradient rate of inductance, as shown in (1).

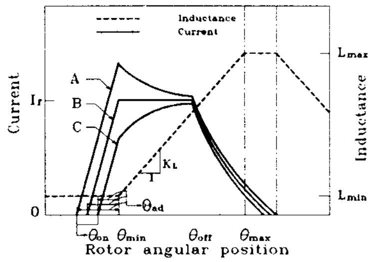
$$T(\theta, i) = \frac{\partial W'(\theta, i)}{\partial \theta} = \frac{1}{2}\frac{dL(\theta, i)}{d\theta} i^2 \quad (1)$$

Where, T is torque, θ is the position angle of rotor, i is phase current, $W'(\theta, i)$ is magnetic co-energy, and $L(\theta, i)$ is inductance between the stator and rotor.

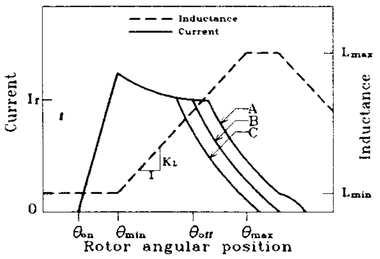
$$\begin{aligned} V &= Ri + \frac{d\lambda(\theta, i)}{dt} \\ &= Ri + L(\theta, i)\frac{di}{dt} + i\frac{dL(\theta, i)}{d\theta}\frac{d\theta}{dt} \end{aligned} \quad (2)$$

In the voltage equation (2), the first term of the right side is the voltage drop of the winding resistance, the second term is the voltage drop of reactance and the last term is both the emf(electromotive magnetic force) and the mechanical output. In order to derive the phase current from (2), an exact information about the inductance profile of the SRM is essential.

Fig. 1 shows the phase current waveforms according to the variation of the switching angle. θ_{min} and θ_{max} in the figure denote the rotor angle when the stator and rotor poles begin to overlap and meet completely.



(a) Variation of the switch ON angle



(b) Variation of the switch OFF angle

Fig. 1. Phase current waveforms according to the variation of
the switch ON and OFF angles

Fig. 1(a) shows the currents in the case that the advance angle(switch-on angle) is adjusted maintaining the switch-off angle fixed. If the switch-on angle varies, the shape of the current waveform at the beginning point of the torque generation range are change, and these are nearly proportional to the advance angle when the winding resistance is neglected. And the phase current waveforms of A and C among three waveforms show that the generated torque is not constant and the torque pulsation is severe during the torque generation range because the variation rate of current is positive or negative. However, the phase current waveform of B which has a uniform current waveform during the torque generation range shows that a uniform torque is generated and the torque pulsation is not severe if the variation rate of inductance is uniform. So that current becomes the standard current in order to drive motor effectively. Fig. 1(b) shows the currents that the switch-off angle varies maintaining the switch-on angle fixed. As the switch-off angle is near the point of maximum inductance, the utility of a inductance is increased and it is favorable to the generation of positive torque. But, if the phase current exists beyond the maximum value of the angle, a negative torque is generated and is the origin of the reduction of the mechanical output power and torque pulsation. Therefore, regardless of load torque and driving speed, if the switch-on angle is to be determined to the shape phase current is to be smooth and the turn-off angle is adjusted not to generated negative torque, the reluctance torque would be utilized effectively and the smooth torque which has minimum pulsation would be obtained. In the conventional SRM driving system, on-off angle must be switched according to the rotor position angle. So the position information of the rotor is essential. Generally, the rotor position angle is detected by equipping resolver or encoder at the axis of motor. Especially, considering the unit price, the incremental encoder is popular because of its price. The output pulse number as position is obtained as a digital value by the up-counter in this incremental encoder, The signals are used to control phase signal by the microprocessor. But the resolution of such a phase switch on-off control method is largely dominated by the sampling rate of the microprocessor. Especially, the higher the speed, the lower the resolution, so the steady state condition of the SRM drive may become unstable. Therefore, such controller is generally embodied by DSP in order to decrease the sampling frequency, but it has a limit to the maximum speed for stable drive.

3. Proposed encoder and logic controller

3.1 Proposed encoder

Like a conventional system, in the case that the phase switch of the SRM is controlled by a microprocessor, the control precision is determined by the resolution of the encoder($\Delta\theta_e$) and the variation of the rotor position angle during sampling period($\Delta\theta_m$). If the number of pulses per revolution is Np, the resolution of mechanical position of a encoder is not related with the speed of motor, and can be given as (3).

$$\Delta\theta_e = \frac{360}{N_p} \ [\text{deg.}] \tag{3}$$

The variation of the rotor position angle($\Delta\theta_m$) is dominated by the speed of motor during the sampling period and the value can be given as (4).

$$\Delta\theta_m = 6 \cdot \omega \cdot T_s \ [\text{deg.}] \tag{4}$$

Ts : the sampling period of the microprocessor [s]

In the method of phase switch control using the microprocessor, the variation of on-off angle is determined by the resolution of the encoder and the sampling period of the microprocessor. And the value can be given as (5) derived from (3) and (4).

$$\Delta\theta_s = \Delta\theta_m + \Delta\theta_e = 6\,T_s\,\omega_r + \frac{360}{N_p} \ [\text{deg.}] \tag{5}$$

Fig. 2 shows the control precision of on-off angle according to the speed of motor.

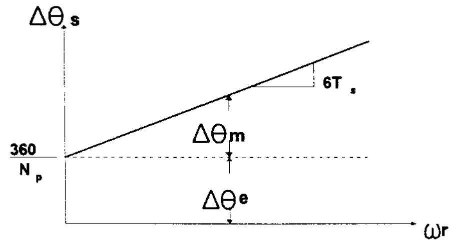
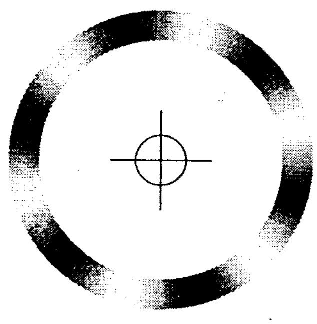


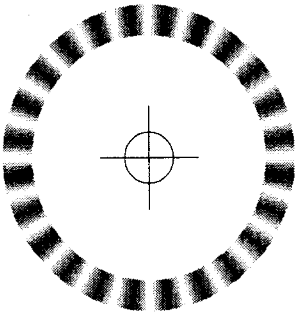
Fig. 2. Error of switching angle according to speed

As the speed of motor increases, the sampling error increases at the slope of 6Ts as shown in Fig. 2. Moreover, if the resolution of the encoder and the position angle variation of the microprocessor does not appear as times of integer, low-order harmonics component appears in the switching angle control. For this reason, a same low-order harmonics component appears in the torque of the SRM. So it gives a bad influence upon the stable drive. The variation of on-off angle is dominated by the resolution of the encoder because the variation of the position angle is generally less than the angle resolution of the encoder $\Delta\theta e$ in the case of low-speed motor. However, as the motor is operated in high speed range, the resolution of the encoder is fixed but the variation of the position angle by sampling is very high. In this case, the variation of on-off angle is dominated by the variation of the position angle by sampling time. Therefore, in order to control the on-off angle which has a similar resolution to the encoder, a high-speed sampling is required. the high-performance microprocessor is essential.

In order to control the phase switch of high resolution without a help of such the high speed microprocessor, a special control method is needed. Hence, in the 8/6 SRM, by the method that the phase switch on-off can become precise using a simple encoder, Two types of linear encoder as shown in Fig. 3. could be proposed. The encoder proposed in Fig. 3 is an encoder for the 8/6 SRM used in this experiment. As shown in Fig. 3, the color of base plate of encoder is change linearly, which is different from conventional digital encoder. So the intensity of transmitted radiation as the rotation of the encoder increases or decreases linearly. The output of the photo transistor is a triangular wave, which is the function of the position angle.



(a) 60° of the period



(b) 15° of the period

Fig. 3. Proposed low cost encoder

Therefore, the rotor position of the SRM is obtained by the output voltage of the photo transistor. In the configuration of the proposed encoder, the output period of the encoder can be defined as shown in Fig. 3(a) equivalent to one period of the SRM.

$$\delta = \frac{360}{P_r} \ [\mathrm{deg.}] \tag{6}$$

where, Pr : No. of poles of rotor

In the case of the 8/6 SRM, the period is 60° mechanical angle.

The output period which should be changed in a phase of the encoder can be defined as shown in Fig. 3(b). In the case of the 8/6 SRM, the period is 15° mechanical angle.

$$\delta_p = 2\frac{360}{P_s P_r} \ [\mathrm{deg.}] \tag{7}$$

where, Ps : No. of poles of stator

Pulse width δP in (7) is the width of the position angle, in which the phase must be in charge in order to generate the continuous torque. If the output period of the encoder is defined as (6), the rotor position angle for the phase switching can be obtained perfectly. So there exists a merit that the rotor position can be obtained also under the starting, but it is very difficult to form the same phase current waveform because of a defect that it is very difficult to make the encoder output linear. If the output period of the encoder is defined as (7), though the encoder output is nonlinear, there exists a merit that the phase switch of same form can be controlled by a simple circuit. However, because the rotor position angle for the phase switching cannot be obtained perfectly, there exists a defect that the rotor position cannot be obtained under the starting.

Among the proposed encoders in this experiment, an encoder of same form as shown in Fig. 3(b), that its period is defined as equation (7) is used to control the phase switch of the SRM. In this method, two photo coupler is needed for forward and backward rotation. Two photo coupler of the encoder is equipped with the phase difference by the mechanical angle γ, and each photo coupler is used as a part for forward or backward rotation. The phase difference of the encoder γ is for forming the phase switch of same form in driving the SRM forward and backward, and it is determined by the profile of the SRM.

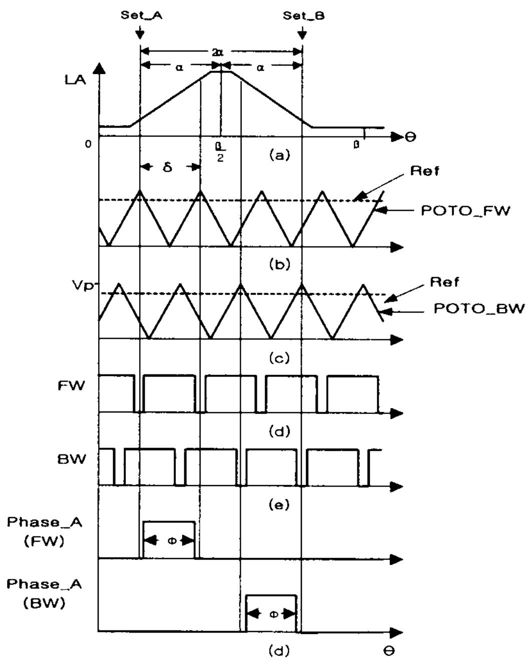


Fig. 4. Switching patterns of the phase switch

Fig. 4 shows the inductance profile about one phase, the photo transistor of the encoder, an command value of the position angle, FW and BW phase signals, and gate signals for forward and backward rotation. In this figure, β denotes the inductance period of the SRM and is equal to (8).

$$\beta = \frac{360}{P_r} \quad (8)$$

When the motor rotates for forward direction, FW phase pulse is formed by comparing the output of the photo coupler of the encoder with the command value of the phase switch as shown in Fig. 4. The FW phase pulse row formed like this should be distributed to the phase switch of each phase in regular order. At this point, the angle displacement when the phase switch is on is as (9).

$$\Phi = \delta \frac{V_{ref}}{V_p} \ [\text{deg.}] \quad (9)$$

The command value of Ref, the angle displacement when the phase switch is on, is generated through one D/A converter without regard to the forward and backward rotation of motor. If the motor rotates with forward direction, the phase switch is determined by FW and otherwise, the phase switch is determined by BW. The command value of the position angle displacement is give only as one value because it can be used to determine whether the motor rotates for forward or backward direction. Therefore, BW phase of the encoder is used for the phase switch on-off in the case of backward rotation, and the rotating direction can be detected by applying FW and BW phase of a determination circuit of the conventional encoder. For forward rotation, a Set_FW is the reference position and each phase switch can be used as a signal obtained at every 4 counter period from the FW phase clock. For backward rotation, a Set_BW is the reference position and each phase switch can be used as a signal obtained at every 4 counter period from the BW phase clock. The decision of forward and backward rotation of motor can be made using FW and BW phase by the same method of the conventional encoder.

3.2 digital logic controller

Fig. 5 shows the inductance profile, FW and BW output generated by the comparison of the ordered-value of the phase switch, and the gate signals of each phase for forward and backward rotation. Each phase switch should be set to ON at every 4 counter period from the FW phase clock for forward rotation as shown in figure 5. For this purpose, 4 bit counter and 2/4 multiplexer are adopted. For backward rotation, each phase switch should be set to ON at every 4 counter period from the BW phase clock. The judgment of forward, backward rotation of motor uses the method of the conventional encoder using the FW, BW phase. The controller is implemented using 80C196KB for indicating control and state. First, for starting, if the rotor of motor is forced to be placed at the point of maximum phase C inductance, it can be placed in the region of increasing phase A inductance for forward rotation and in the region of increasing phase D inductance for backward rotation.

Therefore, the position of the rotor is placed at SET with the current controller by switching on QC of 2×4 decoder by enabling the load unit of the counter.

And for forward rotation, QA should be set to ON by using the load port after selecting the FW signals at the clock input of 4 bit counter(DIR terminals). And QD should be set to ON by using the load port after selecting the BW signals at the clock input of 4 bit counter for backward rotation. In order to monitoring whether the switching sequence under starting and running operations is correct or not, the upper 4 bits of the port 0 are always checked. If the fault in the switching sequence occurs, it will be corrected via port 0. Moreover, the decision of the rotational direction is made by detecting the phase angles of the FW and BW signals that are input to the high speed input(HSI) terminals of the microprocessor. Using the FW or BW signals that are input to the timer 2, the motor speed is evaluated by the M/T method, a conventional calculation method of the encoder speed. DIR terminals are determined by the sign of torque and R/L terminals are determined by forward and backward rotation of motor.

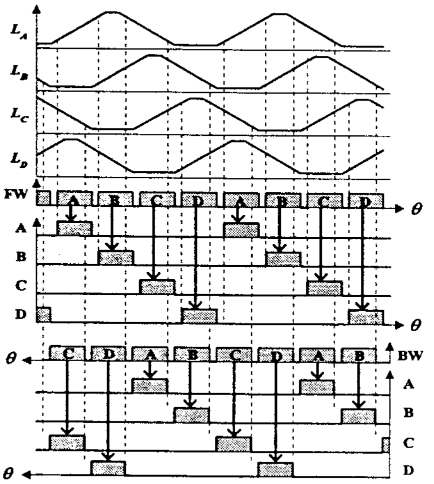


Fig. 5 shows the block diagram of controller for the phase switch.

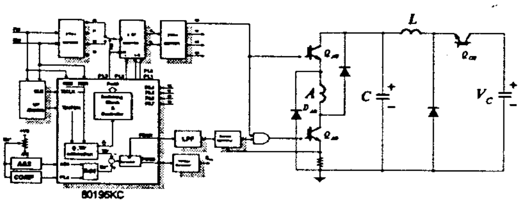
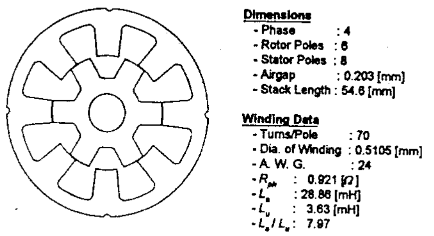


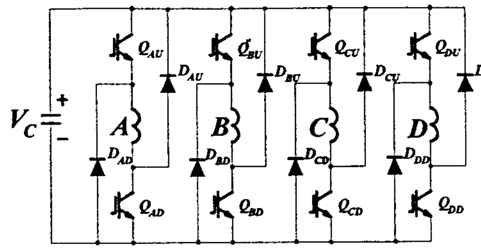
Fig. 6. Gate signal of each phase when SRM is rotating in the forward and backward directions by the proposed encoder

4. Experimental results and discussion

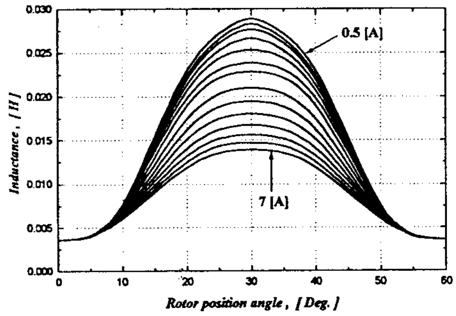
The SRM used in this experiment is 8/6, 400W, 200rpm, 200V SRM. It has the structure as shown in Fig. 7(a) and a conventional classic inverter as shown in Fig. 7(b) is used. Its inductance profile is as shown in Fig. 7(c) and calculated by voltage and current data considering the winding resistance after measuring the current waveform by oscilloscope by adding the voltage pulse until the current approaches to the limit value 7A changing the rotor by 1° . Therefore, obtained inductance profile is a relatively accurate value that can indicate the dynamic driving characteristic of the SRM.



(a) The structure of SRM



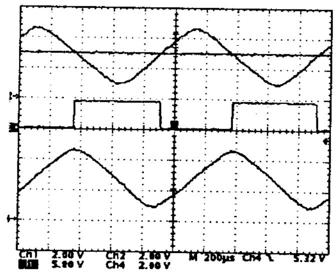
(b) Classic inverter circuit for SRM drive



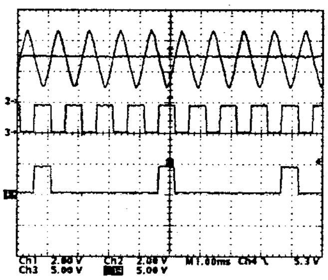
(c) Inductance profiles

Fig. 7. The structure and inductance profiles of SRM and its inverter circuit

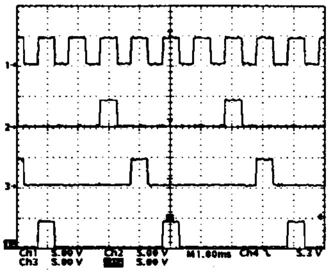
Forward rotation is defined as clockwise, and backward rotation as counterclockwise. Fig. 8(a) shows the linear photo-transistor output, the command value of the position angle, and the output signal of FW. Fig. 8(b) shows the linear photo-transistor output, the command value of the position angle, the output signal of FW, and the gate signal of phase A. The phase B~D phase signal is obtained by shifting the phase A signal by 15° .



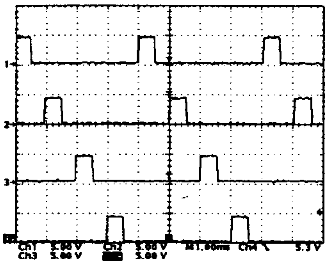
(a) output signals of poto Tr. and encoder



(b) output signals of poto Tr., encoder and gate signal



(c) Gate signal and corresponding encoder signal

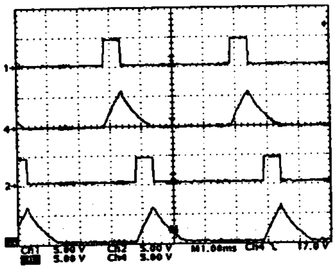


(d) Each gate signals

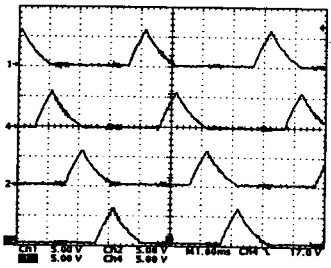
Fig. 8. Waveforms of the phase switch gate signals and phase current(2500rpm)

Fig. 9 shows the waveforms from the experimental results for forward rotation at 2500[rpm]. Fig. 9(a) shows the phase A, B signal and corresponding current waveform for forward rotation, and Fig. 9(b) shows currents of each phase. As shown in the figures, each phase current has almost same form by switching on-off the phase switch at the same rotor position angle.

Fig. 10 shows the waveform of the experimental result for comparing the phase switching stability of the conventional microprocessor method with that of the proposed method for forward rotation of the SRM at 3600[rpm].

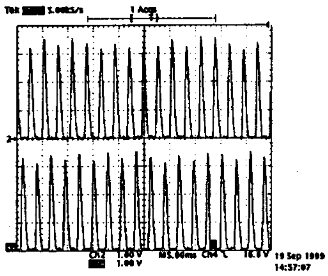


(a) Gate signal and corresponding phase current

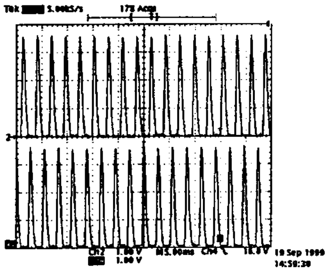


(b) Each phase currents

Fig. 9. Waveforms of the phase switch gate signals and phase current(2500rpm)



(a) Conventional



(b) Proposed

Fig. 10. Comparison of phase current waveforms (3600rpm)

Fig. 10(a) shows the waveform by the method of the conventional switching method using the microprocessor. In this method, the waveform of the phase current cannot be constant because the control resolution of on-off angle of the phase switch is low. It is considered that the phase torque has much ripple by this reason. Moreover, as shown in Fig. 10(b), the proposed phase switching method can switch on or off the phase switch at the same rotor position angle even at high speed. The phase current has almost same form so that speed and torque control can be achieved stable. Accurate and stable turn-on and turn-off of the phase switch gives a high stability at steady state.

4. Conclusion

In this paper, a low-cost linear encoder which enables the high resolution on-off control and the phase switch on-off control method using a simple circuit is proposed.

In the proposed phase switch control method, the control precision of the switch on-off angle is not affected by the sampling period of the microprocessor, and the operating speed of the SRM which is different from the general phase switch control method. So the on-off switching can be always carried out at any desired position.

And it is verified from the experiments that the proposed encoder and logic controller can be a powerful candidate for the practical low-cost SRM drive and the stable driving system.

[Reference]

[1] B. K. Bose, T. J. E. Miller, P. M. Szezesny and W. H. Bocknell, "Microcomputer Control of Switched Reluctance Motor", *IEEE Trans. on Industrial*

Application, vol. 22, no. 4, pp. 708-715, 1986.
[2] D. W. J. Puller "New data base for switched reluctance drive simulation." Proc. IEE, Vol.138, Pt-B, No.6, pp.331-336, 1991.
[3] Paul P.Acarnley, Rolaud J.Hill and Clive W.Hooper: "Detection of Rotor Position in Stepping and Switched Motors by Monitoring of Current Waveforms", IEEE Trans. on IE, Vol.32. No.3, pp.215-222, 1985.
[4] S. Vukosavic and V. R. Stefanovic, "SRM Inverter Topologies: A Comparative Evaluation", IEEE Trans. on IA, Vol.27, No.6, pp. 1034-1047, 1991.
[5] J. T. Bass, "Robust torque Control of Switched-Reluctance Motors without Shaft-Position Sensor", IEEE Trans. on IE. Vol.33, No.3. pp.212-216, 1986.
[6] P. H. Chappell, W. F. Ray and R. J. Blake, "Microprocessor Control of a Variable Reluctance Motor", Proc. IEE, Vol.131, No.2, Part.B, pp.51-60, 1984.
[7] B. K. Bose, T. J. E. Miller, P. M. Szczesny and W. H. Bocknell, "Microcomputer Control of Switched Reluctance Motor", IEEE Trans. on IA, Vol.22, No.4, pp.708-715, 1986.
[8] M. Ehsani, I. Husain and A. B. Kulkarni, "Elimination of Discrete Position Sensor and Current Sensor in Switched Reluctance Motor Drives", IEEE Trans. on IA, Vol.28. No.1, pp.128-135, 1992.
[9] I. E. Liang, Y. Liao, and T. A. Lipo, "A New Variable Reluctance Motor Utilizing An Auxiliary Commutation Winding," IEEE Trans. on IA, Vol.30, No.2, pp.423-432, 1992.
[10] I. Husain and M. Ehsani, "Torque Ripple Minimization in Switched Reluctance Motor Drives by PWM Current Control", IEEE Trans. on Power Electronics, Vol.11, No.1, pp.91-98, 1996.
[11] P. C. Kjaer, J. J. Gribble and T. J. E. Miller, "High-Grade Control of Switched Reluctance Machines", Proc. of MS/IEEE, San Diego, California, pp.92-100, 1996