Characteristics of Analog Encoder for SRM Drive

Sung-Jun Park and Jin-Woo Ahn

Abstract - In a switched reluctance motor drive, it is important to synchronize the stator phase excitation with the rotor position; therefore, the position of rotor is an essential information. Although optical encoders or resolvers are used to provide the position information, these sensors are expensive. Moreover, in the high-speed region, switching angles are fluctuated back and forth out of the preset value, which is caused by the sampling period of the microprocessor.

In this paper, a low cost analog encoder suitable for practical applications is proposed. And the control algorithm to generate switching signals using a simple digital logic is presented. The validity of the proposed analog encoder with a proper logic controller is verified from the experiments.

Keywords - SRM (Switched Reluctance Motor), analog encoder

1. Introduction

An important factor in the selection of a motor and a drive for an industrial application is the cost. The switched reluctance motor (SRM) is a simple, low-cost, and robust motor suitable for variable-speed as well as servo-type applications [1]. The SRM 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 [2], [3]. In SRM drive, it is important to synchronize the stator phase excitation with the rotor position; therefore, the information about rotor position is an 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 proper control of each phase switch, a microprocessor is popularly used to calculate and generate the position signal; however, in this case, the resolution of the position signal is restricted by the sampling period of the used microprocessor as well as that of the encoder. In this paper, a new low-cost analog encoder for high performance switching angle control employing suitable control algorithm for the SRM drive is presented, in which the switch on-off angle is controlled with a simple circuit by using the proposed encoder. In the proposed switching technique, the resolution of switch on-off angle, different from the general methods, is not affected by the sampling period of a microprocessor and the speed of a motor; hence, the on-off switching angle control can be always carried out at any desired position.

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2. Analog Encoder and Controller

2.1 Proposed analog 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 N_p, the resolution of mechanical position of an encoder is not related with the speed of motor, and can be expressed as;

$$\Delta\theta_e = P_r \frac{2\pi}{N_p} \text{ [rad]} \tag{1}$$

Where, P_r : the number of poles of rotor

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 (2).

$$\Delta\theta_m = P_r \cdot \omega_{rps} \cdot T_s \text{ [rad]} \tag{2}$$

Where, Ts: sampling period of the microprocessor [s]

ω_{rps}: the number of revolution per a second

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 (3) derived from (1) and (2).

$$\Delta\theta_s = P_r \frac{2\pi}{N_p} + P_r \cdot \omega_{rps} \cdot T_s \text{ [rad]} \tag{3}$$

Fig. 1 shows the control precision of on-off angle according to the speed of the motor.

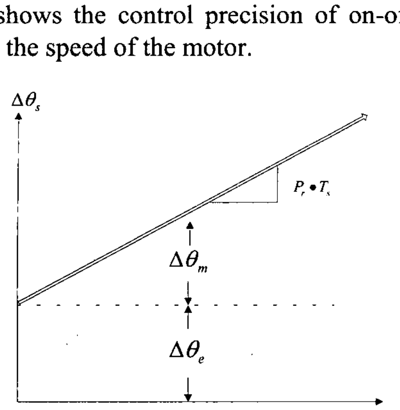


Fig. 1 Error of switching angle according to speed increasing

As the speed of the motor increases, the sampling error increases at the slope of $Pr{\cdot}Ts$ as shown in Fig. 1. 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 severe influence upon the stable drive. The variation of on-off angle is dominated by the resolution of encoder because the variation of position angle is generally less than the angle resolution of the encoder $\Delta\theta_e$ in the case of a low-speed motor. However, in the case of high-speed range, the resolution of encoder is fixed, but the variation of position angle by sampling becomes very high. In this case, the variation of on-off angle is dominated by the variation of position angle by sampling time. Therefore, in order to control the on-off angles, which have a similar resolution to the encoder, a high-speed sampling is required; thus, a high-performance microprocessor is essential.

In order to control the phase switch employing high resolution without a help of such the high-speed microprocessor, a special control method is an alternative plan. Fig. 2 shows the proposed analog encoder for the 8/6 SRM.

As shown in Fig. 2, 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 encoder increases or decreases linearly. The output of photo-transistor is a triangular wave, which is the function of the position angle; therefore, the rotor position of the SRM can be obtained by the output voltage of the photo-transistor.

In the configuration of the proposed encoder, the output period of the encoder α can be defined as the following.

$$\alpha = 2\frac{\pi}{P_r} \text{ [rad]} \tag{4}$$

In the case of the 8/6 SRM, the period is 60° in mechanical angle. The output period that should be changed in a phase of the encoder can be defined as;

$$\beta \geq 2\frac{2\pi}{P_s P_r} \text{ [rad]} \tag{5}$$

Where, P_s : the number of poles of stator

If the output period of the encoder is defined as the equation (4) and the number of photo-transistor is satisfied in the equation (6), the rotor position angle for the phase switching can be obtained perfectly. So there exists the merit that the rotor position can be obtained also under the starting.

$$P_o = \frac{P_s}{2} \tag{6}$$

where, P_o : the number of photo-transistor

In the case of the proposed analog encoder, for 8/6 SRM driving, four photo-couplers are necessary and they are used to determine on and off on each phase. Four photo-couplers of the encoder are equipped with the phase difference by the mechanical angle δ, i.e., 15° in mechanical angle.

Fig. 3 shows the switching patterns of a phase switch. Where the set-angle is selected within the increasing region

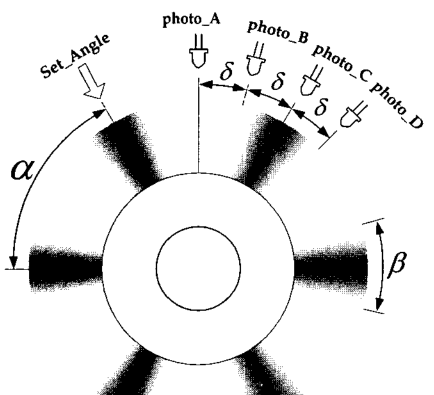


Fig. 2 Proposed analog encoder

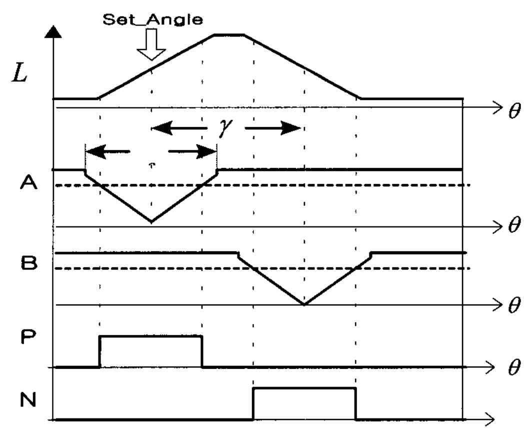


Fig. 3 Switching patterns

of inductance profile. This set-angle is obtained by experimental result. γ is displacement angle which has the same inductance value between motoring and generation region. In figure, L is inductance profile, A and P are encoder and switching signal at CW, B and N are encoder and switching signal at CCW. Each signal for the phase switches is generated comparing phase output value with command one. Therefore, the angle displacement when the phase switch is on is expressed as;

$$\Phi = \delta \cdot \frac{V_{ref}}{V_p} \text{ [deg.]} \tag{7}$$

The command value of V_{ref}, the angle displacement when the phase switch is on, is generated through one D/A converter. In general SRM speed control using phase switch on/off method, On and off angles are separately controlled, because when the on/off angle are controlled at the same time, settling of the control reference is difficult. Therefore, in this case, increasing /decreasing proportion of the on/off angles are controlled within the same rate. In this paper, the angle control is accepted as mentioned above.

Because advance maximum angle (θ_{am}) depends upon amplitude of excite voltage for settling of phase current, current rating of the used as phase switch, and motor parameters, mathematical analysis is severely difficult; And also, delay maximum angle (θ_{dm}) depends on amplitude of the demagnetize voltage and motor parameters; therefore, these values are obtained by trial-and-error.

Once advance and delay maximum angles are obtained by experiment, set angle of the proposed liner encoder is determined. In this paper, set angle is set a mean value between advance maximum angle and delay one. Therefore, maximum dual angle is given as the following equation.

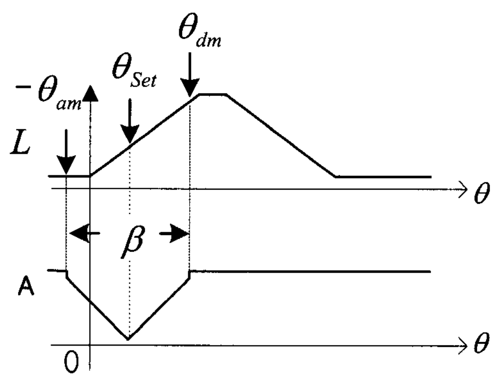


Fig. 4 Determination of set angle & optimal β for the proposed encoder

$$\beta = \theta_{am} + \theta_{dm} \tag{8}$$

As a result, when the on period of phase switch is short at low load, suddenly generated torque due to the dynamic variation of the phase current can be protected by flowing phase current at mid-point during increasing period in inductance profile. And in order to increase output power at rated load, on/off control of the phase switch is possible settling current in minimal inductance area.

2.2 Current controller

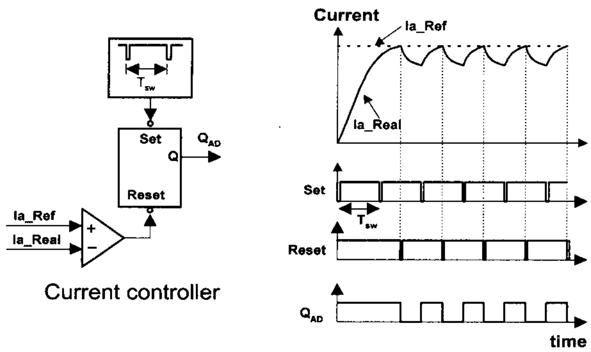


Fig. 5 Current controller & key waveforms

Fig. 5 shows the structure and operation waveforms of current controller employing peak current control method. The current controller is consisted of comparator and flip-flop. Every switching period, a set terminal of flip-flop is enabled to turn on the switch; then the real current will increase.

At this time, a comparator compares the command value of current with that of real current. If the value of real current is higher than that of command value, reset terminal will be enabled to turn off the switch; then current will decrease. The response characteristic of the controller using mentioned above current control method is excellent such as delta modulation method. And also, it can be controlled in constant switching frequency.

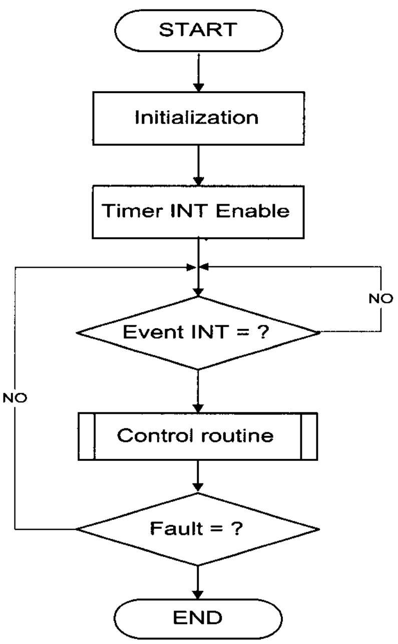


Fig. 6 Flowchart of main routine

Fig. 6 shows the flow chart of main loop under driving the SRM. In main loop, several parameters are initialized, and fault signals due to over-voltage or over-current are generated. Fig. 7 shows control routine.

3. Experimental Results

The SRM used in this experiment is a 8/6, 400W, 200rpm, 200V SRM. A conventional classic inverter and the SRM equipping the proposed analog encoder are used for implementation. The inductance profile of the used SRM is 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.

Fig. 8(a) shows the experimental waveforms of each output signal of phototransistor. In the experiment, because the 8/6 SRM is used, four photo-couplers are equipped and they are used to determine on and off on each phase. As shown in Fig. 8(a), the phase difference by the mechanical angle δ is 15° in mechanical angle. Fig. 8(b) shows the gate signal and phase current corresponding an output of phototransistor when the peak current control method was not applied.

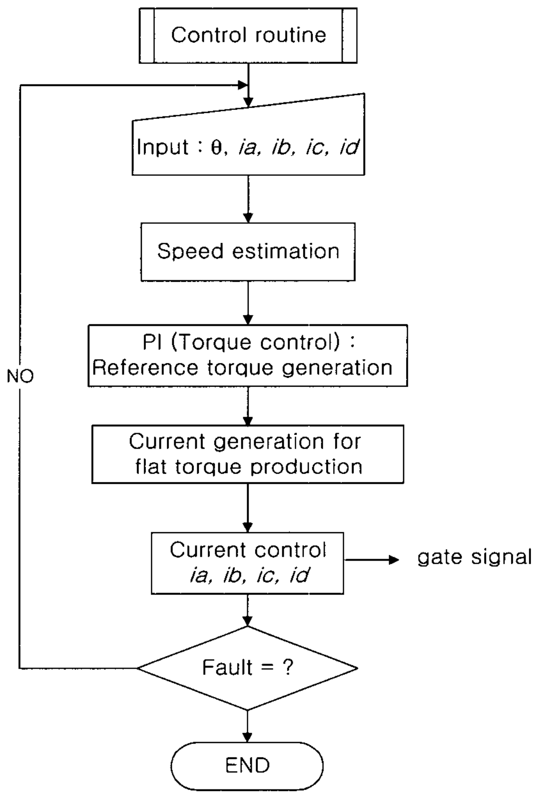
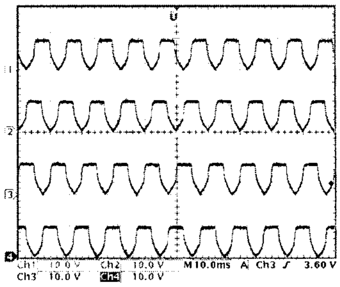
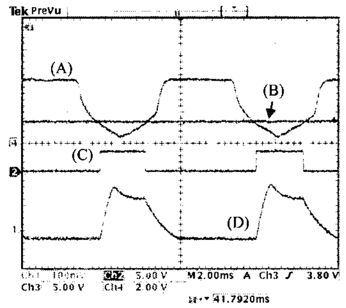


Fig. 7 Control routine



(a)



(b)

Fig. 8 Experimental waveforms of (a) each output signal of photo-Tr. (b) gate signal and phase current corresponding output of photo Tr. (A) output of photo-Tr. (B)reference signal (C) gate signal (D) corresponding phase current

Fig. 9 shows the experimental waveforms of control signal and phase current corresponding output of phototransistor when the peak current control method is used. From the waveforms the response characteristic of the controller using the above mentioned current control method(the delta modulation method) is excellent. And also, it can be controlled in constant switching frequency. In the same condition, the experimental waveforms of each phase current are shown in Fig. 10.

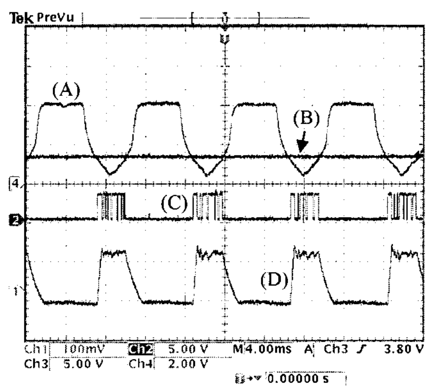


Fig. 9 Experimental waveforms of control signal and phase current corresponding output of photo-Tr. with the peak current control method
(A) output of photo-Tr. (B) reference signal
(C) control signal (D) corresponding phase current

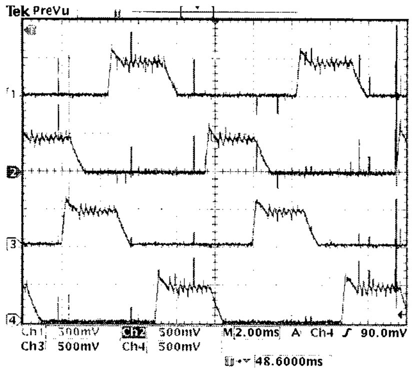
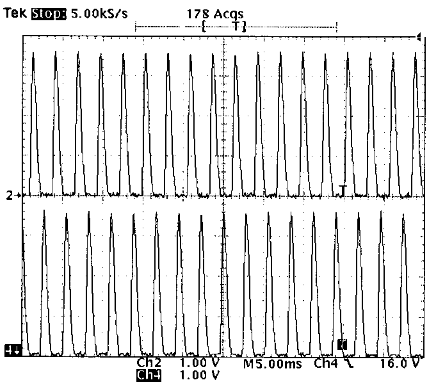
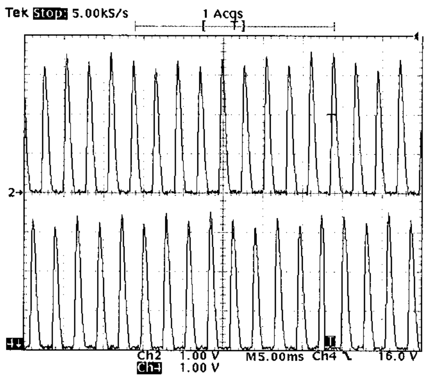


Fig. 10 Experimental waveforms of each phase current when the peak current control method is adapted

Fig 11 is presented to prove the validity of the proposed system by comparing it with the conventional on off method. The conventional system is implemented using 500 pulse per revolution incremental encoder and TMS320F241 DSP, and are driven with the same operating conditions of 1,800 rpm and 1.2 Nm. As shown in the Fig. 11(a), the current pulses have the same shape for the proposed one. On the contrary, as shown in the Fig. 11(b), it is not for the conventional one because the peak values of each current pulse are different from each other. In the conventional system, If the motor speed is increased, it is much clear from the Fig. 11(b) that the switching angles are perturbed back and forth and the current waveforms are also much different from every cycle and phase. This is due to the resolution of the encoder and the sampling period of the DSP controller, as mentioned earlier. Because this switching angle deviation can cause the torque pulsation, the drive system can be unstable in the high speed region.



(a) Proposed



(b) Conventional

Fig. 11 Comparison of phase current waveforms

4. Conclusion

In this paper, a low cost analog encoder suitable for the practical and stable SRM drive is proposed and also the control algorithm to generate the switching signals using a simple digital logic is presented. From the experiments, the validity of the proposed analog encoder with a proper logic controller is verified.

Acknowledgement

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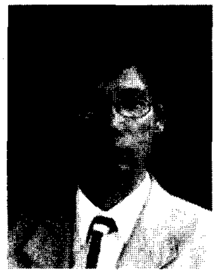

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