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## An Analog Encoder for Precise Angle Control of SRM

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### ABSTRACT

In a switched reluctance motor drive, it is important to synchronize the stator phase excitation with the rotor position, because the position of rotor is an essential information. Although high resolution optical encoders or resolvers are used to provide a precise 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, Analog Encoder, Switching Angle Control

### 1. Introduction

One of a important factor in the selection of a motor and a drive for an industrial application is cost. The switched reluctance motor (SRM) is a simple, low-cost, and robust motor suitable for variable-speed drive as well as servo-type applications<sup>[1]</sup>. The SRM is a single excited machine, which has a simple structure and a superior drive performance over a wide speed range. The SRM has been researched spreading the application range to the industry such as household appliances, electric-car, aircraft, etc<sup>[2]</sup>,<sup>[3]</sup>. 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<sup>[5]</sup>. 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<sup>[6]</sup>. In order to have a 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 microprocessor used as well as that of the encoder.

In this paper, a new low-cost analog encoder for high performance switching angle control suitable for an SRM drive is presented, in which the switch on-off angle is controlled with a simple circuit. In the proposed switching technique, the resolution of switch on-off angle, different from the general methods, is not affected by the sampling

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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.

## 2. Basic Principles

The SR drive is one of the most competitive electric vehicle drives due to its good features that make it comparable with ac drives. The basic characteristics of the SRM are similar to a single-stack variable-reluctance stepper motor, but it is designed more for an efficient power conversion rather than for torque or position control so that motor size, pole geometry, and control strategy differ accordingly.

Fig. 1 shows a general SRM drive system. The torque developed in motor is proportional to the square of switching mmf current and the gradient of phase inductance according to rotor angular position as shown in (1).

$$\tau(\theta) = \frac{1}{2} i(\theta)^2 \frac{dL(\theta)}{d\theta} \quad (1)$$

where,  $L(\theta)$  is inductance profile of the motor.

The SRM is controlled by input voltage, switching-on and off angle. Switching-on and -off angle of the SRM regulate the magnitude and shape of the current waveform. Also it results in affecting the magnitude and shape of the torque developed. To build up the current effectively in the voltage source, an advance switching before the poles meet is needed. The switching-on angle is one of the main factors to control the build up currents. Therefore, this angle is controlled precisely to get optimal driving characteristics.

$$V(\theta) = R \cdot i(\theta) + L(\theta) \frac{di(\theta)}{d\theta} + i(\theta) \frac{dL(\theta)}{d\theta} \quad (2)$$

In the voltage equation for the motor, the first in the right terms of (2) is resistance voltage drop, the second is reactance voltage drop, and the last is the back speed e.m.f which can be converted to mechanical energy. The current level depends on the applied voltage, initial current, back speed e.m.f. and impedance voltage drop.

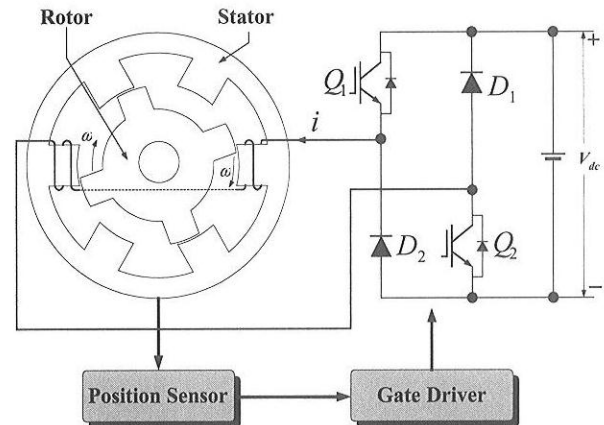


Fig. 1. SRM drive system.

## 3. Analog Encoder

### 3.1 Conventional Encoder System

In general, microprocessor and digitalized encoder system are much used in motor control system because of high performance, easy treatment of data and programmable characteristics. The information of rotor position and speed is obtained in a control period by the digitalized encoder such as incremental and optical encoder.

In case of incremental encoder, the accuracy of rotor position and rotor speed depend on the sampling period and encoder resolution. The control performance is determined by the accuracy of rotor position and performance of microprocessor. The absolute measuring error of rotor position is determined by the resolution of the encoder ( $\Delta\theta_e$ ) and the variation of the rotor position during sampling period ( $\Delta\theta_p$ ). The resolution of mechanical position of an equipped encoder can be express regardless of motor speed and performance of microprocessor as follow.

$$\Delta\theta_e = 2\pi \frac{N_r}{N_p} \text{ [rad]} \quad (3)$$

where,  $N_r$  denotes the number of poles of rotor, and  $N_p$  is the resolution of encoder. The variation of the rotor position angle ( $\Delta\theta_p$ ) is dominated by the speed of motor during the sampling period and it is given as (4).

$$\Delta\theta_p = \omega_r \cdot T_s \text{ [rad]} \tag{4}$$

where,  $T_s$  denotes sampling period of the microprocessor, and  $\omega_r$  is electrical angular speed of the rotor. The absolute measuring error of rotor position is the summation of  $\Delta\theta_e$  and  $\Delta\theta_p$ .

$$\Delta\theta_s = 2\pi \frac{N_r}{N_p} + \omega_r \cdot T_s \text{ [rad]} \tag{5}$$

Fig. 2 shows the absolute measuring error in microprocessor with incremental encoder system according to the speed of the motor. In a low speed region, the absolute measuring error is dominated by the encoder resolution. As the motor speed increases, the variation error of rotor position in the sampling period is increased. In general incremental encoder with 1024 pulse per revolution and 8-rotor poles, the maximum position error is 31.6125 electrical degree in case of 3000 [rpm] and 200 [ $\mu$ s] sampling period. The switching angle of SRM is calculated with measured rotor position, and the measuring error of the rotor position produces additional torque ripples. Therefore, the stability of SRM drive is much decreased with switching angle error. For a high control performance, high resolution encoder and high speed microprocessor are required in a motor control system with conventional incremental encoder and the total cost of the system is to be increased

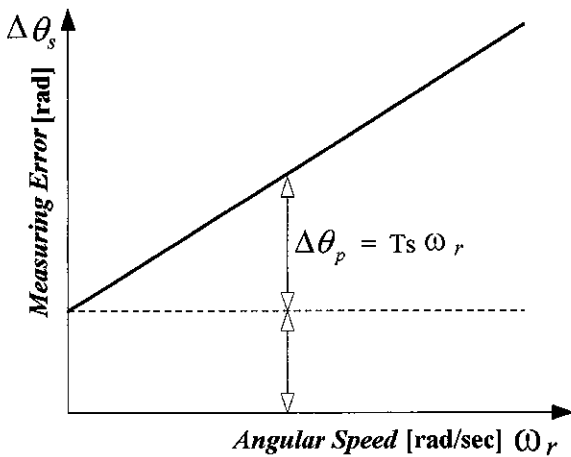


Fig. 2. Measuring error of rotor position according to rotor speed

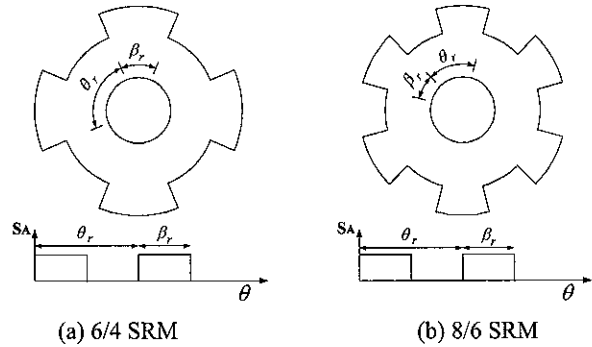


Fig. 3 A simple optical encoder and sensor signal

In case of an optical encoder, the switching angle control is based on signals of an optical encoder aligned to the inductance profile. Fig. 3 shows a simple optical encoder disk and sensor signal of a phase. The structure of an optical encoder is very simple and low cost, but high resolution of switching angle control is very difficult. The switching-on and -off angle are to be calculated from the every rising and falling edges of the optical encoder signals. The accuracy of calculated switching angle depends on microprocessor and rotor speed. In this case, a simple PWM method is adopted for torque control, and a high frequency switching increases switching losses.

### 3.2 The Proposed Encoder

In order to control the motor with a high accurate switching angle, a high resolution encoder and a proper control method are essential. This paper proposes a new type encoder for switching angle control of SRM. The proposed encoder is simple but high resolution switching control is possible.

Fig. 4 shows the proposed analog encoder for 6/4, 8/6 and 12/8 SRM, respectively. The output signal of a proposed encoder is analog signal that is proportional to a gray gradation of the plate while is digital signal in conventional encoder such as incremental and optical encoder. The gray gradation of disk plate is set for linear analog signal of phototransistor. The output of phototransistor is a triangular wave, which is the function of the position angle; therefore, the rotor position of the SRM can be obtained by output voltage of the phototransistor.

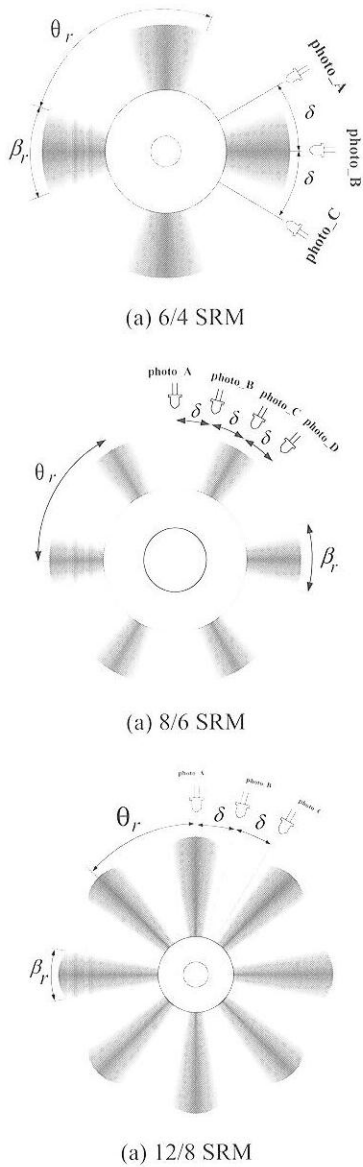


Fig. 4. Disk plate for the proposed analog encoder.

The interval between gradated pattern is determined by the number of rotor poles as follows.

$$\theta_r = \frac{2\pi}{N_r} \text{ [rad]} \tag{6}$$

And the minimum angle of a gradation is determined by a continuous torque production as follow.

$$\beta_r \geq 2 \frac{2\pi}{N_s N_r} \text{ [rad]} \tag{7}$$

where,  $N_s$  and  $N_r$  denote the number of stator and rotor poles, respectively. In Fig. 4, sensor interval  $\delta$  denotes the phase intervals of SRM. Therefore,  $\delta$  is  $15^\circ$  in 8/6 and  $12/8$  and  $30^\circ$  in 6/4 SRM.

The number of photo sensor is determined for a continuous detecting of rotor position as follow.

$$N_o = \frac{N_s}{2} \tag{8}$$

Fig. 5 shows the output signal of the proposed encoder according to the inductance profile.

The dip point,  $\theta_o$  of the output signal is the center point of the maximum dwell angle,  $\beta_r$  of the proposed encoder. In this paper, the maximum dwell angle,  $\beta_r$  is determined by the experimental test for considerations of maximum output. The maximum displacement of switching-on angle,  $\theta_{oi}$  and switching-off angle,  $\theta_{of}$  are determined by the excitation voltage, rated current and motor parameters.

In the motoring mode, switching-on angle is set on the negative slop of sensor signal between  $\theta_{oi}$  and  $\theta_o$ . As a similar, switching-off angle can be set on the positive slop of sensor signal between  $\theta_o$  and  $\theta_{of}$ . The end of negative and positive slope of the encoder signal has step shape for limitation of excitation interval in the maximum dwell angle  $\beta_r$ .

With the proposed simple encoder, very accurate switching angle control can be obtained without any high performance microprocessor.

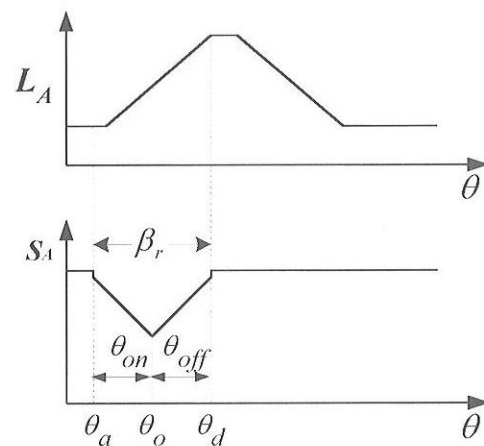


Fig. 5. Inductance profile and encoder signal.

### 4. The Switching Angle Control Topology

In this paper, effective switching angle control method with the proposed encoder is suggested. The proposed switching angle control method is based on two command signals for switching-on and off angle independently

Fig 6 shows the basic principle of the proposed switching angle control topology with the analog encoder. According to the motor speed and load condition, proper switching-on angle,  $\theta_{on}$  and switching-off angle,  $\theta_{off}$  can be controlled independently by the command signal,  $V_{on}$  and  $V_{off}$ , respectively. The switching-on angle,  $\theta_{on}$  is set at the cross point of negative slope of the sensor signal, and switching-on command signal,  $V_{on}$  as follow

$$\theta_{on} = \left(1 - \frac{V_{on}}{V_{max}}\right) (\theta_o - \theta_a) + \theta_a \tag{9}$$

The maximum switching-on angle is in the minimum inductance region, so fast building-up of current is possible at the rated load. And the minimum switching-on angle is in the increasing region of inductance, so smooth building-up of current is possible at a light load with a smooth torque production

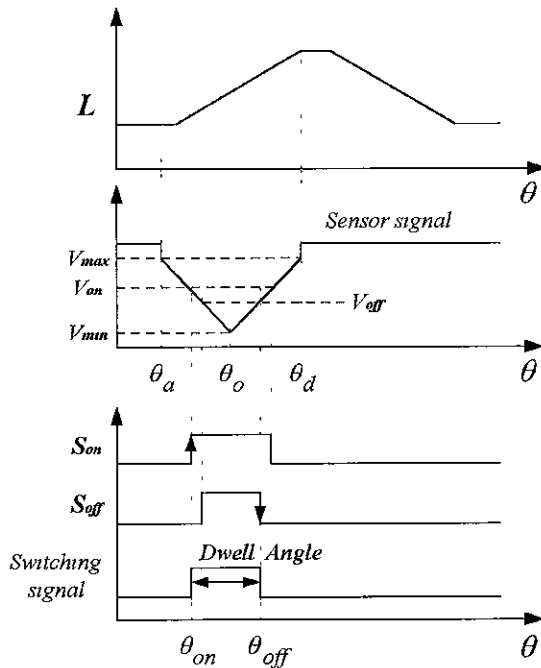


Fig 6. Switching angle control of a phase

As similar, the delay angle,  $\theta_{off}$  is set at the cross point of positive slope of the signal and switching-off command signal,  $V_{off}$

$$\theta_{off} = \frac{V_{off}}{V_{max}} (\theta_d - \theta_o) + \theta_o \tag{10}$$

And the dwell angle is the interval of switching-on and off angle.

$$\theta_{dwell} = \theta_{off} - \theta_{on} \tag{11}$$

### 5. Experimental Results

In order to verify the effectiveness of the proposed encoder and control topology, 12/8 SRM with analog encoder is tested. Table 1 shows the specifications of the motor tested. The inductance profile of the motor is calculated by voltage and current data considering the winding resistance.

The inductance profile is a relatively accurate value that can indicate the dynamic driving characteristic of the motor. The maximum dwell angle is determined at 20° by experimental test for maximum output power

Fig. 7 shows the block diagram of the control system. A simple PIC processor is used as a main processor. For the switching angle control, 2-channel, 10bit D/A converter is used. The calculated switching-on angle as a digital data is out to the a channel of D/A converter as an analog data, then the switching-off angle is out to the other channel of D/A converter. The absolute control resolution is obtained by the resolution of D/A converter as follow

$$\theta_{resolution} = \frac{\beta_r V_{max}}{2^{n+1} (V_{max} - V_{min})} \tag{12}$$

where, n denotes the bit numbers of the D/A converter. In this paper, the absolute resolution of switching angle is about 0.01°.

Fig 8 shows the photograph of prototype encoder. The tested motor has 12 stator poles and 8 rotor poles. Three photo-sensors are equipped in the encoder with phase interval to produce analog position signals

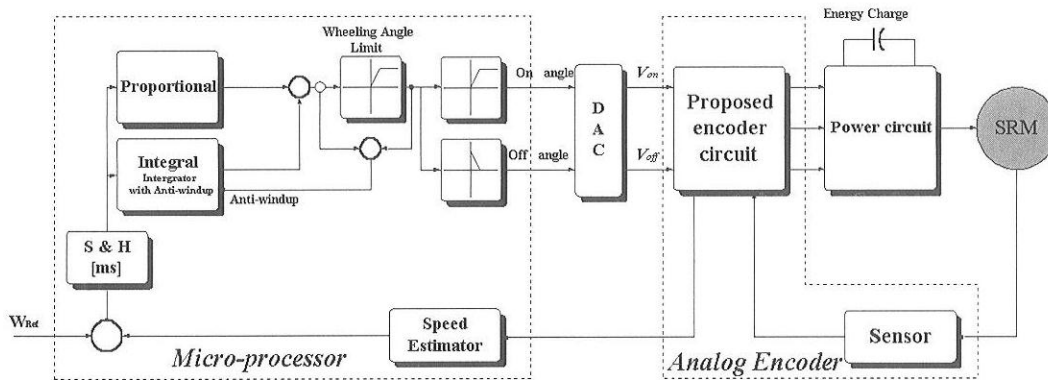


Fig. 7. Block diagram of the control system.

Table 1. Specifications of the prototype motor.

Stator/rotor pole	12/8
Rated power	200 [W]
Rated speed	2000 [rpm]
Rated voltage	200 [V]
Stator pole arc	14 [deg.]
Rotor pole arc	18 [deg.]
Winding resistance	3 [ $\Omega$ ]
Maximum inductance	122 [mH]
Minimum inductance	21 [mH]

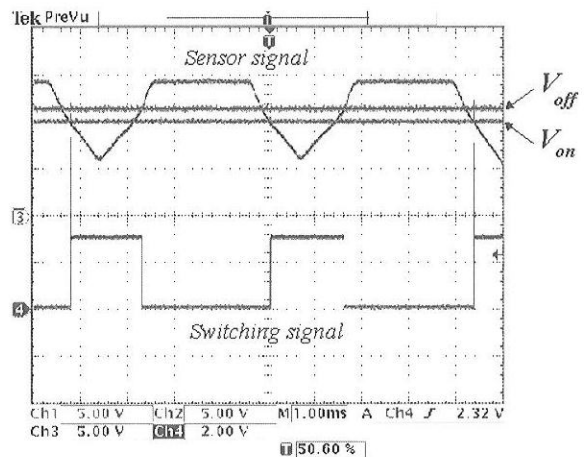


Fig. 9. Signals in the encoder (sensor signal, switching-on reference, switching-off reference and switching signal from top trace, Hor.: 1ms/div.).

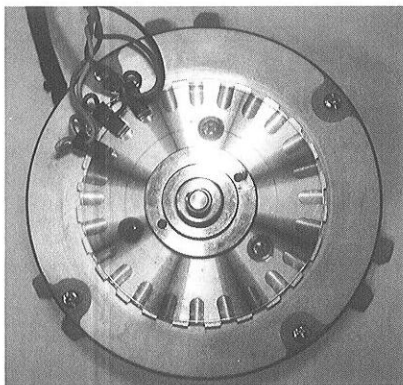
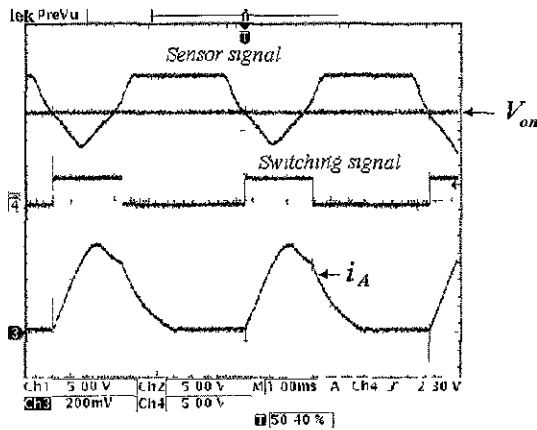


Fig. 8. Prototype encoder.

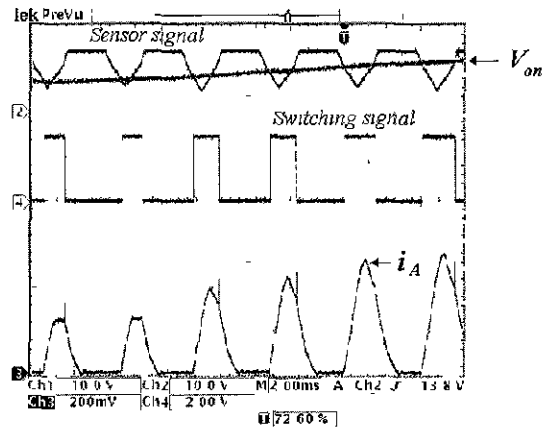
Fig. 9 shows the experimental waveforms of photo sensor, command signals of switching-on and off and the switching angle of a phase. In Fig. 9, the switching-on and switching-off signals are determined by the combination of sensor signal and two switching commands.

Fig. 10 shows the sensor signal, switching-on reference, switching signal and phase current. The waveform of phase current is determined by the sensor signal and switching command.

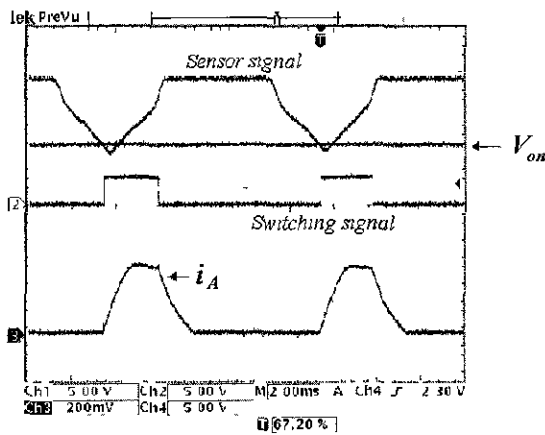
Fig. 11 shows the switching angle adjusting and phase current according to load variation in the proposed encoder and the control system. The load is changed from 1.3 to 2.5 [Nm] in 2000[rpm]. The switching angle is regulated by changing of switching-on reference. With a sudden load variation, the switching angle can be controlled properly, so a smooth torque production is possible. The experimental results show the effectiveness of the proposed encoder and the control method.



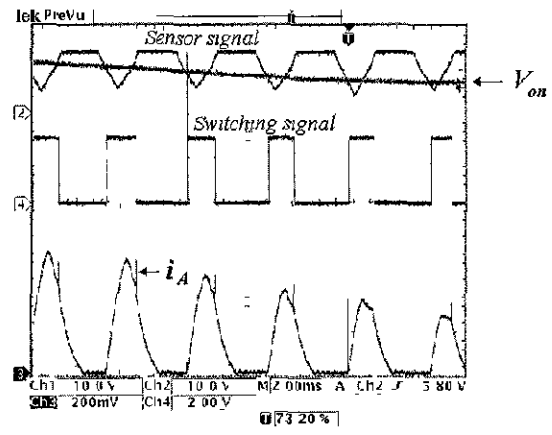
(a) At 1750[rpm] (Hor 1ms/div , Ver (current) 2A/div )



(a) load changing from 1.3 to 2.5 [Nm]



(b) At 800 [rpm] (Hor . 2ms/div , Ver (current). 2A/div )



(b) load changing from 2.5 to 1.3 [Nm]

Fig 10. Signals in the control system (sensor signal, switching-on reference, switching signal and current from top trace).

Fig 11. Switching characteristics of sudden load disturbance at 2000[rpm](Hor 2.0 [ms/div], Ver. (current) 2.0 [A/div])

### 6. Conclusions

In this paper, a low cost and simple structure but high performance analog encoder with proper control method suitable for the practical and stable SRM drive is proposed.

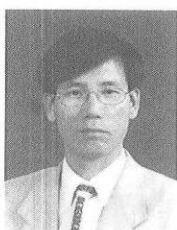
The proposed encoder uses a simple structure of optical Encoder and analog gradation for high resolution of rotor position. A simple limitation of excitation angle can be implemented with step change at the end of gradation pattern. The switching-on and off angle control can be easily implemented by the separate command signals of switching-on and switching-off.

From the experimental results, the effectiveness of the proposed analog encoder with a proper control method is verified.

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