Sensorless Control for the Synchronous Reluctance Motor Using Reference Flux Estimation

Joon-Seon Ahn†, Sol Kim, Yong-Tae Kim*** and Ju Lee***

Abstract - The complex sensorless control scheme is not practical for use in the field of home applian ce systems because it is not economical. Therefore, it is necessary to introduce a simplified sensorless c ontrol scheme that is composed of least calculation to estimate the rotor position. This paper presents th e principle of the rotor position estimation with comparison of the estimated flux linkage and reference flux linkage. In order to verify the feasibility of the control scheme, ACSL is used for the simulation an d TI DSP TMS320F240 is used for the experiment.

Keywords: Advanced Continuous Simulation Language, Digital Signal Processor, Simplified Sensorl ess Control, Synchronous Reluctance Motor

1. Introduction

The Reluctance Synchronous Motor (SynRM) has received much attention as a suitable candidate for variable speed drive applications. The available performance makes it competitive with induction motors in terms of the torque available from any given frame size. However, such a drive must be operated using field oriented control since a constant V/f drive has been found to be unstable [1]. A drawback of the vector controlled SynRM drives is the requirement of the rotor position sensor such as rotary encoders and resolvers [2].

Sensorless control is well known for its variable speed drive applications, as well as its high cost and liability against environmental conditions. The SynRM has features that make the sensorless position estimation process more reliable than it is for the conventional squirrel cage induction motor. The SynRM possesses saliency that allows the rotor position to be sensed since the inductances of the stator windings are dependent on the rotor position [3]. Many articles have reported about the implementation of sensorless control using a complex algorithm for the rotor position estimation [4-6]. Matsuo implemented a rotor position estimator by measuring the rate change of the stator currents [4]. This method goes well with low speed regions. For use in high speed regions, a three-dimensional compensator, which is related to the motor speeds and initial currents, is necessary but very difficult to design. Sul used a combination of a high-frequency current injection and a flux estimation method for position control [5]. However, the injection current caused harmonics and torque pulsation. Schroedl combined two methods of position sensing and used them, with Kalman filtering, to obtain optimal esti- mates [6]. The two techniques employed are independent of knowledge of the machine parameters but they require large computation for implementation. Therefore, it is necessary to introduce a simple structure sensorless control scheme that will draw the industries for its commercialization.

This paper presents the simplified sensorless strategy of SynRM using a comparison with the estimated flux linkage and the reference flux linkage.

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2. Sensorless Control

2.1 Three phase synchronous reluctance motor modeling

Fig. 1 shows an equivalent model of the two pole-three phase synchronous reluctance motor on the arbitrary axis. The balanced three phase source can be transformed into the balanced two phase source like the ds - qs axis in Fig. 1. If the rotor axis, dr - qr rotates synchronously with wr and the arbitrary axis, α-β rotates with wr', the estimated rotor axis, α-β has the difference, $\Delta\theta$ from the real rotor axis, dr - qr. When the position error becomes $\Delta\theta$ zero, the arbitrary axis (the estimated rotor position axis), α-β is identical to the real rotor position axis. It is possible to control it without the position sensor inserting a position compensator that makes the position error be zero. The relationship between the estimated rotor and the real rotor can be expressed as (1).

$$\hat{\theta}_{er} = \theta_r + \Delta\theta \tag{1}$$

where θ_r and $\hat{\theta}_{er}$ are the real rotor position and the estimated rotor position, respectively.

Equation (2) is the voltage equation of the equivalent two phases SynRM in matrix form.

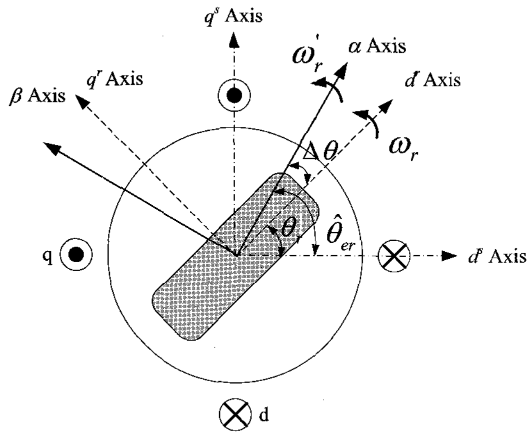


Fig. 1 Equivalent model of the two phase synchronous reluctance motor on the α-β axis (arbitrary axis)

$$V^s_{dq} = \begin{vmatrix} v^s_d \\ v^s_q \end{vmatrix} = r_s \begin{vmatrix} i^s_d \\ i^s_q \end{vmatrix} + p|L| \begin{vmatrix} i^s_d \\ i^s_q \end{vmatrix} \tag{2}$$

$$|L| = \begin{vmatrix} L^s + L^s_0 \cos 2\theta_r & L^s_0 \sin 2\theta_r \\ L^s_0 \sin 2\theta_r & L^s - L^s_0 \cos 2\theta_r \end{vmatrix} \tag{3}$$

$$L^s = \frac{L_d + L_q}{2},\ L^s_0 = \frac{L_d - L_q}{2}$$

$$L_d = L_{ls} + L_{md},\ L_q = L_{ls} + L_{mq}$$

$$L_{md} = \tfrac{3}{2}(L_0 + L_2),\ L_{mq} = \tfrac{3}{2}(L_0 - L_2)$$

Where L_{md}: d-axis magnetizing inductance
L_{mq}: q-axis magnetizing inductance
L_d: d-axis inductance
L_q: q-axis inductance
L_{ls}: leakage inductance

Flux linkage equation is written as (4).

$$\lambda^s_{dq} = \int (v^s_{dq} - r_s i^s_{dq})dt \tag{4}$$

Transforming to the rotationary reference frame using estimated rotor position, flux linkage and current are written as follows,

$$\hat{\lambda}^r_{dq} = S^{-1}_{dq}\lambda^s_{dq},\ \hat{i}^r_{dq} = S^{-1}_{dq} i^s_{dq} \tag{5}$$

Where, $S^{-1}_{dq} = \begin{vmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{vmatrix}$.

2.2 Principle of the Position Estimation

Fig. 2 shows the principle of the position estimation wit h flux linkage. If a position error is the difference between the real position and the estimated position, an estimated fl ux varies with the position error. The estimated flux is calc ulated by the time integral of terminal voltages and the refe rence flux is decided by a synchronous inductance and a c urrent. If the position error is zero, it means that rotor posit ion estimation is correct. If the position error is positive lik e α or negative like β in Fig. 2, the position compensator c auses the position error to be zero. While the position error is zero, we consider that the estimated flux is identical wit h the reference flux and also the same as the position.

$$\lambda^{r*}_d = L_d i^r_d,\ \lambda^{r*}_q = L_q i^r_q \tag{6}$$

$$\lambda_{err} = \hat{\lambda}^r_q - \lambda^{r*}_q \tag{7}$$

Fig. 3 presents a block diagram of the position compensator.

Fig. 4 depicts a comparison between q-axis reference flux and the estimated flux according to the position error. Since SynRM generates negative torque over ±45 degrees, the experiment is carried out with ±40 degrees in Fig. 4.

Since the accuracy of the motor parameters influence the performance of sensorless control, it is necessary to use accurate parameters. The currents and the terminal voltage can be sensed easily but the inductance cannot. In order to obtain the synchronous inductance precisely, d-/q- inductance is calculated by FEM. Fig. 5 shows the d-/q- flux line of the analysis model.

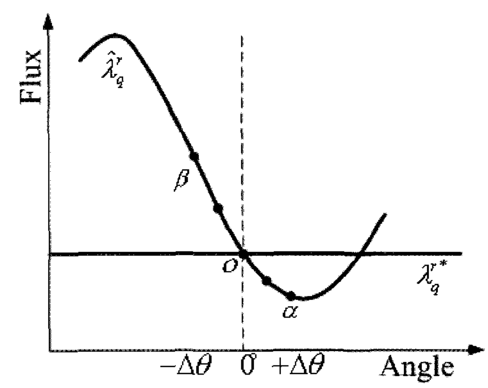


Fig. 2 Principle of the position estimation

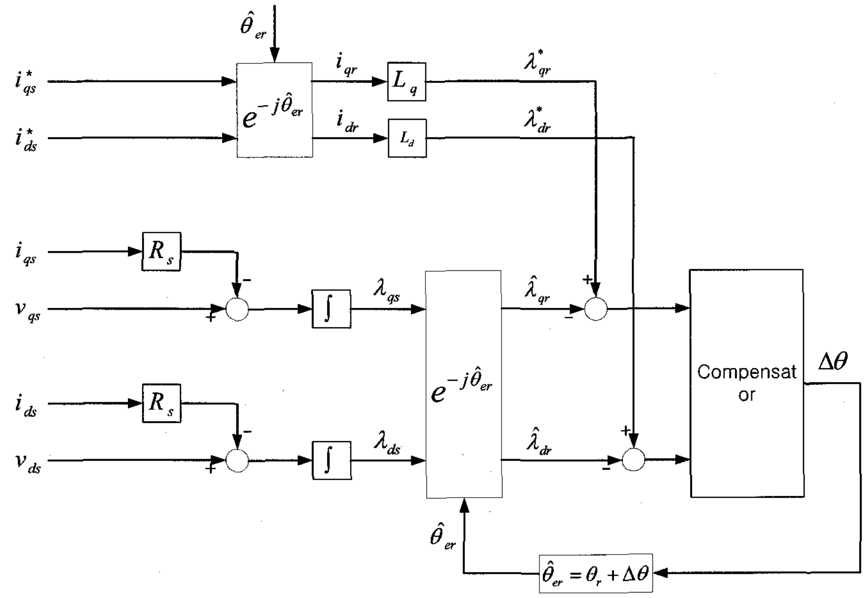
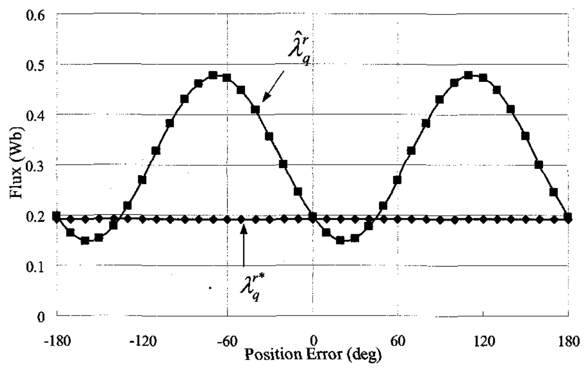
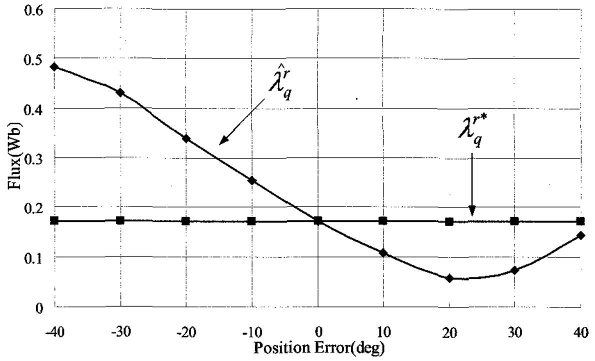


Fig. 3 Block diagram of the position compensator



(a) Simulation result



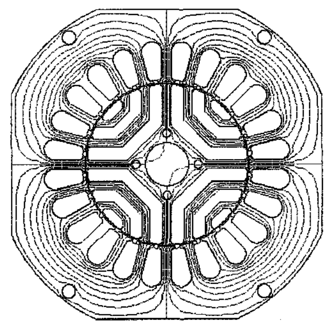
(b) Experimental Result

Fig. 4 Comparison between q-axis reference flux and the estimated flux according to the position error

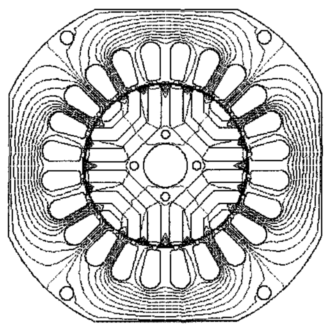
3. Analysis of Simulation and Experiment

3.1 Parameter dependency of the proposed scheme

An on-drop of switching devices and inaccuracy of the stator resistance can cause malfunction of the proposed system. Therefore, it is necessary to investigate the effect of the inaccuracy of the stator resistance. Fig. 6 shows the simulation result of q-axis flux linkage in the rotationary reference frame according to the stator resistance variation.



(a) flux line on the d-axis

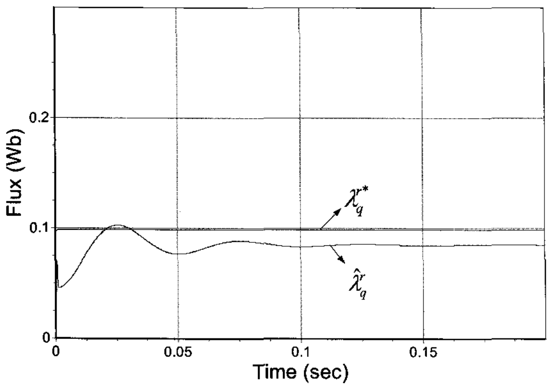


(b) flux line on the q-axis

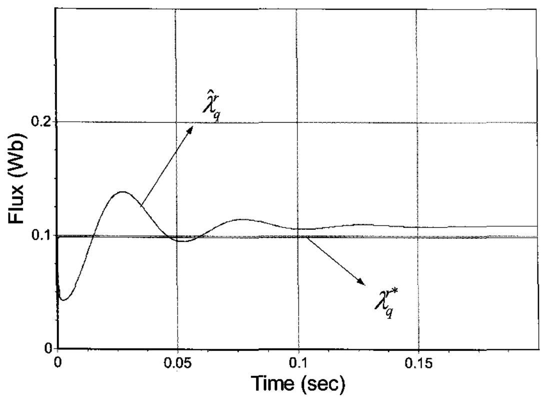
Fig. 5 Flux distribution of SynRM

When the stator resistance is neglected, the estimated flux is lower then the reference flux. When the stator resistance is overestimated, the estimated flux is higher then the reference.

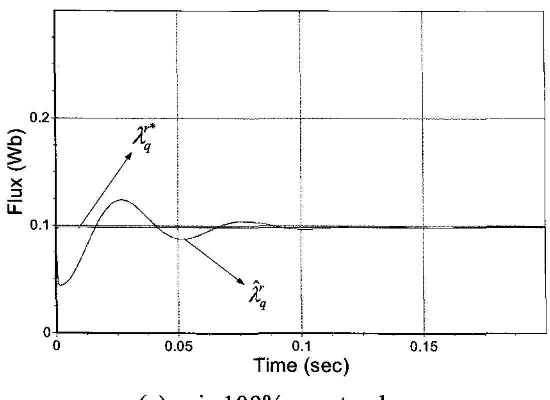
Fig. 7 illustrates the experimental result of q-axis flux li nkage in the steady state. Its result coincides with the simu lation result as in Fig. 6. From the analysis, an accurate par ameter should be used since mis-selection of the motor par ameter might cause inaccuracy in the control system. In or der to increase the reliability of the proposed sensorless co ntrol system, the effects of unbalanced input voltage and in accurate inductance are also considered. Measured stator r esistance is used in this paper.



(a) r_s is neglected

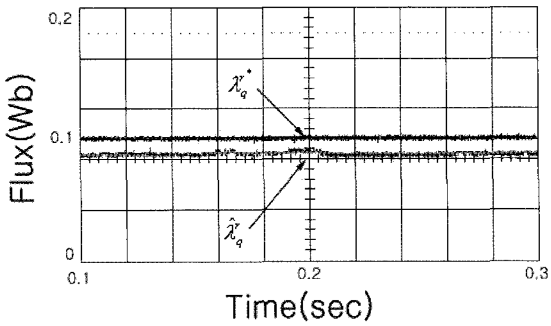


(b) r_s is 200% over estimated value

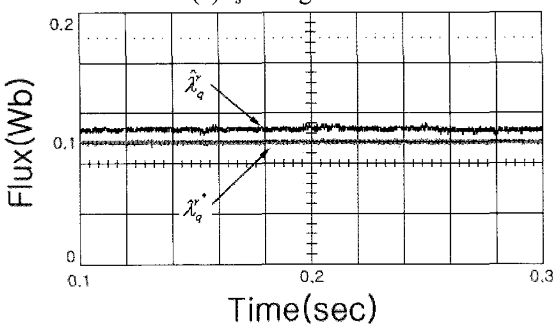


(c) r_s is 100% exact value

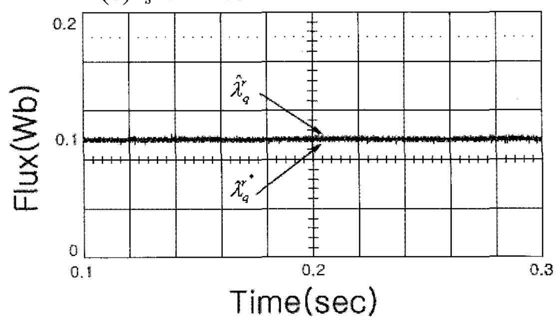
Fig. 6 q-axis flux linkage in the rotationary reference fra me according to the stator resistance variation (Sim ulation result)



(a) r_s is neglected



(b) r_s is 200% over estimated value



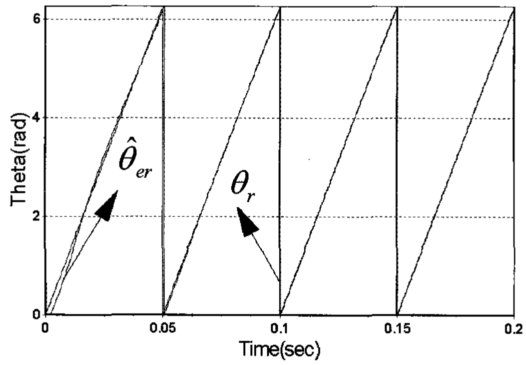
(c) r_s is 100% exact value

Fig. 7 q-axis flux linkage in the rotationary reference fra me according to the stator resistance variation (Exp erimental Result)

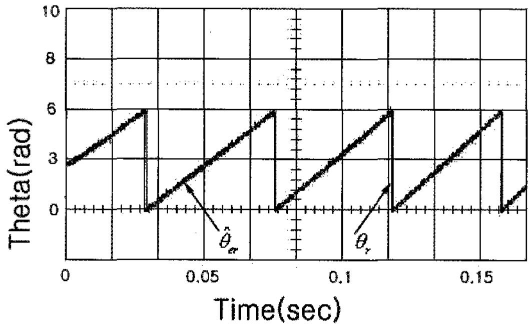
3.2 Position Estimation

After tuning motor parameters precisely, rotor position is estimated. Fig. 8 illustrates the rotor position estimation response of the proposed sensorless control scheme in steady state. The motor is rotating at 300 rpm. The estimated position of the simulation shows 2% of position error as in Fig. 8(a) but the experimental result indicates 5% error.

In order to verify the feasibility of the proposed sensorless control scheme, speed control test should be performed. Fig. 9 indicates the block diagram of the speed controller. The feedback is decided by the derivative of the estimated speed and the normal space vector modulation is implemented. Since a motor for home appliance application is strongly recommended to have sensorless control, a 200W compressor motor is used for the test and simulation. Table 1 explains the specification of the motor.



(a) Simulation result



(b) Experimental result

Fig. 8 Rotor position estimation at 300 rpm

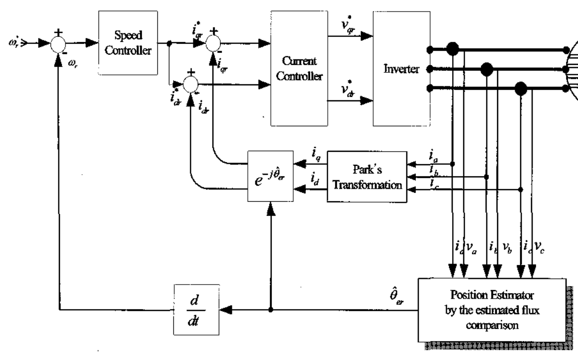
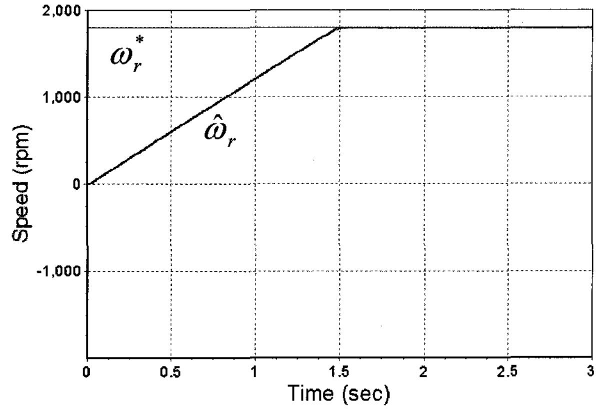


Fig. 9 Block diagram of sensorless controller

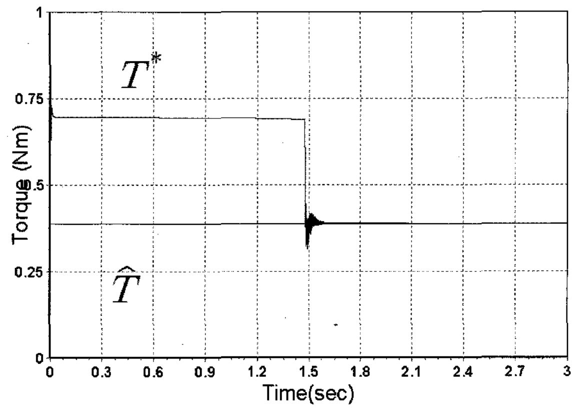
Table 1 Specification of the SynRM

Item	value
Rated Torque	0.4Nm
Rated Speed	1800rpm
Input Voltage	220V
Number of Poles	4
Gap Length	0.3mm
Stack Height	50mm
Saliency Ratio	4.7

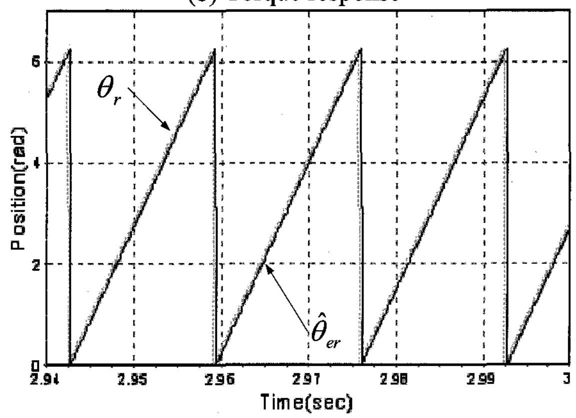
The result of load test simulation is indicated in Fig. 10. There is no effort for consideration of high dynamics beca use the motor mechanism for the compressor requires cons tant speed rotation operation.



(a) Speed response



(b) Torque response



(c) Position response

Fig. 10 The rated load test response (simulation result)

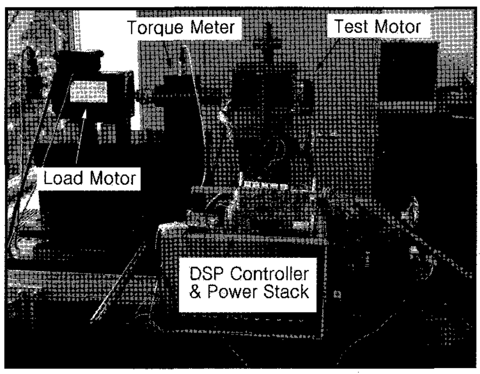
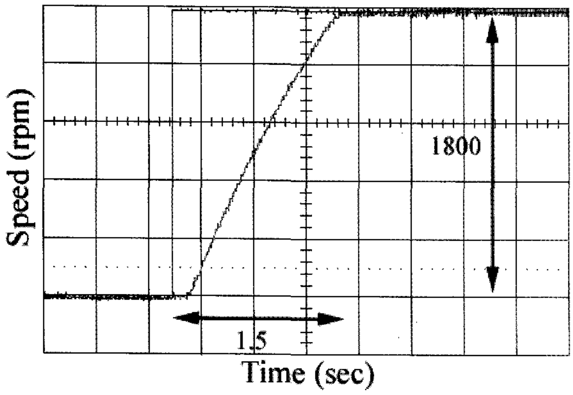
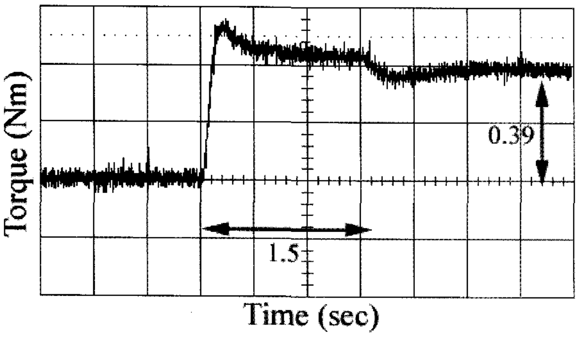


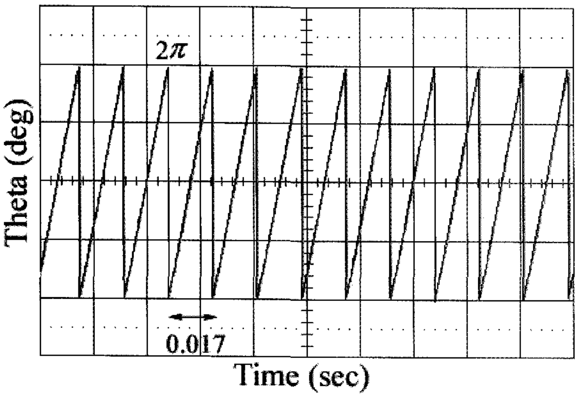
Fig. 11 Experimental setup



(a) Speed response



(b) Torque response



(c) Position response

Fig. 12 The rated load test response (experimental result)

TI DSP TMS320F240 is used for the real time controller. Staiger-Mohilo 0160DM and Powertech Drive-AX 63.1C are used for the torque transducer and load motor. Fig. 11 d escribes the experimental setup.

Fig. 12 indicates speed control test results. Speed reference is rated speed at 1800 rpm. The transient time to the steady state is 1.5 sec. The rated load torque is 0.39 Nm in the steady state. The estimated rotor position follows the real rotor position in Fig. 12(c). The proposed sensorless control scheme goes well in the steady state. If we increase the gain of the speed controller for speed dynamics, it can cause starting failure. To insure reliability of the proposed control scheme during startup, another method should be considered.

4. Conclusion

This paper presented a simplified sensorless control scheme of the SynRM that allows industries to easily implement into their system. The rotor position was estimated by comparing the estimated flux and reference flux. In order to verify the feasibility of the proposed control scheme, the TI DSP control system was implemented. The sensorless drive system performed well in the steady state.

Acknowledgment

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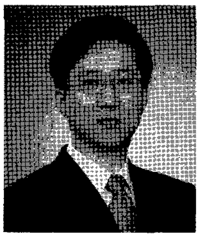

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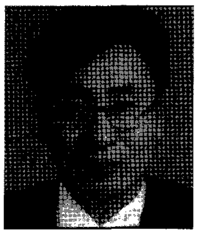

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