A High-Performance Sensorless Control System of Reluctance Synchronous Motor with Direct Torque Control

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Abstract This paper presents an implementation of digital control system of speed sensorless for Reluctance Synchronous Motor (RSM) drives with DTC. The control system consists of stator flux observer, rotor position/speed/torque estimator, two hysteresis band controllers, an optimal switching look-up table, IGBT voltage source inverter, and TMS320C31 DSP controller by using fully integrated control software. The stator flux observer is based on the combined voltage and current model with stator flux feedback adaptive control that inputs are current and voltage sensing of motor terminal with estimated rotor angle for wide speed range. The rotor position is estimated by observed stator flux-linkage space vector. The estimated rotor speed is determined by differentiation of the rotor position used only in the current model part of the flux observer for a low speed operating area. It does not require the knowledge of any motor parameters, nor particular care for motor starting, In order to prove the suggested control algorithm, we have a simulation and testing at actual experimental system. The developed sensorless control system is shown a good speed control response characteristic results and high performance features in 50/1000 rpm with 1.0Kw RSM having 2.57 ratio of d/q reluctance.

Key Ward: RSM, Speed Sensorless, DSP, Flux Observer, DTC

I. INTRODUCTION

In recently, a motion control system with high dynamic performance and accuracy is necessary in industrial application field. A vector control system for motor drives have been widely used because of their advantage such as simplicity, rugged structure, reliability, high maintainability and economy. However, the vector control techniques incorporating fast microprocessor and digital signal processing(DSP) have made possible the application of motor drive system using a position/speed sensor for high-performance system due to sophisticated and large computational time. In order to solve this problem, many researchers have been developed to find out different solutions for motor control system having features of precise and quick torque response, and reduction of the complexity of vector control algorithms [1]-[12].

The direct torque control(DTC) recognized as viable solution to achieve these requirements. In principle the DTC selects one of the six voltage vectors and two zero voltage vectors generated by voltage source inverter to keep stator flux and torque within the limits of two hysteresis band. This method can be directly control of stator flux and torque without using current regulator,

sophisticated estimation, PI control of flux and torque, which are proposed to decrease the parameter sensibility problem characterizing the vector algorithms [1]-[3].

The synchronous reluctance motors(RSM) have recently attracted as a viable alternative to induction, synchronous and switched reluctance machines in medium-performance drive applications. This has been made possible by limitating some traditional RSM drawbacks, such as poor power factor and low-torque density, related to the limited saliency ratio obtainable using conventional rotor design. Its stator has windings similar to those of a three-phase induction motor and a rotor designed with appreciably different values of the reluctance on the direct and quadrature axes. This RSM has the advantages of both the induction motor and the permanent magnet motor. Because of their inherent simplicity and ruggedness, RSM can be used in many industrial and automotive applications [5][7].

Unfortunately, RSM is disadvantaged as they need a suitable position transducer in order to synchronize the stator current vector with the rotor position. Since position transducers increase costs, sizes, and circuit complexity of motor drives, while often reducing their reliability, position/speed sensorless control system for motor drives have been recently proposed where estimation of the actual rotor position/speed is obtained by motor terminal current and voltage measurement [6][7][10].

In the present paper, an implementation of digital sensorless speed control system for RSM drives with direct torque control is proposed. The suggested sensorless control algorithm is shown a good speed control response and high-performance features in 50/1000 rpm with 1.0 Kw RSM having 2.57 ratio of d/q reluctance.

II. DIRECT TORQUE CONTROL

1. Conception of DTC

A DTC algorithm is possible to control of directly the stator flux linkage and the electromagnetic torque by the selection of optimum inverter switching pattern. The selection is made to restrict the flux and torque errors within respective flux and torque hysteresis bands, to obtain fast torque response, low switching frequency, and low harmonic losses. So that DTC allow very fast torque response and flexible control of a RSM. The main advantage of the DTC are absence of coordinate transformations and voltage decoupling block, reduced number of controller and effect of motor parameter variation, actual flux-linkage vector position does not

have to be determine, but only the sector where the flux linkage is located [6]-[8].

2. Flux, Torque and Speed Observer

The core of DTC is the control of the amplitude and rotating speed of stator flux linkage. The calculation of stator flux is then very important. One of the best and simplest calculation methods is to calculator the stator flux from stator current, voltage and estimated rotor angle, which is good character in wide speed area [9]. Fig.1 shows such a closed-loop, stationary frame, observer, which is hereafter described as the "closed-loop flux observer". A closed-loop flux observer is globally stable in stationary frame and does work at wide speed [11]. The stator flux-linkage in the stator reference frame is Eq. (5). The electromagnetic torque(Te) can be calculated by the observed stator flux-linkage space vector and the measured terminal currents, estimated from Eq. (6).

$$\begin{bmatrix} I_{dr}^s \\ I_{qr}^s \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r \\ -\sin\theta_r & \cos\theta_r \end{bmatrix} \begin{bmatrix} I_{ds}^s \\ I_{qs}^s \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} \Phi_{dr}^s \\ \Phi_{qr}^s \end{bmatrix} = \begin{bmatrix} I_{dr}^s \cdot Ld \\ I_{qr}^s \cdot Lq \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} \Phi_{ds\_CM}^s \\ \Phi_{qs\_CM}^s \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r \\ -\sin\theta_r & \cos\theta_r \end{bmatrix} \begin{bmatrix} \Phi_{dr}^s \\ \Phi_{qr}^s \end{bmatrix} \tag{3}$$

$$\varepsilon_\Phi = \Phi_{dqs\_CM}^s - \Phi_{dqs}^{s*} \tag{4}$$

$$\Phi_{dqs}^s = \int [(V_{dqs}^s - R_s \cdot I_{dqs}^s) + \varepsilon_\Phi (K_1 + \frac{K_2}{P})] dt \tag{5}$$

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\Phi_{ds}^s I_{qs}^s - \Phi_{qs}^s I_{ds}^s\right) \tag{6}$$

Where, I_{dqs}^s represent stator current, I_{dqr}^s represent rotor current, Φ_{dqs}^s represent stator flux-linkage, Φ_{dqr}^s represent rotor flux-linkage.

Based on this system, a sensorless DTC drive has been constructed. Fig. 2 is shown Speed and Torque Estimator. The speed of the stator flux space vector and rotor can be estimated from Eq. (7) and (8). A digital low pass filter used to compute the speed of the stator flux space vector. An Eq. (9) represents the angle between the stator and rotor flux linkage space vector.

$$\theta_\Phi = \tan^{-1}(\Phi_{qs}/\Phi_{ds}) \tag{7}$$

$$\omega_r = \frac{d(\theta_\Phi - \delta)}{dt} \tag{8}$$

$$\delta = \frac{1}{2}\sin^{-1}\left(\frac{4 \cdot L_{ds} \cdot L_{qs} \cdot Te}{3P \cdot |\Phi^2| \cdot (L_{ds} - L_{qs})}\right) \tag{9}$$

3. Optimal switching vector

The DTC algorithm selects optimal switching voltage vector from a look-up table, based on the actual flux and torque value. Those voltage vector construct six non-zero active switching vectors and two zero switching vectors[5]. If a stator flux increase is required then $d\Phi$ =1, if a stator flux decrease is required then $d\Phi$ =0, the digital output

signal of two-level hysteresis comparator are determined Eq. (10). If a torque increase is required then dTe=1, if a torque decrease is required them dTe=-1, and if no change is a torque is required then dTe=0, the digital output signal of three-level hysteresis comparator are determined Eq. (11) and Eq. (12) [7][8].

Fig. 1. Stator Flux Observer for RSM

Fig. 2. Position, Speed and Torque Estimator

Fig. 3. Proposed Sensorless Control System of RSM

Table 1. Applied RSM Parameters.

Inertia moment	0.003	Rs	1.0[ohm]
Poles of stator	4	Rated torque	4.04[Nm]
Poles of rotor	4	Reted current	5.0[A]
Rated output	1000[W]	Lq	14[mH]
Rated rpm	2400[rpm]	Ld	36[mH]

$$d\Phi = 1, \quad if \ |\Phi_s| \le |\Phi_s^*| - |\Delta\Phi_s|$$

$$d\Phi = 0, \quad if \ |\Phi_s| \ge |\Phi_s^*| - |\Delta\Phi_s| \tag{10}$$

$$dTe = 1, \quad if \ |T_e| \le |Te_e^*| - |\Delta T_e|$$

$$dT_e = 0, \quad if \; |T_e| \geq T_e^*$$ (11)

$$dT_e = -1, \quad if \; |T_e| \geq |T_e^*| + |\Delta T_e|$$
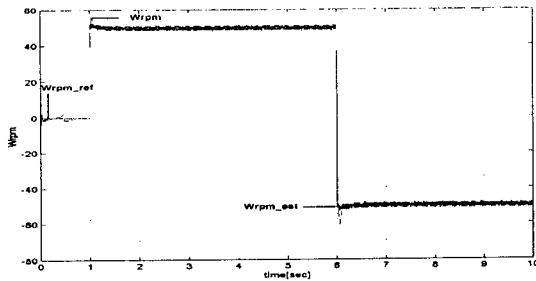
$$dT_e = 0, \quad if \; T_e \leq T_e^*$$ (12)
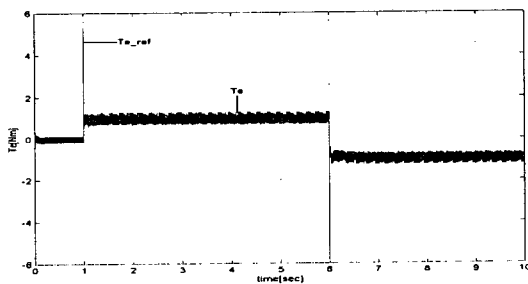
III. SYSTEM AND CONGIGURATION

Fig. 3 is shown the proposed speed sensorless control system of RSM with DTC. The control system consists of stator flux observer, rotor position/speed estimator, torque estimator, two hysteresis band controllers, an optimal switching look-up table, IGBT voltage source inverter, and TMS320C31 DSP controller by using fully integrated control software. Table 1 is shown applied RSM parameters

IV. SIMULATION RESULTS

A simulation of configured SIMULINK environment has been carried out for the evaluation of a proposed control system. In order to show some speed response and high performance characteristics, we carried out some simulations in both low speed range and high-speed range. Fig. 4 shows the simulation results for the speed control response during 10 seconds with a rotor speed ±50[rpm]. Fig. 4(a) represents speed response characteristics, (b) torque response, (c) stator flux waveform in transient state, (d) locus of stator flux. Fig. 5 shows the simulation results for the speed control response during 10 seconds with a rotor speed ± 1000[rpm]. Fig. 5(a) represents speed response characteristics, (b) torque response, (c) stator flux waveform in transient state.
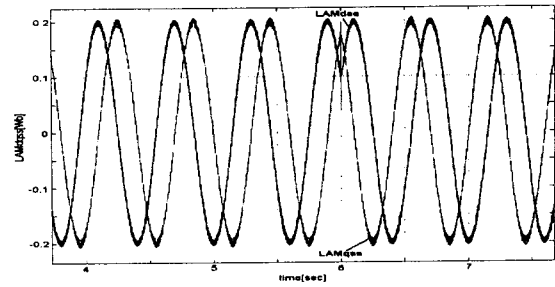
(c) Stator flux waveform in transitent state

(d) Locus of stator flux

Fig. 4. Simulation results at ±50[rpm]

(a) Speed response charecteristics

(b) Torque response characteristics
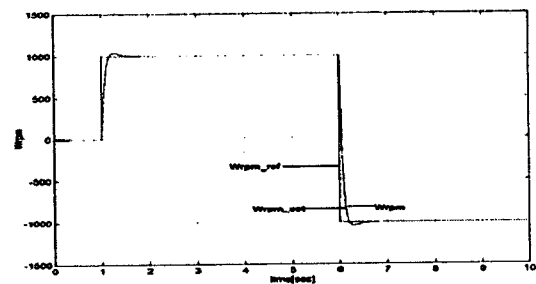
(a) Speed response charecteristics
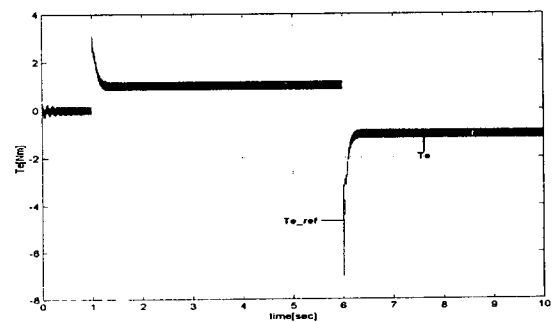
(b) Torque response characteristics
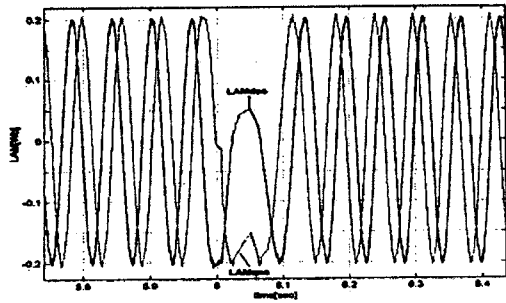
(c) Stator flux waveform in transient state

Fig. 4. Simulation results at ±1000[rpm]
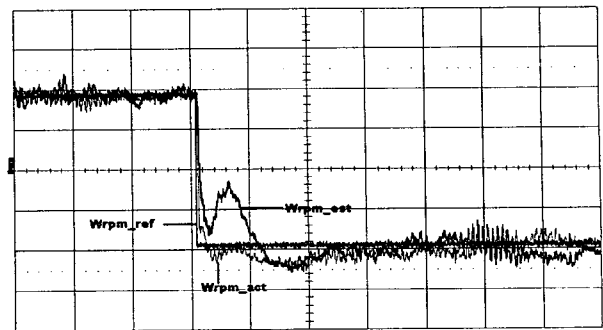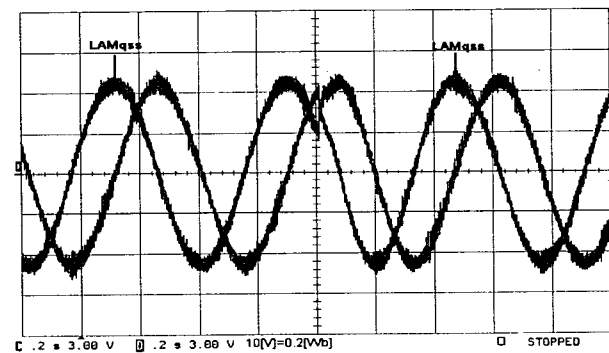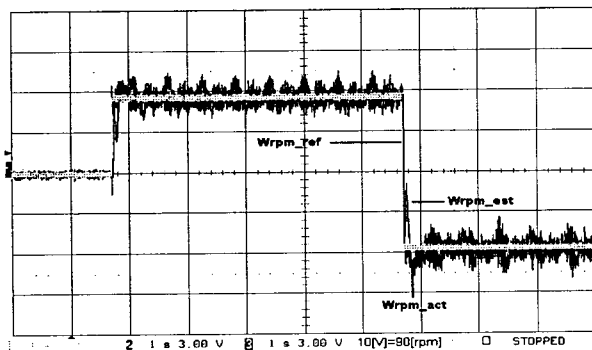
V. EXPIMENTAL RESULTS

In order to investigate the experimental validation of the proposed the control system with a DSP based has been used, the experimental set-up includes a fully digital controlled IGBT inverter and 1kW RSM, which having 2.57 ratio of reluctance values(Ld/Lq). The control scheme has been implemented on a 60MHz TMS320C31 DSP. Table 2 is shown applied system parameters. Fig. 5 shows the experimental results for the response of speed control during 10 seconds with a rotor speed ±50[rpm]. Fig. 5(a) represents speed response characteristics, (b) extended speed response in transient state, (c) torque response, (d) stator flux waveform in transient state, (e) locus of stator flux and (f) stator current waveform. Fig. 6 shows the experimental results for the response of speed control system during 5 seconds with a rotor speed ±1000[rpm]. Fig. 6(a) represents speed response characteristics, (b) torque response, (c) stator flux waveform in transient state, (d) locus of stator flux state.

Table 2. Applied system parameters

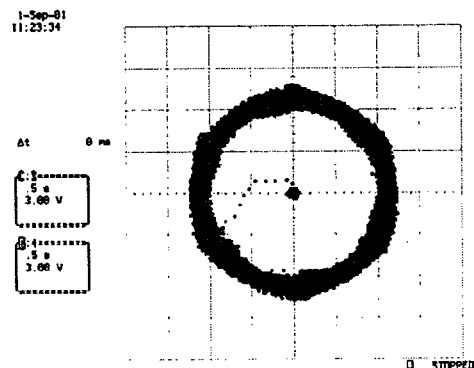| Current sampling time	0.1[msec]
Theta estimation time	0.1[msec]
Speed estimation time	1[msec]
Torque Hys. Band	0.05*Te_ref
Flux Hys. Band	0.05*LAM_ref
Flux Controller	K1=8.0, K2=15.0
Speed Controller	Ki=2.5, Kp=0.25

(a) Speed response charecteristics

(b) Extended Speed response in transient state

(c) Torque response characteristics

(d) Stator flux waveform in transitent state

(e) Locus of stator flux

Idss   Iqss

10[V]=6[A]   A . = .. .uu v   '1 STOPPEU
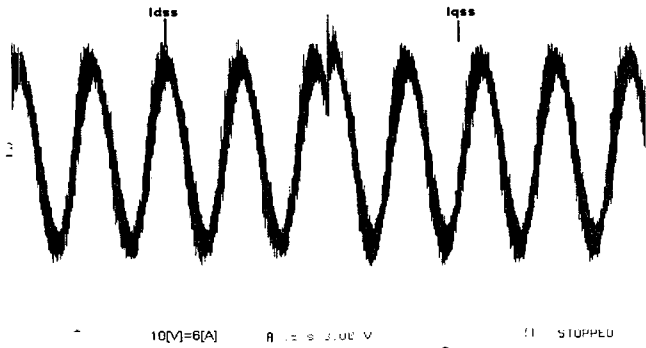
(f) Stator current waveform

Fig. 6. Experimental results at ±50[rpm]

Wrpm_ref

Wrpm_act

Wrpm_est

10[V]=1200[rpm] 2 . . . BB V   3 . . . nn V   □ STOPPFn

(a) Speed response charecteristics

To_ref   To

10[V]=10[Nm]   B . . . . . .   □ STnPPFn

(b) Torque response characteristics

LAMdss

LAMqss

10[V]=0 2[Wb]   A SU ms . UU V   □ STOPPED

(c) Stator flux waveform in transitent state

31 Aug-81
11.22.40

Δt   8.8 ms

2

A. ========
UU rs
. fift '.
=========

□ STOPPED
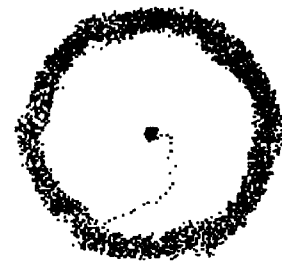
(d) Locus of stator flux

Fig. 7. Experimental results at ±1000[rpm]

VI. CONCLUSION

This paper presents preliminarily an implementation of digital sensorless speed control system for RSM drives with direct torque control. In order to prove the suggested sensorless control algorithm, we have a simulation and testing at actual experimental system. The developed sensorless control system is shown a good speed control response characteristic results and high performance features in 50/1000 rpm with 1.0 Kw RSM having 2.57 ratio of d/q reluctance. In this sensorless control system, there was no problem at high-speed range, but there were some problems at low speed range such as torque pulsation and speed ripple. Maybe, this problem is due to DTC algorithm and the speed estimator using low pass filter. Hereafter, we will research about this problem.
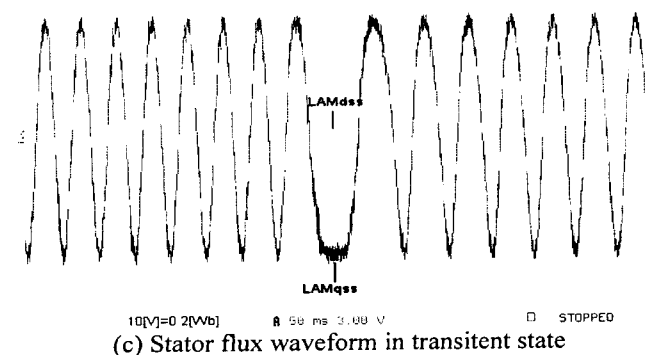
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