Sensorless Indirect Field Oriented Control of Two-phase Induction Motor by Model Reference Adaptive Speed Estimator

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Abstract: This paper investigated the speed sensorless indirect field oriented control of a two-phase induction motor to implement adjustable-speed drive for low-power appli-cations. The approach in this paper was based on the model reference adaptive control observing the rotor flux, which estimate motor mechanical speed acquiring only stator quantities, the stator currents and voltages. It was simulated and implemented on 150W laboratory drive, where its ef-fectiveness was verified.
Sensorless, Field Oriented Control, Two-phase, Model Reference

1. INTRODUCTION

The single-phase or two-phase induction motors have been widely used in the low or middle power level fields, especially in households where a three-phase supply is not available. Nowadays also, most of these applications, especially those with low nominal power, is used fixed-speed drives or conventional adjustable speed drives by voltage control using triacs or thyristors. Therefore, there are great potential for energy savings if one manages to introduce energy efficient speed adjustable vector control into these areas on massive scale[1]-[2].

However, the problem lies in generally high cost for speed adjustable vector control compared to fixed or conventional adjustable speed drives, and difficulties in mounting the speed sensors due to environmental or mechanical restrictions.

In recent years, due to the advance of power electronic technology and low-cost digital signal processor, adjustable speed drives are being broadly applied. And a large amount of research effort has been spent in order to develop a reliable, low-cost control strategy for three-phase ac motor drives not needing speed sensors, called "sensorless" techniques.

Numerous methods of sensorless vector control of three-phase induction motors are nowadays available. The majority of methods in the process of speed estimation rely on the utilization of the induction machine model. One of the most frequently applied control approaches appears to be model reference adaptive control(MRAC), originally introduced in [3] and further developed in [4], which is characterized by relatively simple implementation requirements.

This paper investigate the speed sensorless technique by the rotor flux based speed estimation of MRAC type for two-phase induction motor, which uses the observed rotor flux error signal as the input to a PI controller which feeds back the estimated rotor speed. The validity and performance of the proposed technique was estimated by simulation and experimental results on laboratory 150W two-phase induction motor drive system.

2. MATHEMATICAL MODELING OF THE TWO-PHASE INDUCTION MACHINE

The two-phase induction motor is composed of two symmetrical windings. That is, the number of windings of d-axis is the same as that of the windings of q-axis, and displaced 90 electrical degrees between these windings[2]. Therefore, the mathematical model equations of two-phase induction motor may be equal to that of three-phase induction motor.

2.1. Stationary Reference Frame Model

A mathematical model of the two-phase may be described by the following set of ordinary differential equations in the stationary reference frame($\omega = 0$):

$$v_{ds}^s = R_s i_{ds}^s + p\lambda_{ds}^s \quad (1)$$

$$v_{qs}^s = R_s i_{qs}^s + p\lambda_{qs}^s \quad (2)$$

$$0 = R_r i_{dr}^s + p\lambda_{dr}^s + \omega_r \lambda_{qr}^s \quad (3)$$

$$0 = R_r i_{qr}^s + p\lambda_{qr}^s - \omega_r \lambda_{dr}^s \quad (4)$$

where, the stator and rotor flux linkage is described with the following equations (5)~(8):

$$\lambda_{ds}^s = L_s i_{ds}^s + L_m i_{dr}^s \quad (5)$$

$$\lambda_{qs}^s = L_s i_{qs}^s + L_m i_{qr}^s \quad (6)$$

$$\lambda_{dr}^s = L_r i_{dr}^s + L_m i_{ds}^s \quad (7)$$

$$\lambda_{qr}^s = L_r i_{qr}^s + L_m i_{qs}^s \quad (8)$$

Where, R_s, R_r, L_s, L_r and L_m are the stator resistance, rotor resistance, stator inductance, rotor inductance and mutual inductance, respectively. Subscripts d and q denotes variables in the d,q-axis winding. Parameters and quantities with sub- or superscripts s and r are those in the stator and in the rotor, respectively. p denotes derivative operator. ω_r is rotor electrical angular velocity.

The instantaneous electromagnetic torque produced by the machine is then given by the equation:

$$T_e = P\frac{L_m}{L_r}(\lambda_{dr}^s i_{qs}^s - \lambda_{qr}^s i_{ds}^s) \quad (9)$$

where, P is the number of pole pairs.

2.2. Synchronously Rotating Reference Frame Model

A mathematical model of the two-phase may be described by the following set of ordinary differential equations in the synchronously rotating reference frame($\omega = \omega_e$):

$$v_{ds}^e = R_s i_{ds}^e + p\lambda_{ds}^e - \omega_e \lambda_{qs}^e \quad (11)$$

$$v_{qs}^e = R_s i_{qs}^e + p\lambda_{qs}^e + \omega_e \lambda_{ds}^e \quad (12)$$

$$0 = R_r i_{dr}^e + p\lambda_{dr}^e - (\omega_e - \omega_r)\lambda_{qr}^e \quad (13)$$

$$0 = R_r i_{qr}^e + p\lambda_{qr}^e + (\omega_e - \omega_r)\lambda_{dr}^e \quad (14)$$

where the superscript e denotes synchronously rotating reference frame. The stator and rotor flux linkage is described with the following equations:

$$\lambda_{ds}^e = L_s i_{ds}^e + L_m i_{dr}^e \quad (15)$$

$$\lambda_{qs}^e = L_s i_{qs}^e + L_m i_{qr}^e \quad (16)$$

$$\lambda_{dr}^e = L_r i_{dr}^e + L_m i_{ds}^e \quad (17)$$

$$\lambda_{qr}^e = L_r i_{qs}^e + L_m i_{qs}^e \quad (18)$$

The electrical torque equation is

$$T_e = P\frac{L_m}{L_r}(\lambda_{dr}^e i_{qs}^e - \lambda_{qr}^e i_{ds}^e) \quad (19)$$

3. SENSORLESS INDIRECT FIELD ORIENTED CONTROL TWO-PHASE INDUCTON MOTOR

3.3. Structure of MRAC speed estimator

The MRAC is a very popular method to estimate rotor speed using stator quantities. Specifically, only the stator currents and stator voltages are measured. In many cases, it is even acceptable for the voltage values to come directly from the calculated values, which eliminates the associated voltage measurements.

Basic structure of the sensorless indirect rotor flux oriented two-phase induction motor is shown in Fig. 1. MRAC Speed estimator operates in the stationary reference frame and is described with the following equations[5]:

$$p\lambda_{dr}^s = \frac{L_r}{L_m}[v_{ds}^s - (R_s + L_s\sigma p)i_{ds}^s] \quad (20)$$

$$p\lambda_{qr}^s = \frac{L_r}{L_m}[v_{qs}^s - (R_s + L_s\sigma p)i_{qs}^s] \quad (21)$$

$$p\hat{\lambda}_{dr}^s = \frac{L_m}{T_r}i_{ds}^s - \frac{1}{T_r}\hat{\lambda}_{dr}^s - \omega_r\hat{\lambda}_{qr}^s \quad (22)$$

$$p\hat{\lambda}_{qr}^s = \frac{L_m}{T_r}i_{qs}^s - \frac{1}{T_r}\hat{\lambda}_{qr}^s + \omega_r\hat{\lambda}_{dr}^s \quad (23)$$

$$\varepsilon = \hat{\lambda}_{dr}^s \lambda_{qr}^s - \hat{\lambda}_{qr}^s \lambda_{dr}^s \quad (24)$$

where T_r is rotor time constant and σ is the motor leakage coefficient($\sigma = 1 - L_m^2/(L_s L_r)$).

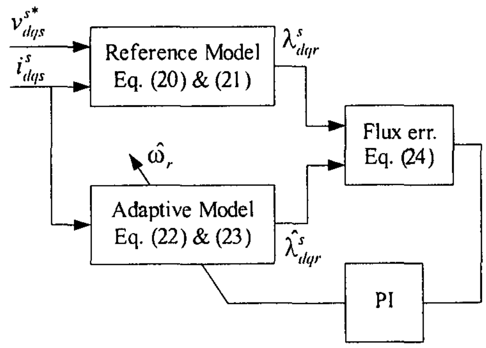


Fig. 1 Structure of MRAC system for speed estimation.

MRAC method uses two independent observes to estimate the same quantities, the components of the rotor flux vector: one reference model not involved ω_r based on (20) and (21), and one adaptive model involved ω_r based on (22) and (23).

The error from these two quantities is used to drive PI controller that generates the estimate $\hat{\omega}_r$ for the adaptive model. The estimated speed is used as feedback in the closed loop.

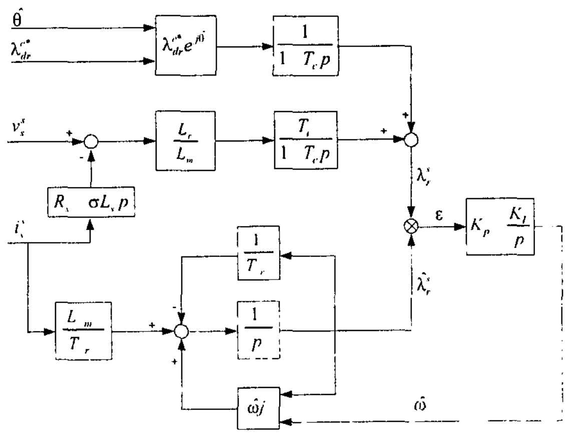


Fig.2 Block Diagram of MRAC speed estimator

In practice, the rotor flux by pure integration based on (20) and (21) can pose significant problems, particularly at lot frequency, because of sensor noise, dc offset, and parameter detuning effect.

Generally, to overcome these problems, high pass filter is applied to (20), (21). And then rotor flux is observed as follow:

$$\lambda^s_{dr} = \frac{T_c}{1+T_c p}\frac{L_r}{L_m}[v^s_{ds} - (R_s + L_s\sigma p)i^s_{ds}] \quad (25)$$

$$\lambda^s_{qr} = \frac{T_c}{1+T_c p}\frac{L_r}{L_m}[v^s_{qs} - (R_s + L_s\sigma p)i^s_{qs}] \quad (26)$$

If the time constant T_c is small value, the influence of voltage and current offset is decreased. Against, if T_c is increased, phase error of the observed rotor flux is decreased. Therefore, this method is effective in medium or high speed range rather than slow speed range. In this paper, to improve the loss of performance due to use the high pass filter, the low pass filtered reference rotor flux involved in reference model of MARC as following equations and Fig. 2.

$$\lambda^s_{dr} = \frac{T_c}{1+T_c p}\frac{L_r}{L_m}[v^s_{ds} - (R_s + L_s\sigma p)i^s_{ds}] + \frac{1}{1+T_c p}\lambda^{e,*}_{dr}\cos\theta_e \quad (27)$$

$$\lambda^s_{qr} = \frac{T_c}{1+T_c p}\frac{L_r}{L_m}[v^s_{qs} - (R_s + L_s\sigma p)i^s_{qs}] + \frac{1}{1+T_c p}\lambda^{e,*}_{dr}\sin\theta_e \quad (28)$$

3.2. Indirect field oriented control using MRAC speed estimator

Fig. 3 shows a configuration of the indirect field oriented control system using the MRAC speed estimator, which was implemented in the two-phase induction motor drive. The estimated speeded $\hat{\omega}_r$ was used as feedback of the speed loop.

In the indirect field oriented control scheme shown in Fig. 3, the slip frequency is calculated by following equation:

$$\omega_{sl} = \omega_e - \hat{\omega}_r = -\frac{R_r i^{e,*}_{qr}}{\lambda^{e,*}_{dr}} = \frac{R_r}{L_r}\frac{i^{e,*}_{qs}}{i^{e,*}_{ds}} \quad (29)$$

where the superscript * indicates reference values. The position of rotor flux is

$$\theta_e = \int(\hat{\omega}_r + \omega_{sl})dt \quad (30)$$

4. SIMULATION & EXPREMENTAL RESULT

4.1. Experimental System Configuration

Fig. 3 and Fig. 4 show the proposed two-phase induction motor system using the MRAC speed estimation algorithm.

The speed and current controllers were implemented by PI controllers.

The current regulated four-switch voltage-fed inverter[6] and 150W two-phase induction motor was available for computer simulation and experimental study. The parameter of are given in Table I.

The control system was implemented with the 32-bit digital processor TMS320VC33 operating with a clock frequency of 100 MHz and sampling interval is 125 for current control and speed estimation loop.

A sinusoidal PWM algorithm was used. Because the experimental target system is for a low power household appliance which seriously considered about energy efficiency, the PWM switching frequency of implemented system is 4 kHz with a dead time of 6 considering the switching loss,.

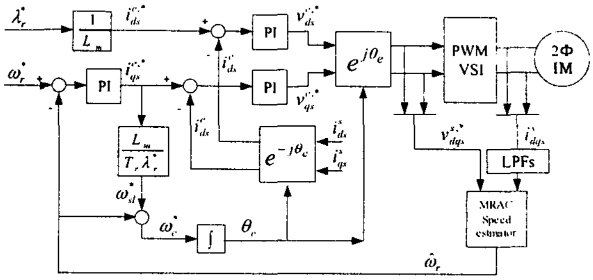


Fig.3 The block diagram of the simulation and field oriented control for two-phase induction machine drive system

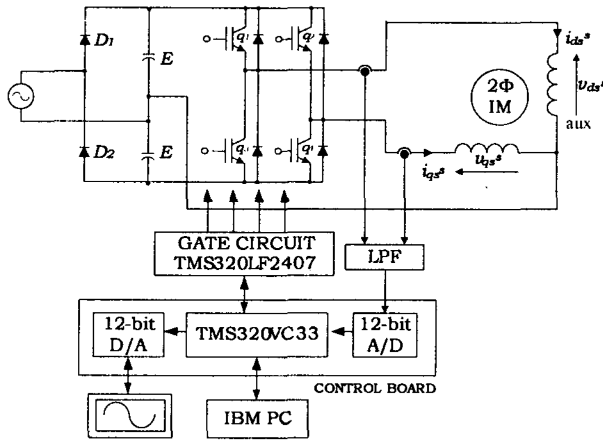


Fig.4 System hardware configuration.

Table 1 Parameter of Two-phase Induction Motor(75)

Rated output	150 [W]
Rated voltage	220 [V]
Rated main/aux winding current	1.63 [A]
Stator main/aux winding resistor	19.0 [Ω]
Rotor resistor	13.3 [Ω]
Main/aux winging inductance	34.7 [mH]
Rotor inductance	29.2 [mH]
Mutual inductance	371.4 [mH]
Pole	4

The dc link can be supplied from a single-phase ac source by inserting a diode rectifier.

The pulse width of four-switch inverter in the Fig. 4 can be calculated directly from the reference voltages of each phase.

The pulse width τ_1 and τ_2 of the switch q_1 and q_2 at ON mode are determined by:

$$\tau_1 = \frac{T}{2} + \frac{T}{E} v_{ds}^* \quad (31)$$

$$\tau_2 = \frac{T}{2} + \frac{T}{E} v_{qs}^* \quad (32)$$

4.2. Simulation Results

A detailed computer simulation was developed on MATLAB/SIMULINK. The validity of the MRAC speed estimation for two-phase induction motor is verified by the simulation results under no-load condition and the results are given in Fig. 5, 6 and 7 at trapezoidal reference(167.6 rad/s to -167.6rad/s, 800rpm to -800rpm). Fig. 6, zoomed waveform of Fig.5 shows the start-up response. Fig. 7 shows the transition waveform at the forward to reverse operation.

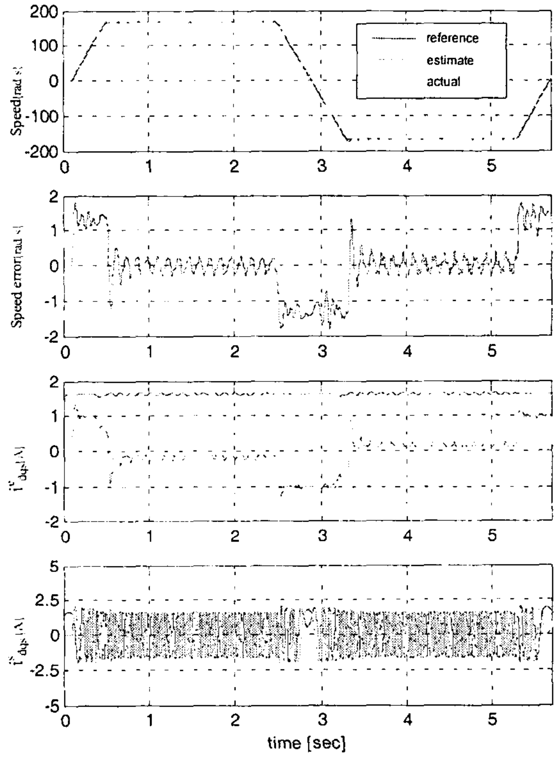
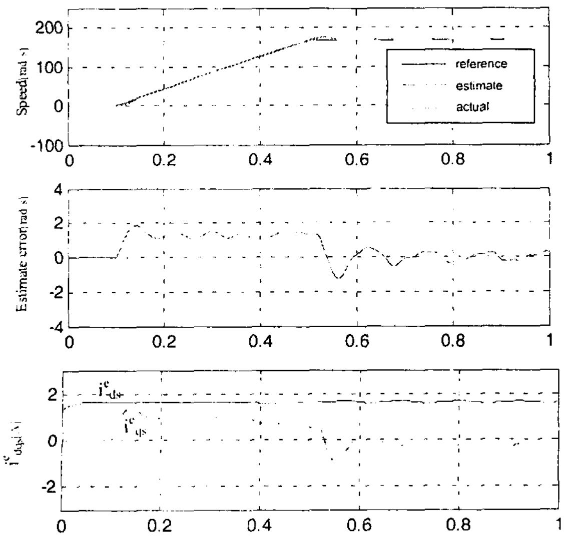
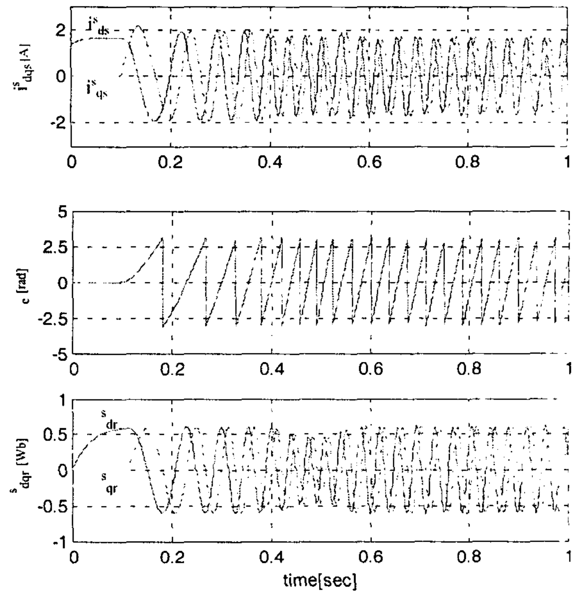


Fig.5 Simulation result : Response to trapezoidal reference. (Speed reference: 0 – 167.6 - -167.6 rad/s)



(a)



(b)

Fig.6 Simulation result : Zoomed waveform of start-up

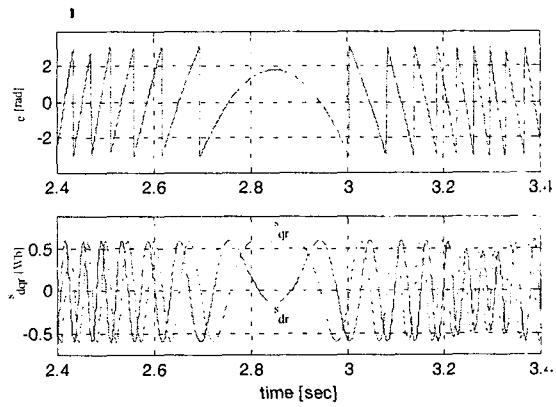


Fig.7 Simulation result : Zoomed waveform of forward to reverse operation

4.3. Experimental Results

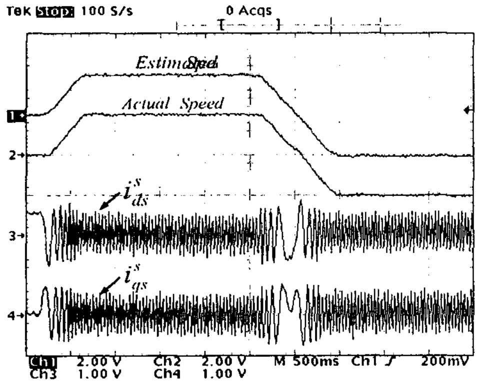
Experiments on the target system were achieved in the same process as computer simulations for two-phase induction motor under no-load condition, and the results are given in Fig. 8, 9 and 10 at trapezoidal reference(167.6 rad/s to -167.6rad/s, 800rpm to -800rpm) and start-up reference(0 to 800rpm).

In practical aspects, because the target system is a low power system with very low stator current, the following points were considered.

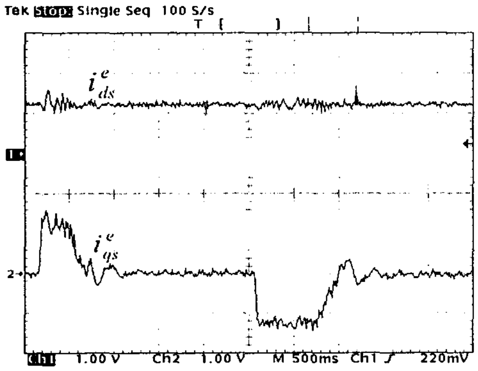
First, speed, current PI controller and adaptive rule gain of MRAC must be well tuned for each other.

Second, LPFs(low pass filters) was used at sensing input stage shown Fig. 4 and estimated speed output stage of MRAC. In the implementation, the cutoff frequency is 1.57 kHz and 10Hz for each. When the filter cutoff frequency was higher, the closed loop system suffered from excessive noise and oscillations.

Third, input voltages of MRAC was used the calculated reference voltages instead of the measured ones.

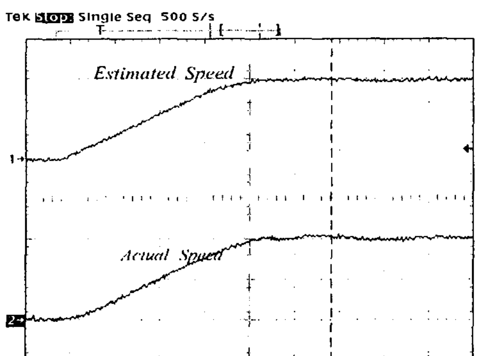


(a)

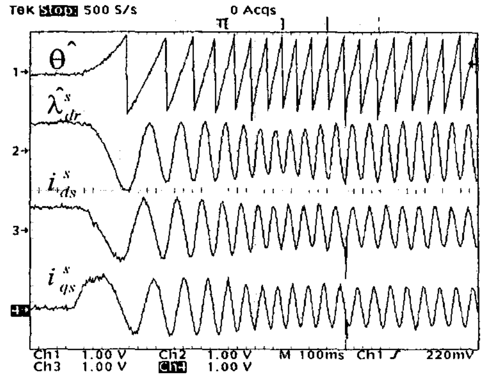


(b)

Fig.8 Experimental result - response to trapezoidal reference.
(Speed reference: 0 – 167.6 - -167.6 rad/s)
(a) Ch.1~2: speed response, Ch.3~4: stator current(1A/1V)
(b) Ch.1~2: sync. frame d-, q-axis current(0.5A/1V)

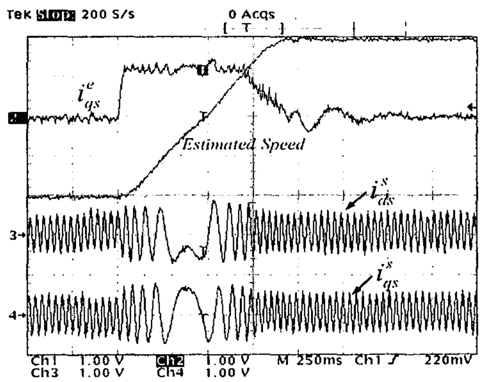


(a)

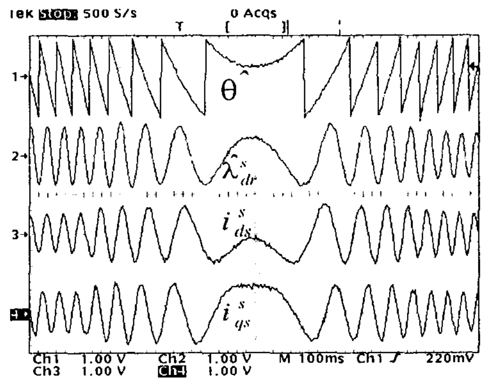


(b)

Fig.9 Experimental result – Start-up (a) speed response
(b) Ch. 1: estimated theta, Ch. 2: estimated d-axis rotor flux, Ch.3~4 : stator current(1A/1V)



(a)



(b)

Fig. 10 Experimental result - forward to reverse operation.
(a) Ch. 1: estimated speed, Ch. 2 : i_{qs}^{e} , 0.5A/1V,
Ch. 3 ~ 4:measured stator current(1A/1V)
(b) Ch. 1: estimated theta, Ch. 2 – estimated d-axis rotor flux, Ch. 3 ~ 4: measured stator current(1A/1V)

5. CONCLUSION

The computer simulation and experiments was carried out for the speed adjustable sensorless indirect field oriented control of two-phase induction motor drive using model reference adaptive speed estimator.

The validity and performance of the proposed system was proved by simulation and experimental results.

From the experimental results of the speed, current waveform and rotor flux waveform at zero speed area by the ramp type command, it is verified that the proposed control method was performed the adjustable speed control with good result.

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