TELKOMNIKA, Vol.11, No.1, January 2013, pp. 503~512
ISSN: 2302-4046

Rotor Speed and Stator Resistance Identification Scheme for Sensorless Induction Motor Drives

Zicheng Li[1,2]*, Zhouping Yin[1], Youlun Xiong[1] and Xinzhi Liu[2]
[1]State Key Laboratory of Digital Manufacturing Equipment & Technology, Huazhong University of Science & Technology, Wuhan, China
[2]School of Electrical & Information Engineering, Wuhan Institute of Technology, Wuhan, China
Corresponding author, e-mail: lizich@sohu.com

Abstract

This paper proposes a rotor speed identification method for sensorless induction motor drives based on a model reference adaptive system (MRAS). In this scheme, the error between estimated stator current and real stator current is regarded as the system error to estimate the rotor speed. Adaptive full-order flux observers for estimating the rotor speed are developed using Lyapunov's stability theory. The stator resistance identification algorithm is developed with rotor speed estimating method in a systematic manner. Because of the stator resistance varies with inner temperature of the motor, the influence of motor speed estimation due to stator resistance identification error is analyzed. The error compensation method for stator resistance estimation is also proposed. Simulation and experimental results show the good performance for the proposed scheme in speed and robustness for sensorless induction motor drives.

Keywords*: rotor speed identification, stator resistance estimation, model reference adaptive system, speed sensorless, induction motor*

1. Introduction

In recent years sensorless induction motor drives have been widely used due to their attractive features such as reliability, flexibility, robustness and poor cost. One of the most well-known methods used for control of induction motor drives are the Field Oriented Control (FOC) developed by Blaschke [1]. FOC of induction motor drives is known to have a good dynamic performance with comparable to that of the Direct Torque Control (DTC) techniques developed by Takahashi [2]. FOC technique has been used porpularly for sensorless control of induction motor drives. However, when a very high accuracy is desired, the performance of speed estimation is not good particularly at low speeds. The main reason of the speed estimation error is imprecise of flux observer and the off-set of the stator current sensor. Besides, it is very sensitive to the variation of motor parameters such as stator resistance. The method based on model reference adaptive system (MRAS) is one of the major approaches for rotor speed estimation [3, 4]. Various control algorithms based on MRAS have been proposed [5, 6]. A scheme applied the electromagnetic torque in generalized error and obtained better effect in static state. Stator back-EMF is used as the error to estimate the rotor speed for sensorless induction motor drives [7,8]. These algorithms are mainly based on the rotor flux or stator voltage estimations, which are obtained from the electrical quantities, and they are complicated and have difficulties in low speeds or zero speeds. Besides they are sensitive to the motor parameters variation in motor running particularly stator resistance and rotor resistance deviation [9-11].

This paper proposes a method for both rotor speed identification and stator resistance estimation in sensorless induction motor drives based on MRAS. The error between estimated stator current and real stator current is regarded as the system error to estimate the rotor speed and the stator resistance simultaneously. Adaptive full-order flux observers for estimating the rotor speed are developed by Lyapunov's stability theory. The sensorless induction motor drive system of indirect FOC is composed according to the schemes above. The feasibility of speed identification and stator resistance esitmation for sensorless induction motor drives is verified by simulation results based on matlab. The speed and current have good performance at very low

Received August 8, 2012; Revised December 7, 2012; Accepted December 13, 2012

speeds. It also develops a sensorless induction motor driver to implement the proposed method based on DSP and the experimental results verified its effectiveness.

2. Rotor Speed Adaptive Flux Observer

For an induction motor, if the stator currents and rotor flux are selected as the state variables, the state equations for induction motor can be described in the stationary reference frame as follows [12]:

$$\frac{d}{dt}\begin{bmatrix} i_s \\ \varphi_r \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}\begin{bmatrix} i_s \\ \varphi_r \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u_s = Ax + Bu_s \quad (1)$$

$$i_s = Cx \quad (2)$$

Where:

$i_s = \begin{bmatrix} i_{s\alpha} & i_{s\beta} \end{bmatrix}^T$ stator current

$\varphi_r = \begin{bmatrix} \varphi_{r\alpha} & \varphi_{r\beta} \end{bmatrix}^T$ rotor flux

$u_s = \begin{bmatrix} u_{s\alpha} & u_{s\beta} \end{bmatrix}^T$ stator voltage

$A_{11} = -\{R_s / (\sigma L_s) + (1-\sigma) / (\sigma \tau_r)\} I$

$A_{12} = \{L_m / (\sigma L_s L_r \tau_r)\} I - \{L_m \omega_r / (\sigma L_s L_r)\} J$

$A_{21} = (L_m / \tau_r) I$

$A_{22} = -(1/\tau_r) I + \omega_r J$

$B = 1/(\sigma L_s) I$, $C = \begin{bmatrix} I & 0 \end{bmatrix}$

$I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ unit matrix

$J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$ skew symmetric matrix

R_s , R_r stator and rotor resistor

L_s , L_r stator and rotor self inductor

L_m mutual inductor

$\tau_r = L_r / R_r$ rotor time constant

$\sigma = 1 - L_m^{\ 2} / L_s L_r$ leakage coefficient

ω_r motor electrical angular velocity

The adaptive full-order flux observers can be written as follows:

$$\frac{d\hat{i}_s}{dt} = \hat{A}_{11}\hat{i}_s + \hat{A}_{12}\hat{\varphi}_r + \frac{1}{\sigma L_1} u_s + G(\hat{i}_s - \hat{i}) \quad (3)$$

$$\frac{d\hat{\varphi}_r}{dt} = \hat{A}_{22}\hat{\varphi}_r + (L_m / \hat{\tau}_r)\hat{i}_s \quad (4)$$

Where, i_s and u_s are measured values of stator current vector and stator voltage vector respectively, and "^" signifies the estimated values. G is observer gain matrix, which decides the stability of the system as follows:

$$G = \begin{bmatrix} g_1 & g_2 \\ -g_3 & g_4 \end{bmatrix}^T \tag{5}$$

Since stator current is easy to be measured, the stator current is selected as the error feedback value. The observer is a closed loop system, which is obtained by the estimated model of the induction motor. Therefore, the error between the state currents i_s and $\hat{i}_s$ can be used the system error as follows:

$$e = i_s - \hat{i}_s \tag{6}$$

The error e can be used to a speed adaptive control mechanism which gains and adjusts estimated speed $\hat{\omega}_r$. At the same time, the estimated speed $\hat{\omega}_r$ is introduced in the adjustable model and the estimated stator current $\hat{i}_s$ is changed consequently. While speed adaptive mechanism should guarantee that, the system error e would approach zero if estimated speed $\hat{\omega}_r$ is asymptotic to real speed ω_r. Figure 1 shows the total shunt MRAS diagram. Where $\hat{\omega}_r = f(i_s - \hat{i}_s)$ is the equation of the speed estimation.

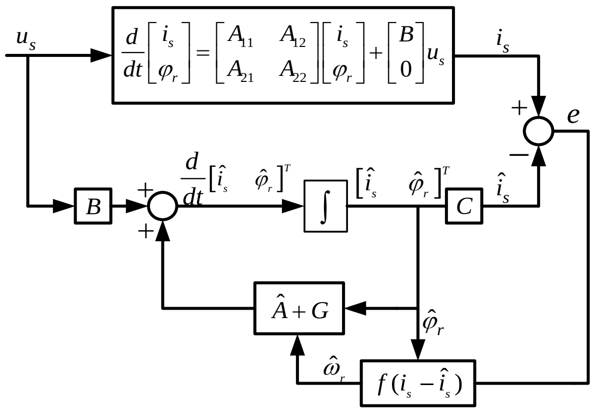


Figure 1. The block diagram of MRAS

3. Adaptive Scheme for Rotor Speed and Stator Resistance

3.1. Speed Adaptive Estimation Scheme

The error equation is defined by subtracting reference model from adjustable model as follows:

$$\frac{de}{dt} = \frac{d(i_s - \hat{i}_s)}{dt} = A_{11}(i_s - \hat{i}_s) + G(i_s - \hat{i}_s) + (A_{12} - \hat{A}_{12})\hat{\varphi}_r \tag{7}$$

that is,

$$\frac{de}{dt} = (A_{11} + G)(i_s - \hat{i}_s) + \{L_m / (\sigma L_s L_r)\} J \hat{\varphi}_r \tag{8}$$

the above (8) can be simplified as:

$$\frac{de}{dt} = A_m e + A_d(t) x_m \tag{9}$$

where:

$A_m = A_{11} + G$, $A_d(t) = [L_m / (\sigma L_s L_r)](\omega_r - \hat{\omega}_r)$, $x_m = J\hat{\varphi}_r$

A Lyapunov's function is selected as:

$$V = e^T P e + t_r [A_d(t) F^T(t) A_d(t)] \tag{10}$$

where P and F are both positive symmetric matrixes. Get the derivative of V to time as follows:

$$\frac{dV}{dt} = e^T (A_m{}^T P + P A_m) e + 2t_r \{A_d{}^T(t)[P e x_m{}^T - F^{-1} A_d(t)]\} \tag{11}$$

If it makes A_m be Gourvatz matrix by configuring matrix G, matrix P can be gained by Lyapunov's equation:

$$A_m{}^T P + P A_m = -Q \quad 12)$$

where Q is arbitrary positively definite matrix.

Then it is chosen to make V be negative definite as follows:

$$P e x_m{}^T - F^{-1} d(A_d(t)) / dt = 0 \tag{13}$$

An adaptive control law [13] about $A_d(t)$ is obtained by equation:

$$A_d(t) = \int_0^t F P e x_m{}^T d\tau + A_d(0) \tag{14}$$

that is, we can obtain as follows:

$$\{L_m / (\sigma L_s L_r)\}(\omega_r - \hat{\omega}_r) = \int_0^t FP[\hat{\varphi}_{r\alpha}(i_{s\beta} - \hat{i}_{s\beta}) - \hat{\varphi}_{r\beta}(i_{s\alpha} - \hat{i}_{s\alpha})] d\tau + A_d(0) \tag{15}$$

obviously，equation (15) can be equivalent as follows by a PI control equation:

$$\hat{\omega}_r = (k_{P1} + k_{I1} / s)[\hat{\varphi}_{r\alpha}(i_{s\beta} - \hat{i}_{s\beta}) - \hat{\varphi}_{r\beta}(i_{s\alpha} - \hat{i}_{s\alpha})] \tag{16}$$

where k_{P1} and k_{I1} are PI parameters of speed adaptive estimator and $1/s$ is the integral operator.

Therefore, according to Lyapunov's theory we can conclude that a right matrix P is gained from equation (12) if a random positive matrix Q is given. So, global asymptotic stability of the system is guaranteed if adaptive gain F is positive matrix and input us is random parted continuous function. Equation (16) can be used to estimate rotor speed conveniently.

3.2. Stator Resisitance Adaptive Estimation Scheme

In accordance with the same principle of above speed adaptive estimation, if rotor speed is regarded as be invariable, it can be described as follows:

$$\frac{de}{dt} = \frac{d(i_s - \hat{i}_s)}{dt} = A_{11} i_s - \hat{A}_{11} \hat{i}_s + A_{12}(\varphi_r - \hat{\varphi}_r) + G(i_s - \hat{i}_s) \tag{17}$$

according to (1), we have

$$\frac{d(\varphi_r - \hat{\varphi}_r)}{dt} = A_{21}(i_s - \hat{i}_s) + A_{22}(\varphi_r - \hat{\varphi}_r) \tag{18}$$

that is,

$$\varphi_r - \hat{\varphi}_r = -A_{22}{}^{-1} A_{21}(i_s - \hat{i}_s) \tag{19}$$

substituting (19) into (17) gives

$$\frac{d(i_s - \hat{i}_s)}{dt} = (G - A_{22}{}^{-1} A_{21} A_{12})(i_s - \hat{i}_s) - (R_s - \hat{R}_s)/(\sigma L_s)\hat{i}_s \tag{20}$$

so, the above (20) can be simplified as:

$$\frac{de}{dt} = A_m e + A_d(t) x_m \tag{21}$$

where:

$A_m = G - A_{12}{}^{-1} A_{21} A_{12}$, $A_d(t) = (R_s - \hat{R}_s)/(\sigma L_s)$, $x_m = \hat{i}_s$

Therefore, according to the same Lyapunov's theory as above speed adaptive scheme, stator resistance can be identificated by another PI control equation as follows:

$$\hat{R}_s = (k_{P2} + k_{I2}/s)[i_{s\alpha}(\hat{i}_{s\alpha} - \hat{i}_{s\alpha}) + \hat{i}_{s\beta}(\hat{i}_{s\beta} - \hat{i}_{s\beta})] \tag{22}$$

where k_{P2} and k_{I2} are PI parameters of speed adaptive estimator.

3.3. Error Compensation for Stator Resistance

The stator resistance varied with inner temperature of motor influences the stator currents and rotor flux estimation [14], so it is necessary to compensate the stator resistance error for accurate speed estimation.

According to induction motor model, the α stator voltage can be calculated in the stator reference frame.

$$u_{s\alpha} = R_s i_{s\alpha} + \sigma L_s di_{s\alpha}/dt + (L_m/L_r)[(L_m/\tau_r)i_{s\alpha} - (1/\tau_r)\varphi_{r\alpha} - \omega_r \varphi_{r\beta}] \tag{23}$$

where, it is assumed that only the stator resistance R_s is varied with inner temperature of the induction motor. Then, the α stator voltage equation including $\hat{R}_{s1}$, $\hat{\varphi}_{r\alpha}$ and $\hat{\varphi}_{r\beta}$ is represented as follows:

$$u_{s\alpha} = \hat{R}_{s1} i_{s\alpha} + \sigma L_s di_{s\alpha}/dt + (L_m/L_r)[(L_m/\tau_r)i_{s\alpha} - (1/\tau_r)\hat{\varphi}_{r\alpha} - \omega_r \hat{\varphi}_{r\beta}] \tag{24}$$

where, $\hat{R}_{s1}$ is given by $\hat{R}_s - \hat{R}_{s1} = \Delta R_s$ and ΔR_s is the actual variation of the stator resistance.

The subtraction of (24) from (23) yields the following.

$$\Delta R_s = (L_m / L_r)[\omega_r(\hat{\varphi}_{r\beta} - \varphi_{r\beta}) + (1/\tau_r)(\hat{\varphi}_{r\alpha} - \varphi_{r\alpha})] / i_{s\alpha} \tag{25}$$

thus, the actual value of the stator resistance $\hat{R}_{s1}$ is compensated by

$$\hat{R}_{s1} = \hat{R}_s - \Delta R_s = \hat{R}_s - (L_m / L_r)[\omega_r(\hat{\varphi}_{r\beta} - \varphi_{r\beta}) + (1/\tau_r)(\hat{\varphi}_{r\alpha} - \varphi_{r\alpha})] / i_{s\alpha} \tag{26}$$

So, it can be utilized to update the actual value of the stator resistance.

4. Simulation and Experimental Results

Some simulation results are presented to emphasize the estimated scheme capability to compensate for the stator resistance error on estimated stator resistance and therefore on the speed estimated accuracy. The proposed sensorless control algorithm for induction motor drives has been applied to the indirect FOC of an induction motor drive. Figure 2 shows an overall control diagram of the sensorless induction motor drive system based on slip frequency FOC based on matlab.

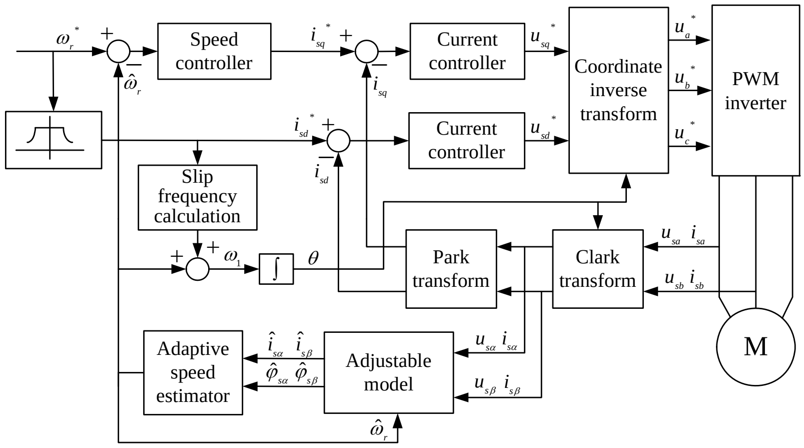


Figure 2. Control diagram of sensorless control system for induction motor drives

The simulation is performed for the verification of the above control scheme. Figure 3 shows the system component for sensorless induction motor drives based on MRAS. It is simulated by a sampling period of 25μs. the motor parameters for simulation are as Table 1. The PI gains of the speed adaptive scheme are: $k_{P1} = 0.02$, $k_{I1} = 500$. The PI gains of the speed adaptive scheme are: $k_{P1} = 0.05$, $k_{I1} = 50$.

Figure 4(a) is simulation results of estimated and real rotor speed based on proposed MRAS method. Figure 4(b) shows the rotor speed response in the case where the stator resistance of the model is increased by 50% above the nominal value. Obviously, the estimated speed fluctuates. However, Figure 5(a) is the simulation result of rotor speed after adding stator resistance compensation according to equation (26). Comparing with Figure 4(b), Figure 5(a) indicates that estimated speed can trace the real speed by adding stator resistance offset. Figure 5(b) shows the estimated and real current waveforms with stator resistance estimation and error compensation for stator resistance. Figure 6 show the electromagnetic torque and estimated current waveforms in the case of sensorless induction motor drives with speed close control based on indirect FOC.

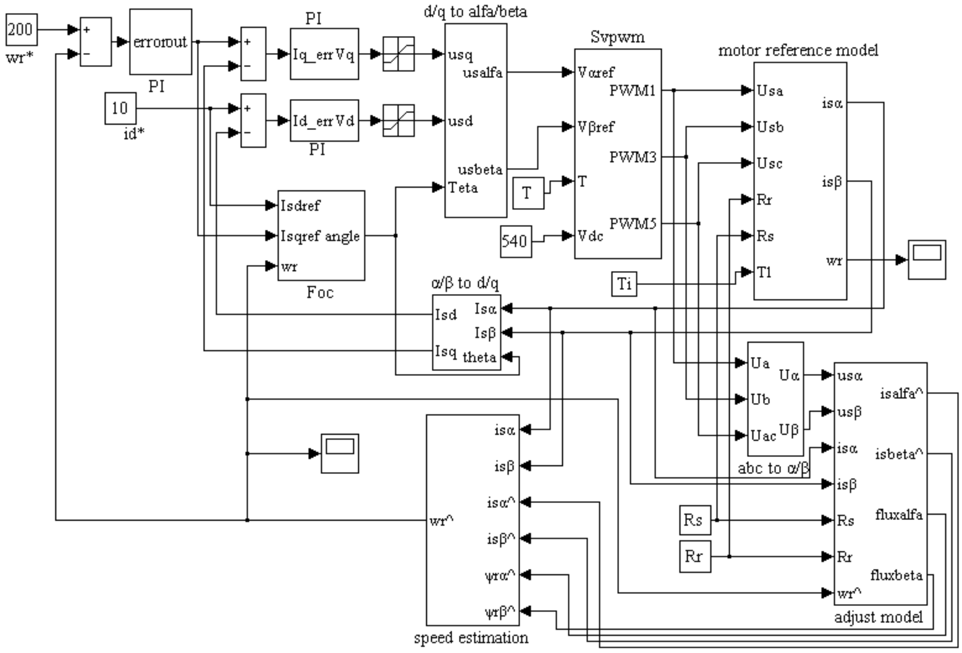
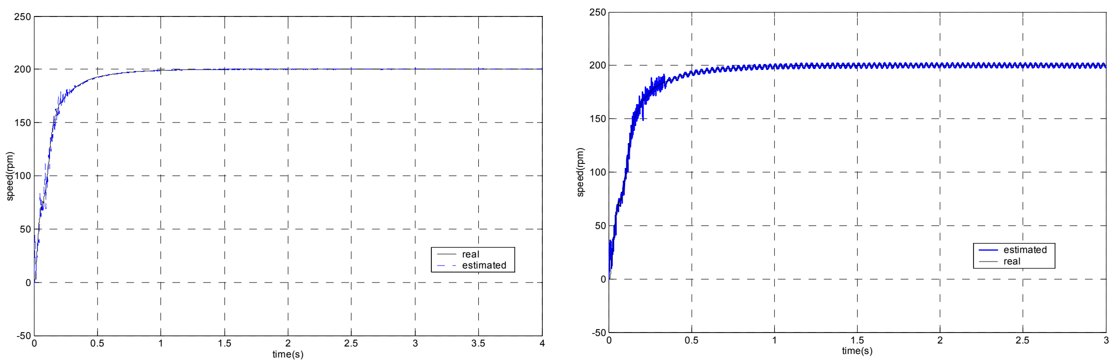


Figure 3. Simulation diagram of sensorless induction drives based on MRAS using matlab

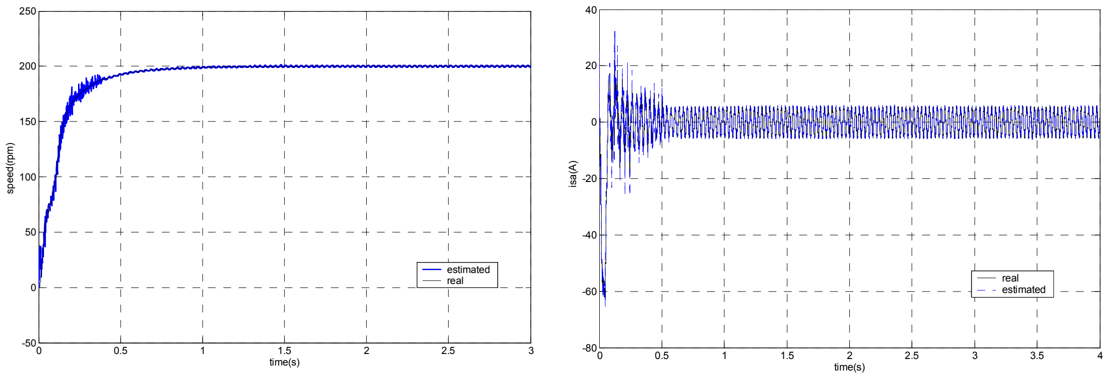
Table 1. Constructed Motor Specification

Variable	Value
Rated voltage	380(V)
Rated frequency	50(Hz)
Number of pole	4
Rated speed	1450(rpm)
Stator resistance	1.48(Ω)
Rotor resistance	2.62(Ω)
Stator incuctance	210(mH)
Rotor inductance	210(mH)
Mutual inductance	200(mH)



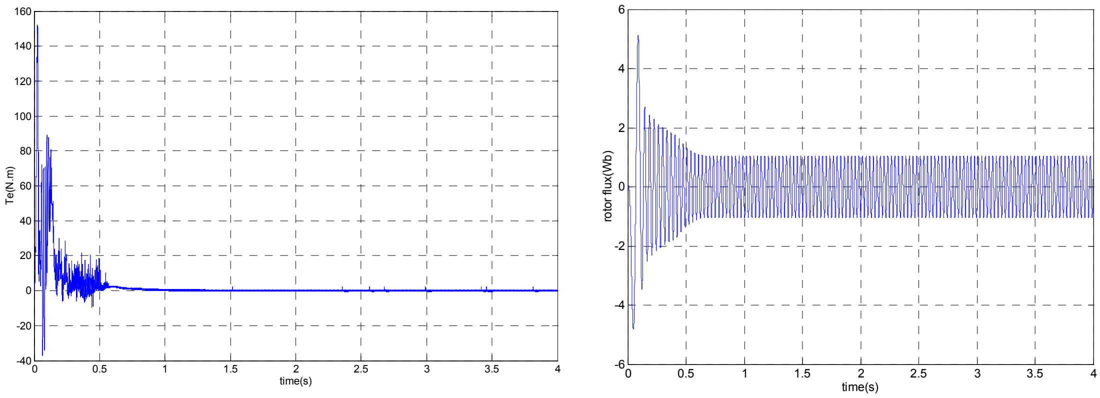
(a) (b)

Figure 4. Rotor speed waveforms: (a) No change of stator resistance, (b) Without stator resistance compensation on condition of 50% increasing Simulation diagram of sensorless



(a) (b)

Figure 5. Simulation waveforms of adding stator resistance compensation on condition of 50% increasing Rotor speed waveforms: (a) Rotor speed waveform, (b) Estimated and real current waveforms



(a) (b)

Figure 6. Simulation waveforms of proposed sensorless control drives: (a) Electromagnetic torque waveform, (b) Estimated current waveform

Hardware implementation for the proposed scheme has been configurated by sensorless induction motor drivers based TMS320LF2407A DSP processor. The currents are measured by current sensors. The voltage and current signals are adjusted and sampled simultaneously with 10-bit A/D converters in DSP. The configuration of the proposed sensorless induction motor drive system built for experimental research is shown in Figure 7.

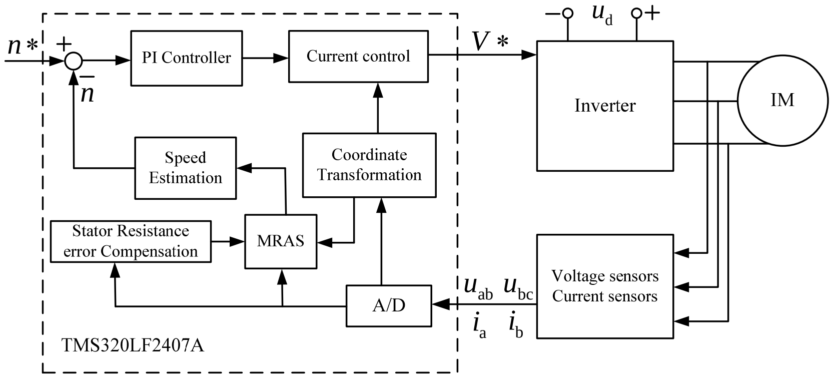
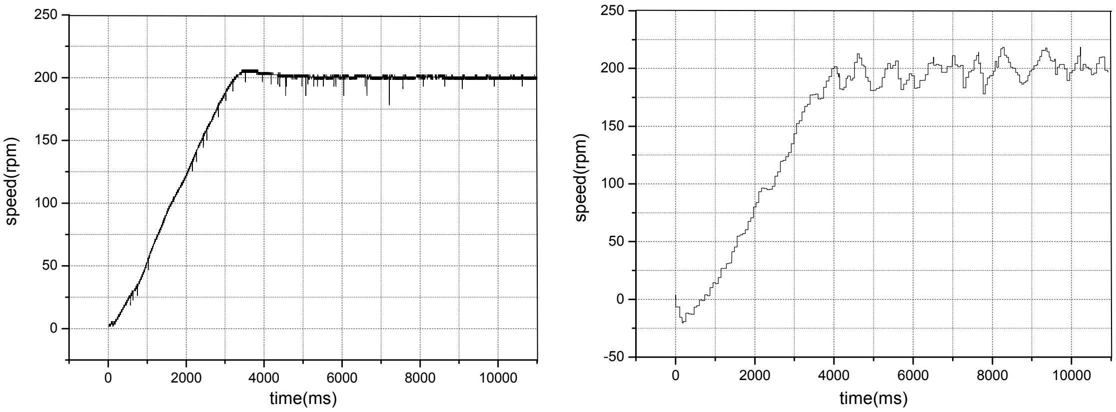


Figure 7. The configuration of experimental system based on DSP

Table 2 shows the motor parameters to examine the performance of the developed sensorless induction motor drive technique based on MRAS. The PI gains of the speed adaptive scheme are: $k_{P1} = 0.02$, $k_{I1} = 500$. The PI gains of the speed adaptive scheme are: $k_{P1} = 0.05$, $k_{I1} = 50$.

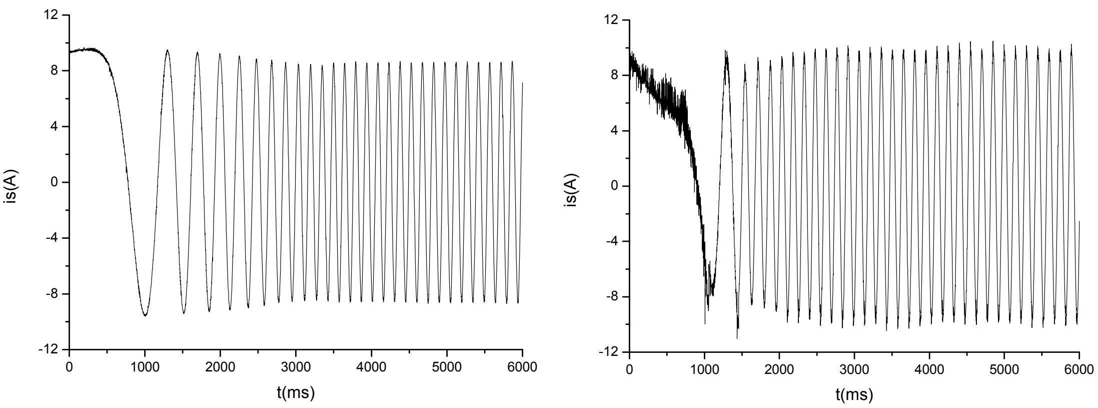
Table 2. Motor Parameters

Variable	Value
Rated voltage	380(V)
Rated frequency	50(Hz)
Number of pole	4
Rated speed	1460(rpm)
Rated power	13(KW)
Rated current	25.4(A)
Stator resistance	1.56(Ω)
Rotor resistance	1.22(Ω)
Stator incuctance	250(mH)
Rotor inductance	250(mH)
Mutual inductance	240(mH)



(a) (b)

Figure 8. Experimental waveforms for proposed sensorless induction motor drives: (a) Real rotor speed, (b) Estimated rotor speed



(a) (b)

Figure 9. Experimental waveforms for proposed sensorless induction motor drives: (a) Real current, (b) Estimated current

Rotor speed and phase current waveforms with stator resistance identification based on proposed compensation method are respectively shown in Figure 8 and Figure 9. It can be seen from the figure that the estimated and real rotor speed can track each other in both steady state and dynamic operation. Just like rotor speed, Figure 9 shows that the estimated stator current soincides with the real one and current waveform has been significantly improved adding stator resistance error compensation. Experimental results verified the proposed sensorless induction motor drives schmem with rotor speed and stator resistance identification based on MRAS.

5. Conclusion

This paper has proposed a method for both rotor speed estimation and stator resistance identification based on MRAS. Error compensation for stator resistance in sensorless induction motor drives is also presented. The algorithm is given to compensate the stator resistance deviation, which results in the speed estimation error. The proposed scheme is proved by the Lyapunov's criterion and applied to a indirect oriented induction motor control without rotor speed sensors. The performance of the proposed scheme is verified by simulation results and the validity of the proposed control strategy using indirect FOC is successfully verified from the experimental results.

Acknowledgement

This study was supported in part by National Fundamental Research Program of China (973) (No.2009CB724204).

References

[1] YA Kwon, SK Kim. A high-performance strategy for sensorless induction motor drive using variable link voltage. *IEEE Transactions on Power Electronics*. 2007; 22(1):329–332.
[2] XH Nian, T Wang, J wang, W Gui. *Adaptive stator resistance estimation method for speed sensorless DTC controlled IM drives*. Proceedings of the 22th Annual IEEE Applied Power Electronics Conference (APEC). Anaheim. 2007;1:214-221.
[3] Zicheng Li, Shanmei Cheng, Kai Cai. *The simulation study of sensorless control for induction motor drives based on MRAS*. Proceedings of the 7th International Conference on System Simulation and Scientific Computing (ICSC). Beijing. 2008; 1: 235–239.
[4] J Guzinski, H Abu-Rub, HA Toliyat. An advanced low-cost sensorless induction motor drive. *IEEE Transactions on Industry Applications*. 2003; 39(6):1757–1764.
[5] G Pellegrino, P Guglielmi, E Armando, RI Bojoi. Self-commissioning algorithm for inverter nonlinearity compensation in sensorless induction motor drives. *IEEE Transactions on Industry Applications*. 2010; 46(4):1416–1424.
[6] Anwen Shen, Zicheng Li. The vector control in sensorless induction motor drives based on MRAS. *Journal of Huzhong University of Science and Technology*. 2005; 33(12):51–53.
[7] Pellegrino G, Guglielmi P, Armando E, Bojoi RI. Self-commissioning algorithm for inverter nonlinearith compensation in sensorlss induction motor drives. *IEEE Transactions on Industry Application*. 2010; 46(4):1416-1424.
[8] M Ghanes, LJ De, A Glumineau. Cascade and high-gain observers comparison for sensorless closed-loop induction motor control. *IET Control Theory and Applications*. 2008; 2(2):133–150.
[9] Cortajarena JA, De Marcos J, Alvarez P, Vicandi FJ. *Sensorless induction motor parameter identification and control*. Proceedings of IEEE International Conference on Industrial Technology. Eibar. 2010; 1:404-409.
[10] Baburaj K, Muhammed FR, Colin G. Online stator and rotor resistance estimation scheme using artificial nerual networks for vector controlled speed sensorless induction motor drive. *IEEE Transactions on Industrial Electronics*. 2007; 54(1):167-176.
[11] Zaky MS, Khater MM, Shokralla SS, Yasin HA. Wide-speed-range estimation with online parameter identification schemes of sensorless induction motor drives. *IEEE Transactions on Industrial Electronics*. 2009; 56(5):1699-1707.
[12] Kwon YA, Kim SK. A high-performance strategy for sensorless induction motor drive using variable link voltage. *IEEE Transactions on Power Electronics*. 2007; 22(1):329-332
[13] X Liu. Applied adaptive control. Xi'an. Northwestern Polytechnical University Press. 2003.
[14] Ghanes M, Gang Zheng. On sensorless induction motor drives: sliding-mode observer and output feedback controller. *IEEE Transactions on Industrial Electronics*. 2009; 56(9): 3404-3413.