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FIELD ORIENTATION CONTROL INDUCTION MOTOR DRIVE WITH FUZZY ADAPTION SPEED ESTIMATION

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Abstract. *A field orientation control induction motor drive with fuzzy adaption rotor speed estimation is presented. First, the rotor field orientation control induction motor drive scheme is established. Then, the current-and-voltage serial-model rotor-flux estimator is developed to acquire the flux position angle of the coordinate transformation. The designed fuzzy adaption speed estimation based on the developed rotor flux estimator guarantees to obtain exact estimation rotor speed. Simulation and experimental results confirm the effectiveness of the proposed approach.*

Keywords: Field orientation control, Flux estimator, Fuzzy adaption, Speed estimation

1. Introduction.

Induction motor (IM) drive applying the field orientation control strategy has the possession of maximum torque-current ratio. The concept of the field orientation control is utilizing the suitable coordinate transformation [1], the 3-phase AC signals of an IM can be distributed into the flux-current and torque-current component, owing to the fact that both current components are DC signals and orthogonal, and these enable the performance of an IM drive is comparable to DC motor drive. The implementation of the field orientation control IM drive requires position encoder to detect rotor-shaft position. This sensor, however, deteriorates the drive reliability and is unsuitable for hostile environment. Consequently, the speed sensorless field orientation control strategy applying the flux estimator approaches has been adopted to replace the conventional field orientation control IM drives [2].

In this paper, the field orientation control approach with fuzzy adaption speed estimation strategy is presented for the sensorless IM drives. A current-and-voltage serial-model rotor-flux estimator is developed to acquire flux position angle for execution of the coordinate transformation between the synchronous reference coordinate and stationary reference coordinate frame. The fuzzy adaption control strategy is applied to guarantee the estimation rotor-shaft speed is exact. This rotor speed estimation approach has advantages of simple scheme and easy implantation comparing with extended Kalman filter and neural network methods [3]. Simulation and experimental results confirm the validity of the proposed approach.

2. Speed Sensorless Rotor Field Orientation Control IM Drive.

The stator and rotor voltage equations of an IM in the synchronous reference coordinate frame are

$$(R_s + j\omega_e L_s + L_s p)\vec{i}_s^{\,e} + (j\omega_e L_m + L_m p)\vec{i}_r^{\,e} = \vec{v}_s^{\,e} \tag{1}$$

$$(j\omega_{sl} L_m + L_m p)\vec{i}_s^{\,e} + (R_r + j\omega_{sl} L_r + L_r p)\vec{i}_r^{\,e} = 0 \tag{2}$$

where R_s and R_r are the stator and rotor resistance, respectively, L_s, L_r and L_m are the stator, rotor and mutual inductance, respectively, $\vec{i}_s = i_{ds} + ji_{qs}$ and $\vec{i}_r = i_{dr} + ji_{qr}$ are the stator and rotor current vector, respectively, $\vec{v}_s = v_{ds} + jv_{qs}$ is the stator voltage vector,

ω_e is speed of the synchronous reference coordinate frame, ω_r is the electric speed of the rotor, $\omega_{sl} = \omega_e - \omega_r$ is the slip speed, and $p = d/dt$ is the differential operator. The stator and rotor flux are given by, respectively,

$$\vec{\lambda}_s^e = L_s \vec{i}_s^e + L_m \vec{i}_r^e \tag{3}$$

$$\vec{\lambda}_r^e = L_r \vec{i}_r^e + L_m \vec{i}_s^e \tag{4}$$

where $\vec{\lambda}_s = \lambda_{ds} + j\lambda_{qs}$, $\vec{\lambda}_r = \lambda_{dr} + j\lambda_{qr}$. Under the rotor field orientation control scheme [4], setting $\lambda_{qr}^e = 0$, and substituting (4) into (2), the estimated slip speed can be derived as

$$\hat{\omega}_{sl} = \frac{L_m i_{qs}^e}{\tau_r \lambda_{dr}^e} \tag{5}$$

where "$\wedge$" stands for the estimated value and $\tau_r = L_r/R_r$ is the rotor time constant. The d-axis estimated rotor flux can be obtained by

$$\hat{\lambda}_{dr}^e = \frac{L_m}{1 + \tau_r s} i_{ds}^e \tag{6}$$

In order to attain linear control of the d- and q- axis stator current control loop, define the feed-forward voltage compensation as, respectively,

$$\sigma L_s \left(-\omega_e i_{qs}^e - \frac{1-\sigma}{\sigma \tau_r L_m} \hat{\lambda}_{dr}^e \right)$$

$$\sigma L_s \left(\omega_e i_{ds}^e + \frac{1-\sigma}{\sigma L_m} \hat{\lambda}_{dr}^e \right)$$

Hence, the decoupled d-axis and q-axis voltage equations are derived as, respectively [4],

$$v_{ds}^{e^*} = \sigma L_s \left(v_{ds}^{e'} - \omega_e i_{qs}^e - \frac{1-\sigma}{\sigma \tau_r L_m} \hat{\lambda}_{dr}^e \right) \tag{7}$$

$$v_{qs}^{e^*} = \sigma L_s \left(v_{qs}^{e'} + \omega_e i_{ds}^e + \frac{1-\sigma}{\sigma L_m} \hat{\lambda}_{dr}^e \right) \tag{8}$$

where $\sigma = 1 - L_m^2/(L_s L_r)$ is the leakage inductance coefficient, $v_{ds}^{e'}$ and $v_{qs}^{e'}$ are the output of the d-axis and q-axis stator current controller, respectively, $v_{ds}^{e^*}$ and $v_{qs}^{e^*}$ are the voltage command of the d-axis and q-axis stator current control loop, respectively. The developed electromagnetic torque of an IM can be obtained by

$$T_e = \frac{3P}{4} \hat{\lambda}_{dr}^e i_{qs}^e \tag{9}$$

where P is the pole number of the motor. Owing to the fact that $\hat{\lambda}_{dr}^e$ and i_{qs}^e are orthogonal and independent in (9), it enables the performance of the field orientation control IM drive to be comparable to DC motor drive.

In the stationary reference coordinate frame ($\omega_e = 0$), substituting (3) and (4) into (1) and (2), respectively, then the current-model rotor-flux estimator and voltage-model rotor-flux estimator can be derived as [4], respectively,

$$\hat{\vec{\lambda}}_{ri}^s = \frac{L_m/\tau_r}{s + (1/\tau_r - j\omega_r)} \vec{i}_s^s \tag{10}$$

$$\hat{\vec{\lambda}}_{rv}^s = \frac{1}{s} \frac{L_r}{L_m} \left(\vec{v}_s^s - R_s \vec{i}_s^s \right) - \frac{\sigma L_s L_r}{L_m} \vec{i}_s^s \tag{11}$$

The proposed fuzzy adaptive rotor speed estimation scheme is shown in Figure 1. According to model reference adaptive system (MRAS) theory [5], the voltage-model rotor-flux estimator is selected as the reference model that is without the identified parameter ω_r, and the current-model rotor-flux estimator is selected as the adjustable model that has the possession of the identified parameter ω_r, and then the difference between the

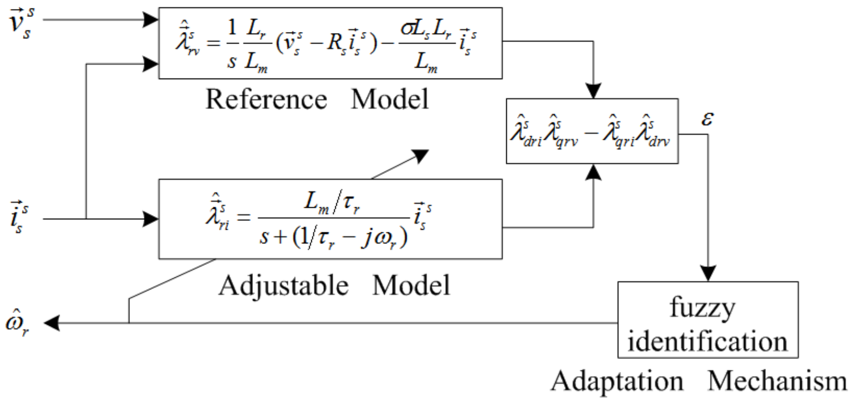

Figure 1. Fuzzy MRAS rotor speed identification based on the rotor flux estimator

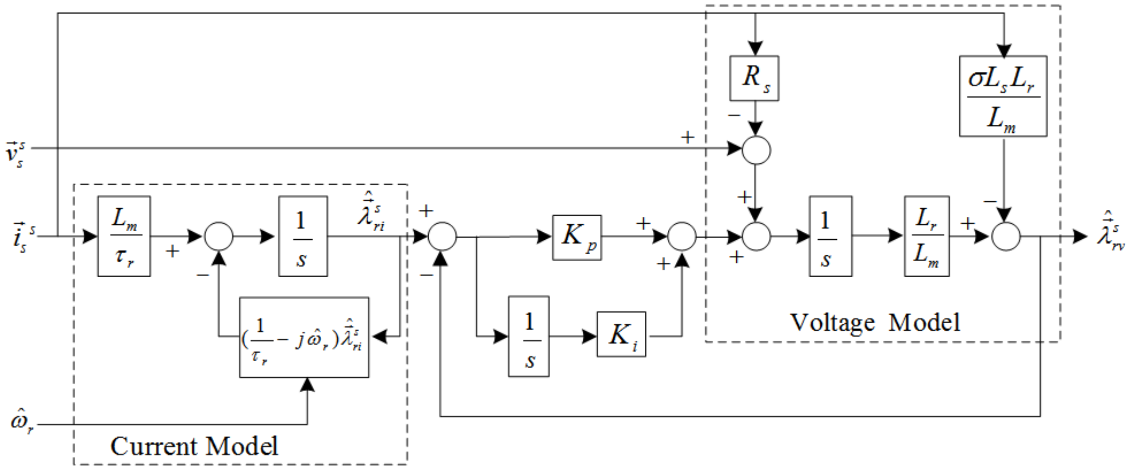

Figure 2. Current-and-voltage serial-model rotor-flux estimator

reference model and adjustable model can be expressed as (12), where this difference ε is served as the input of the fuzzy identification adaptive mechanism to estimate the rotor speed.

$$\varepsilon = \hat{\lambda}_{dri}^s\hat{\lambda}_{qrv}^s - \hat{\lambda}_{qri}^s\hat{\lambda}_{drv}^s \tag{12}$$

The current-and-voltage serial-model rotor-flux estimator is shown in Figure 2, where the difference between the estimated current-model rotor-flux and the estimated voltage-model rotor-flux is served as the input of a proportion-integral (PI) controller, and then the output of this PI controller is conducted as the voltage compensation for the voltage-model rotor-flux estimator [4].

The d-axis and q-axis rotor flux is acquired from the current-and-voltage serial-model rotor-flux estimator, which is shown in Figure 2. Hence, the rotor flux position angle of the coordinate transformation can be estimated as

$$\hat{\theta}_e = \tan^{-1}\left(\frac{\hat{\lambda}_{qr}^s}{\hat{\lambda}_{dr}^s}\right) \tag{13}$$

3. **Fuzzy Logic Identification Design.** The design of the fuzzy logic identification is conducted by applying the linguistic imprecise knowledge of human experts and the behavioral character of the plant. The fuzzy logic identification is composed of fuzzification, fuzzy knowledge base, fuzzy inference, and defuzzification [6].

Table 1. The meaning of fuzzy set

NL	Negative Large
NS	Negative Small
ZE	Zero Error
PS	Positive Small
PL	Positive Large

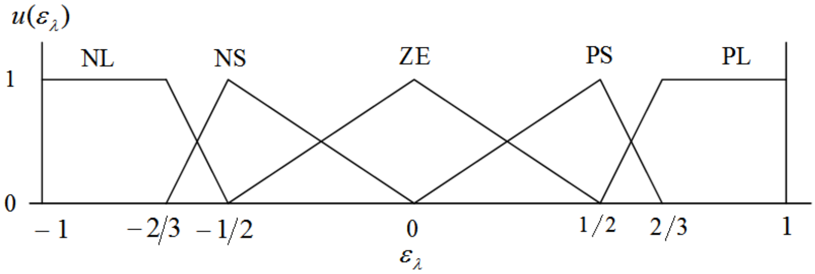

Figure 3. Membership functions for ε_λ

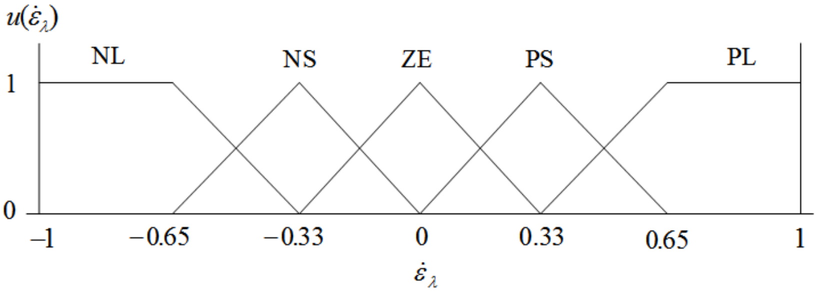

Figure 4. Membership functions for $\dot{\varepsilon}_\lambda$

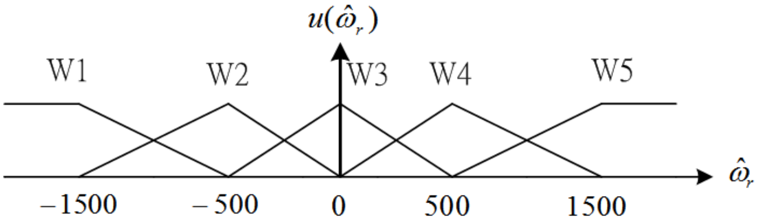

Figure 5. Membership functions for $\hat{\omega}_r$

3.1. **Fuzzification.** The function of fuzzification converts crisp input values into corresponding fuzzy values. The numbers of fuzzy sets determine the estimation rotor flux of the fuzzy logic identification. In this system, the fuzzy set is defined as Negative Large (NL), Negative Small (NS), Zero Error (ZE), Positive Small (PS), and Positive Large (PL), which is shown in Table 1.

The membership functions for the flux error (ε_λ) and its derivative ($\dot{\varepsilon}_\lambda$), and the desired estimation rotor speed ($\hat{\omega}_r$) are shown in Figures 3, 4, and 5.

3.2. **Fuzzy inference.** The output feature is decided by the fuzzy rule and the output measure relies on the fuzzy inference. The Min-Min-Max method is applied to dominate the fuzzy inference. The first Min term is considered as fuzzification step, which applies minimum trigger as the membership level. The second Min term is considered as output membership level for each fuzzy inference rule. The third Max term is considered as integrating the same output membership functions into individually rule.

Table 2. Fuzzy rule table

ε_λ $\dot{\varepsilon}_\lambda$	NL	NS	ZE	PS	PL
NL	$W1_1$	$W1_2$	$W2_3$	$W2_4$	$W3_5$
NS	$W1_6$	$W2_7$	$W2_8$	$W3_9$	$W4_{10}$
ZE	$W2_{11}$	$W2_{12}$	$W3_{13}$	$W4_{14}$	$W4_{15}$
PS	$W2_{16}$	$W3_{17}$	$W4_{18}$	$W4_{19}$	$W5_{20}$
PL	$W3_{21}$	$W4_{22}$	$W4_{23}$	$W5_{24}$	$W5_{25}$

3.3. **Fuzzy rule.** The fuzzy rule is composed of the linguistic term if-then, for which the output membership function demanding to be trigged is decided by the fuzzy rule, i.e., it defines the relation between the output and the input. The total 25 rules are shown in Table 2.

3.4. **Defuzzification.** Defuzzification converts the inferred fuzzy output value into the crisp output value and then applies the crisp output value to dominating the plant. At this step, the center of sum defuzzification is used, which is defined as

$$y^* = \frac{\sum\limits_{l=1}^{m} p_l h(B_l')}{\sum\limits_{l=1}^{m} h(B_l')} \tag{14}$$

where $h(B_l')$ is the height of each B_l', and p_l is the most center value of y before the top of B_l' is cut off.

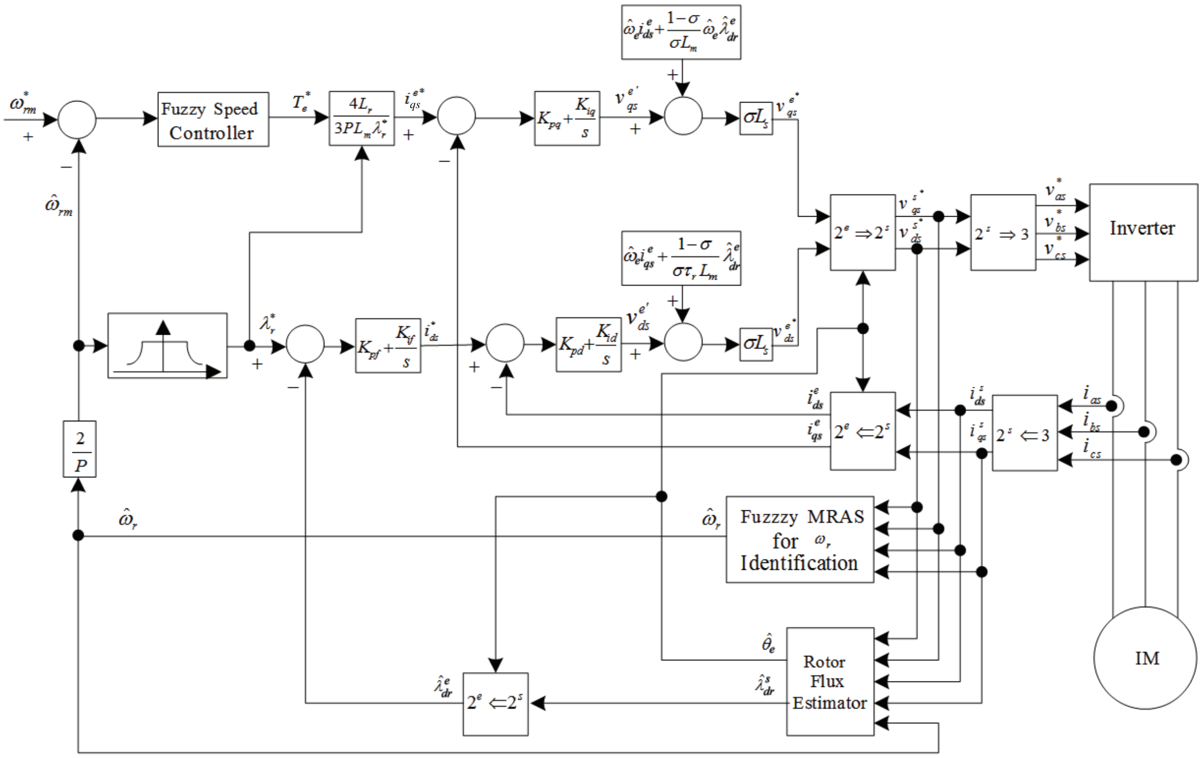

Figure 6. Field orientation control IM drive with fuzzy adaption rotor speed estimation

4. **Simulation and Experimental Testing.** The block diagram of the proposed field orientation control IM drive with fuzzy adaption rotor speed estimation is shown in Figure 6, which includes speed controller, flux controller, d-axis and q-axis stator-current controllers, d-axis and q-axis voltage decouple, rotor flux estimator, fuzzy MRAS speed estimation, and coordinate transformation. In the proposed system, the current-and-voltage serial-model rotor-flux estimator is used to estimate the rotor flux angle position of the coordinate transformation. The adaptation mechanism of MRAS is designed by a fuzzy logic identification approach to estimate the rotor speed. PI type controllers for the speed control loop, flux control loop, d-axis and q-axis stator-current control loops are designed by the root-locus method. A 3-phase, 220V, 0.75kW, Δ-connected, standard squirrel-cage IM that serves as the controlled plant for experimentation is used to confirm the effectiveness of the proposed field orientation control IM drive with fuzzy adaption rotor speed estimation.

The simulation and experimental responses for the proposed system with 1800 rpm reversible steady-state speed command and loading 2 N-m (half rated) are shown in Figures 7 and 8, and each figure includes four responses: the command and estimation rotor speed, the stator current, the electromagnetic torque, and the rotor flux locus.

Based on the simulation and experimental responses shown in Figures 7 and 8, the proposed field orientation control IM drive with fuzzy adaption rotor speed estimation has shown that desired performance can be acquired.

5. **Conclusions.** The adaptive rotor speed on-line identification strategy has been proposed for the rotor field orientation control IM drive. The developed current-and-voltage serial-model rotor-flux estimator acquired the flux position angle for execution coordinate transformation between the synchronous and stationary reference coordinate frame. The designed fuzzy MRAS rotor speed estimation scheme based on the developed rotor flux

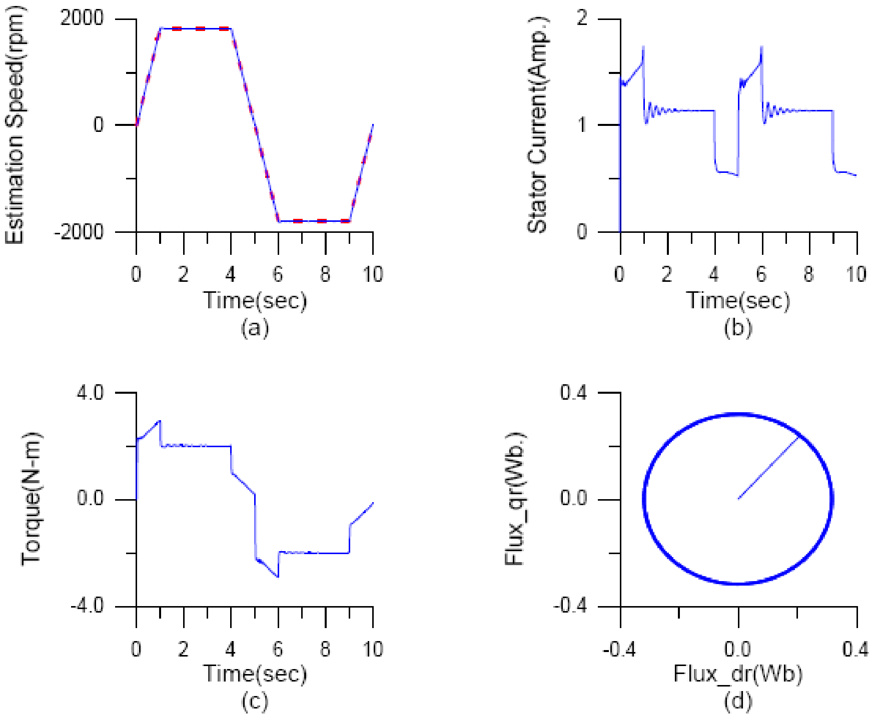

FIGURE 7. Simulation responses of the proposed fuzzy adaption rotor speed estimation field orientation control IM drive with reversible steady-state speed command 1800 rpm and loading 2 N-m: (a) command (dotted line) and estimated (solid line) rotor speed, (b) stator current, (c) electromagnetic torque, (d) rotor flux locus

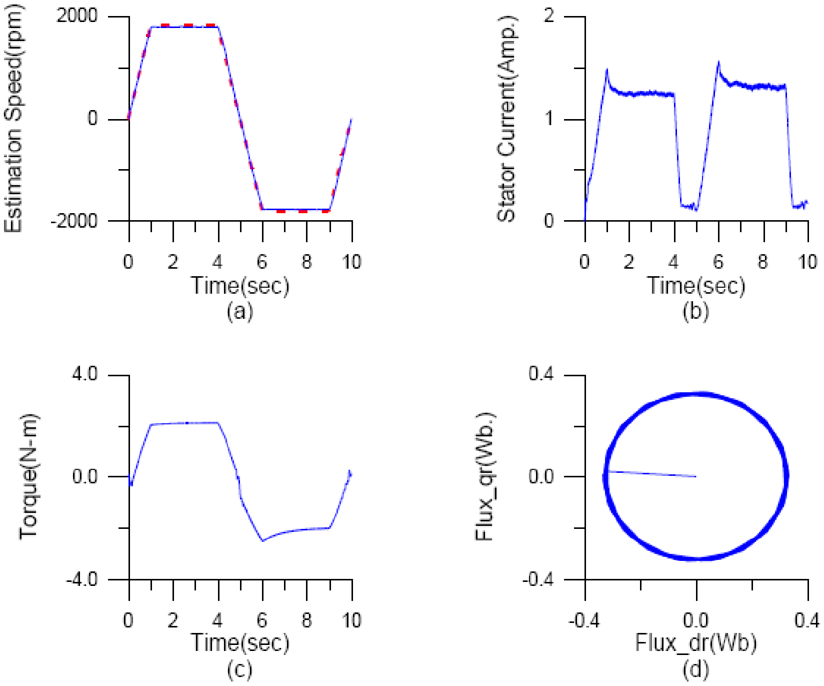

Figure 8. Experimental responses of the proposed fuzzy adaption rotor speed estimation field orientation control IM drive with reversible steady-state speed command 1800 rpm and loading 2 N-m: (a) command (dotted line) and estimated (solid line) rotor speed, (b) stator current, (c) electromagnetic torque, (d) rotor flux locus

estimator guarantees to obtain exact estimation rotor speed. Simulation and experimental responses confirm the effectiveness of the proposed approach. Applying the flux observer to estimate rotor speed is the future extension research of this system.

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