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SPEED ESTIMATION ADAPTIVE INDIRECT ROTOR FLUX VECTOR CONTROLLED INDUCTION MOTOR DRIVE

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Abstract. *The synchronous speed adaptation and rotor resistance parameter identification skills applied the adaptive control approaches to being presented for a speed estimation indirect rotor flux vector controlled induction motor drive. The voltage-and-current serial-model rotor-flux estimator is established to execute proper coordinate transformation. The reactive power based model reference adaptive system is developed to attain exact synchronous speed. The rotor resistance parameter on-line identification scheme is designed by fixed trace algorithm to acquire accurate slip speed. Simulated and experimental results confirm the proposed approach.*
Keywords: Speed estimation, Flux estimator, Adaptive control, Rotor flux vector control

1. **Introduction.** Induction motor (IM) compared with DC motor has possession of lower weight and volume, more reliability, and fewer maintenance requirements, and these enable IM drives to be adopted in precise automation applications [1-3]. Nevertheless, the mathematical model of an IM is time-varying, nonlinear and coupling. Applying AC motor flux vector controlled (FVC) theory [4], the complex mathematical model of an IM is converted as a DC separately excited motor, the torque and flux can be controlled separately, and this promotes FVC IM drives to be applied in superior performance industrial servo apparatuses. The implementation of FVC methods requires encoder to detect the rotor-shaft position. This sensor, however, reduces the drive reliability and is unsuitable for hostile environment. Hence, the speed estimation FVC methods, which adopt flux linkage and speed estimator, have been extensively used in replacing of the conventional FVC IM drives [5]. The estimated rotor-shaft speed is obtained by subtracting the slip speed from the synchronous speed for implementation of a speed estimation indirect rotor flux vector controlled (RFVC) IM drive [6]. However, the rotor resistance parameter is required to calculate the slip speed, and this parameter is affected by resistance-temperature variation. The fixed trace algorithm (FTA) is utilized to on-line identify the rotor resistance parameter in this paper [7]. Model reference adaptive system (MRAS) is one of popular estimation methods for speed estimation IM drive [8], which has a number of advantages including simple structure, easy implementation and lower parameters sensitivity. An MRAS synchronous speed estimation scheme based on the reactive power of an IM is developed to attain exact estimation synchronous speed in this research, the proposed estimated synchronous speed approach has the advantages of rapid response, and need not resistance parameters and integrator, and the acquired estimation synchronous speed is unaffected by temperature sensitivity. The content of this paper is organized as follows. The mathematical model of an IM is discussed in Section 2. In Section 3, the synchronous speed adaptation and rotor resistance parameter identification skills applied

the adaptive control approaches to being analyzed and designed. Simulation and experimental testing for the proposed scheme are presented in Section 4. Finally, Section 5 draws the conclusions of this study.

2. **Mathematical Model of an IM.** The stator and rotor voltage vector equations of an IM in the arbitrarily reference coordinate frame are, respectively [9],

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

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

where "j" stands for the imaginary part, 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, $\vec{i}_s^a = i_{ds}^a + j i_{qs}^a$ and $\vec{i}_r^a = i_{dr}^a + j i_{qr}^a$ are the stator, and rotor current vector, respectively, $\vec{v}_s^a = v_{ds}^a + j v_{qs}^a$ is the stator voltage vector, ω is speed of the arbitrarily reference coordinate frame, ω_r is the electric speed of the rotor, $\omega_{sl} = \omega - \omega_r$ is the slip speed, and $p = d/dt$ is the differential operator.

The two-axis voltage state matrix equation of an IM is obtained by rewriting (1) and (2) as

$$p\begin{bmatrix} i_{ds}^a \\ i_{qs}^a \\ i_{dr}^a \\ i_{qr}^a \end{bmatrix} = \frac{1}{L_\sigma}\begin{bmatrix} -R_s L_r & -(\omega L_\sigma + \omega_r L_m^2) & R_r L_m & -\omega_r L_m L_r \\ (\omega L_\sigma + \omega_r L_m^2) & -R_s L_r & \omega_r L_m L_r & R_r L_m \\ R_s L_m & \omega_r L_m L_s & -R_r L_s & -(\omega L_\sigma - \omega_r L_s L_r) \\ -\omega_r L_m L_s & R_s L_m & (\omega L_\sigma - \omega_r L_s L_r) & -R_r L_s \end{bmatrix} \begin{bmatrix} i_{ds}^a \\ i_{qs}^a \\ i_{dr}^a \\ i_{qr}^a \end{bmatrix} + \frac{1}{L_\sigma}\begin{bmatrix} L_r & 0 \\ 0 & L_r \\ -L_m & 0 \\ 0 & -L_m \end{bmatrix}\begin{bmatrix} v_{ds}^a \\ v_{qs}^a \end{bmatrix} \tag{3}$$

where $L_\sigma = L_s - L_m^2/L_r$ is the stator leakage inductance.

The developed electromagnetic torque of an IM is acquired by

$$T_e = \frac{3}{4} P L_m \left(i_{qs}^a i_{dr}^a - i_{ds}^a i_{qr}^a \right) \tag{4}$$

where P is the pole number of the motor. The mechanical equation of the motor is

$$J_m p\omega_{rm} + B_m \omega_{rm} = T_e - T_L \tag{5}$$

where T_L is the load torque, B_m is the viscous friction coefficient, J_m is the inertia of the motor, and ω_{rm} is the mechanical speed of the motor shaft. The speed of the motor shaft is also obtained by

$$\omega_{rm} = \frac{2}{P}\omega_r \tag{6}$$

The simulation model of an IM is established by using (3), (4), (5) and (6).

3. **Speed Estimation Indirect RFVC IM Drive.** In this paper, the speed estimation indirect RFVC IM drive is established, which used the measured motor parameters such as voltages and currents to estimate the rotor flux. The stator and rotor voltage vector equations of an IM in the synchronous reference coordinate frame ($\omega = \omega_e$) are expressed as [9]

$$\vec{v}_s^e = R_s \vec{i}_s^e + j\omega_e \vec{\lambda}_s^e + p\vec{\lambda}_s^e \tag{7}$$

$$0 = R_r \vec{i}_r^e + j\omega_{sl} \vec{\lambda}_r^e + p\vec{\lambda}_r^e \tag{8}$$

where $\vec{\lambda}_s^e = \lambda_{ds}^e + j\lambda_{qs}^e$ and $\vec{\lambda}_r^e = \lambda_{dr}^e + j\lambda_{qr}^e$ are the stator and rotor flux vector, respectively, and ω_e is speed of the synchronous reference coordinate frame. The stator and rotor flux vectors are also expressed by

$$\vec{\lambda}_s^e = L_s\vec{i}_s^e + L_m\vec{i}_r^e \tag{9}$$

$$\vec{\lambda}_r^e = L_r\vec{i}_r^e + L_m\vec{i}_s^e \tag{10}$$

Under RFVC condition, substituting (10) into (8) and setting $\lambda_{qr}^e = 0$, the slip speed and rotor flux are acquired, respectively, as

$$\omega_{sl} = \frac{L_m}{\tau_r\lambda_{dr}^e}i_{qs}^e \tag{11}$$

$$\lambda_{dr}^e = \frac{L_m}{1+\tau_r s}i_{ds}^e \tag{12}$$

where $\tau_r = L_r/R_r$ is the rotor time constant and s is the Laplace operator. The developed electromagnetic torque is obtained as

$$T_e = \frac{3P}{4}\frac{L_m}{L_r}\lambda_{dr}^e i_{qs}^e \tag{13}$$

According to (13), the developed electromagnetic torque is dominated independently by the q-axis stator current i_{qs}^e and the d-axis rotor flux λ_{dr}^e. Owing to that both are orthogonal, the maximum torque current ratio is acquired. Hence, the excellent speed control approach that analogizes a DC separately excited motor drive is attained.

The two-axis voltage state equation of an IM in RFVC scheme is obtained by rewriting Equation (3) as

$$p\begin{bmatrix} i_{ds}^e \\ i_{qs}^e \\ \lambda_{dr}^e \end{bmatrix} = \begin{bmatrix} -\dfrac{R_s}{\sigma L_s} - \dfrac{1-\sigma}{\sigma\tau_r} & \omega_e & \dfrac{1-\sigma}{\sigma\tau_r L_m} \\ -\omega_e & -\dfrac{R_s}{\sigma L_s} & -\dfrac{(1-\sigma)\omega_e}{\sigma L_m} \\ \dfrac{L_m}{\tau_r} & 0 & -\dfrac{1}{\tau_r} \end{bmatrix}\begin{bmatrix} i_{ds}^e \\ i_{qs}^e \\ \lambda_{dr}^e \end{bmatrix} + \frac{1}{\sigma L_s}\begin{bmatrix} v_{ds}^e \\ v_{qs}^e \\ 0 \end{bmatrix} \tag{14}$$

where $\sigma = L_\sigma/L_s$ is the leakage coefficient. Because (14) is a nonlinear-coupling differential equation, the linear control can be attained by applying feed-forward compensation skill. The linear output of the q-axis stator current controller is acquired as

$$v_{qs}^{e'} = \left(K_{pq} + \frac{K_{iq}}{s}\right)\left(i_{qs}^{e^*} - i_{qs}^e\right) \tag{15}$$

where K_{pq} and K_{iq} are the proportional and integration gain constants of the q-axis stator current controller, respectively, and $i_{qs}^{e^*}$ is the q-axis stator current command. The decoupling equation of the second row of (14) is

$$pi_{qs}^e = -\frac{R_s}{\sigma L_s}i_{qs}^e + v_{qs}^{e'} \tag{16}$$

Comparing (16) with the second row of (14), the decoupled q-axis stator current loop is obtained by defining the feed-forward voltage compensation of the q-axis stator current loop as

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

where $\hat{\lambda}_{dr}^e$ is the estimated d-axis rotor flux. Hence, the output of the decoupled q-axis stator current loop is expressed as

$$v_{qs}^{e^*} = \sigma L_s\left(v_{qs}^{e'} + \omega_e i_{ds}^e + \frac{1-\sigma}{\sigma L_m}\omega_e\hat{\lambda}_{dr}^e\right) \tag{17}$$

Similarly, the output of the decoupled d-axis stator current loop is also obtained as

$$v_{ds}^{e*} = \sigma L_s \left(v_{ds}^{e'} - \omega_e i_{qs}^e - \frac{1-\sigma}{\sigma \tau_r L_m} \hat{\lambda}_{dr}^e \right) \tag{18}$$

where $v_{ds}^{e'}$ is the linear output of the d-axis stator current controller.

3.1. **Current-and-voltage serial model rotor-flux estimator.** The fundamental rotor-flux estimator is classified into voltage model and current model, in which the current-model rotor-flux estimator is adopted in low speed region, and the voltage-model rotor-flux estimator is suitable for high speed application [9]. In this research, a serial current-and-voltage model-based rotor-flux estimator is proposed, the estimated rotor flux is obtained by using the measured phase voltages and currents of an IM, and then the proper coordinate transformation is deduced from the estimated rotor flux.

Utilizing (9) and (10), the stator flux vector is derived as

$$\vec{\lambda}_s^e = \sigma L_s \vec{i}_s^e + \frac{L_m}{L_r} \vec{\lambda}_r^e \tag{19}$$

Substituting (19) into (7), the stator voltage vector equation is also rewritten as

$$\vec{v}_s^e = (R_s + j\omega_e \sigma L_s + \sigma L_s p)\, \vec{i}_s^e + \frac{L_m}{L_r}(j\omega_e + p)\vec{\lambda}_r^e \tag{20}$$

Then, setting $\omega_e = 0$ (stationary reference coordinate frame) in (20), the voltage-model rotor-flux estimator is developed as

$$p\hat{\vec{\lambda}}_{rv}^s = \frac{L_r}{L_m} \left[\vec{v}_s^s - (R_s + \sigma L_s p)\vec{i}_s^s \right] \tag{21}$$

where "^" stands for the estimated value.

Then, substituting (10) into (8), the rotor voltage vector equation is rewritten as

$$0 = \frac{1}{\tau_r} \left(\vec{\lambda}_r^e - L_m \vec{i}_s^e \right) + \left[j(\omega_e - \omega_r) + p \right] \vec{\lambda}_r^e \tag{22}$$

And also setting $\omega_e = 0$ in (22), the current-model rotor-flux estimator is developed as

$$p\hat{\vec{\lambda}}_{ri}^s = \frac{L_m}{\tau_r} \vec{i}_s^s - \left(\frac{1}{\tau_r} - j\omega_r \right) \hat{\vec{\lambda}}_{ri}^s \tag{23}$$

The current-and-voltage serial-model rotor-flux estimator is shown in Figure 1, the difference between the output of the estimated current-model rotor-flux and estimated voltage-model rotor-flux is regulated by a proportional-integration (PI) controller, and then the output of this PI controller is the voltage compensation of the voltage-model rotor-flux estimator.

Since $\hat{\lambda}_{dr}^s$ and $\hat{\lambda}_{qr}^s$ are acquired from the current-and-voltage serial-model rotor-flux estimator, and then the proper rotor flux position angle for execution coordinate transformation is estimated as

$$\hat{\theta}_e = \tan^{-1} \left(\frac{\hat{\lambda}_{qr}^s}{\hat{\lambda}_{dr}^s} \right) \tag{24}$$

3.2. **Adaptive estimated synchronous speed scheme.** The reactive power of an IM absorbed from the power source is expressed as

$$Q = i_{ds}^e v_{qs}^e - i_{qs}^e v_{ds}^e \tag{25}$$

Utilizing (25) and (7), the reactive power of an IM is resulted as

$$Q = \omega_e \left(i_{ds}^e \lambda_{ds}^e + i_{qs}^e \lambda_{qs}^e \right) + i_{ds}^e s \lambda_{qs}^e - i_{qs}^e s \lambda_{ds}^e \tag{26}$$

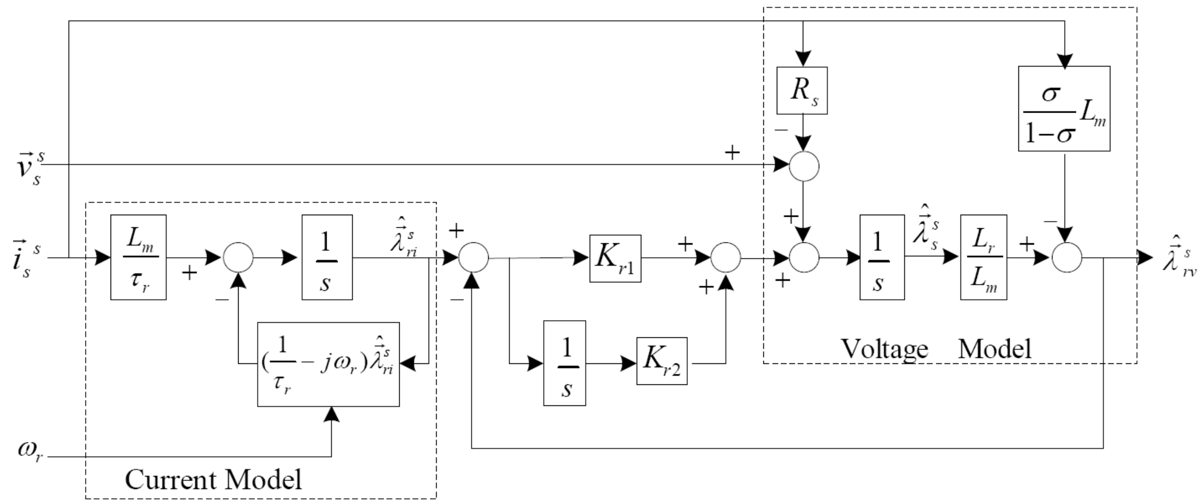

FIGURE 1. Current-and-voltage serial-model rotor-flux estimator

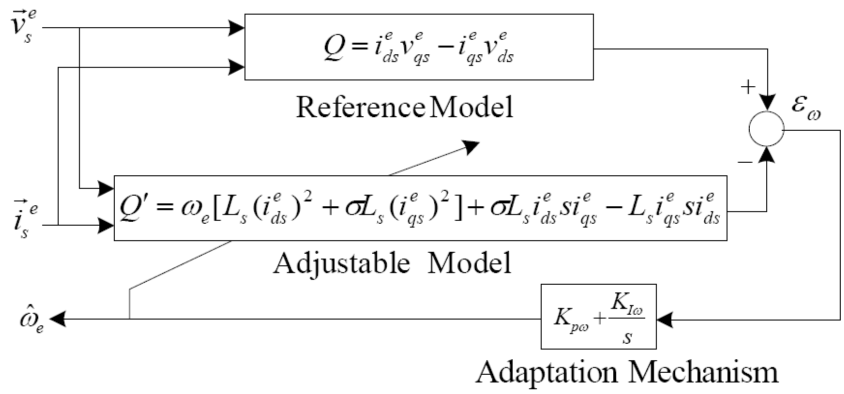

FIGURE 2. Synchronous speed identification based on the reactive power MRAS scheme

In accordance with (19) and (12), the steady state stator flux vector under RFVC condition is also derived as

$$\vec{\lambda}_s^e = \lambda_{ds}^e + j\lambda_{qs}^e = L_s i_{ds}^e + j\sigma L_s i_{qs}^e \tag{27}$$

Substituting (27) into (26), the reactive power of an IM is also rewritten as

$$Q' = \omega_e\left[L_s(i_{ds}^e)^2 + \sigma L_s(i_{qs}^e)^2\right] + \sigma L_s i_{ds}^e s i_{qs}^e - L_s i_{qs}^e s i_{ds}^e \tag{28}$$

According to MRAS theory [10], the reference model does not contain the estimated variable and the adjustable model requires the estimated variable. Hence, selecting (25) and (28) as the reference and adjustable model, respectively, and then the difference between the output of the reference model and adjustable model is disposed by an adaptation mechanism to identify the synchronous speed, the proposed MRAS identified synchronous speed scheme on the basis of the reactive power of an IM is shown in Figure 2.

The proposed MRAS synchronous speed identification skill contains neither stator resistance nor rotor resistance; hence the estimated synchronous speed is unaffected by temperature variation.

3.3. **FTA rotor resistance parameter identification scheme.** The estimated synchronous angular speed $\hat{\omega}_e$ is derived from the reactive power based MRAS identification scheme, and the estimator rotor speed $\hat{\omega}_r$ can be obtained by subtracting the slip speed $\hat{\omega}_{sl}$ from $\hat{\omega}_e$. However, the rotor resistance is necessary for the slip speed calculation, and this resistance is affected by temperature variation. Hence, FTA is adopted to identify the rotor resistance parameter in the proposed system.

In the stationary reference coordinate frame, (8) is rewritten as

$$0 = R_r\vec{i}_r^s - j\omega_r\vec{\lambda}_r^s + s\vec{\lambda}_r^s \tag{29}$$

Utilizing the imaginary part of (29), the rotor speed is expressed as

$$\omega_r = \frac{s\lambda_{qr}^s + R_r i_{qr}^s}{\lambda_{dr}^s} \tag{30}$$

Then, substituting (30) into the real part of (29), the identified rotor resistance parameter can be expressed by the estimated rotor flux and rotor current, that is

$$\hat{R}_r = -\frac{\lambda_{dr}^s s\lambda_{dr}^s + \lambda_{qr}^s s\lambda_{qr}^s}{i_{dr}^s\lambda_{dr}^s + i_{qr}^s\lambda_{qr}^s} \tag{31}$$

FTA is originated from the recursive least square (RLS) approach, the forgetting factor of FTA is updated in accordance with each identification result, and the forgetting factor of RLS is a fixed value; hence, the divergence conditions are avoided during execution identifications in FTA [10], and FTA rotor resistance parameter identification is derived as

$$\hat{R}_r[n+1] = \hat{R}_r[n] - \frac{\gamma\hat{R}_r[n+1]}{1+\gamma\hat{R}_r[n+1]^2}\left(\hat{R}_r[n]\alpha[n+1] - \beta[n+1]\right) \tag{32}$$

where $\alpha[n+1]$ is $-\left(i_{dr}^s\lambda_{dr}^s + i_{dq}^s\lambda_{qr}^s\right)$ that is the denominator of (31), $\beta[n+1]$ is $\lambda_{dr}^s s\lambda_{dr}^s + \lambda_{qr}^s s\lambda_{qr}^s$ which is the numerator of (31), and $\gamma > 0$ is a gain factor.

The block diagram of FTA rotor resistance parameter identification scheme is shown in Figure 3, in which the current and flux vectors of the rotor are disposed by iteration process of FTA, and then the identified rotor resistance parameter is obtained. This identified rotor resistance parameter is delivered to the speed estimator.

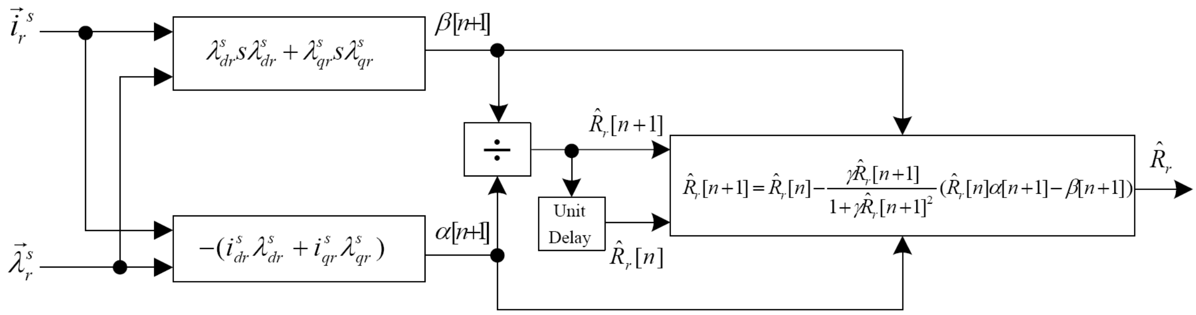

FIGURE 3. FTA rotor resistance parameter identification scheme

The block diagram of the proposed speed estimation adaptive indirect RFVC IM drive that applies MRAS synchronous speed estimation and FTA rotor resistance parameter identification is shown in Figure 4, which includes speed controller, flux controller, d-axis and q-axis stator-current controllers, voltage decoupling, flux estimator, speed estimation, coordinate transformation, MRAS synchronous speed estimation, and FTA rotor resistance parameter on-line identification.

4. **Simulation and Experimental Testing.** The simulated and experimental researches for the proposed rotor resistance parameter on-line identification scheme, which validly improves motor resistance temperature-rising effect of the speed estimation adaptive indirect RFVC IM drive are shown in Figures 5 and 6, in which the rotor resistance is linear increased 0.5Ω from $t = 11$ sec to $t = 12$ sec to simulate resistance temperature-rising effect, and the simulated and measured responses at first three running cycles are shown. Each figure contains four responses: the actual shaft speed, the estimated shaft speed, the rotor flux linkage locus, and the estimated rotor resistance. The simulated and measured

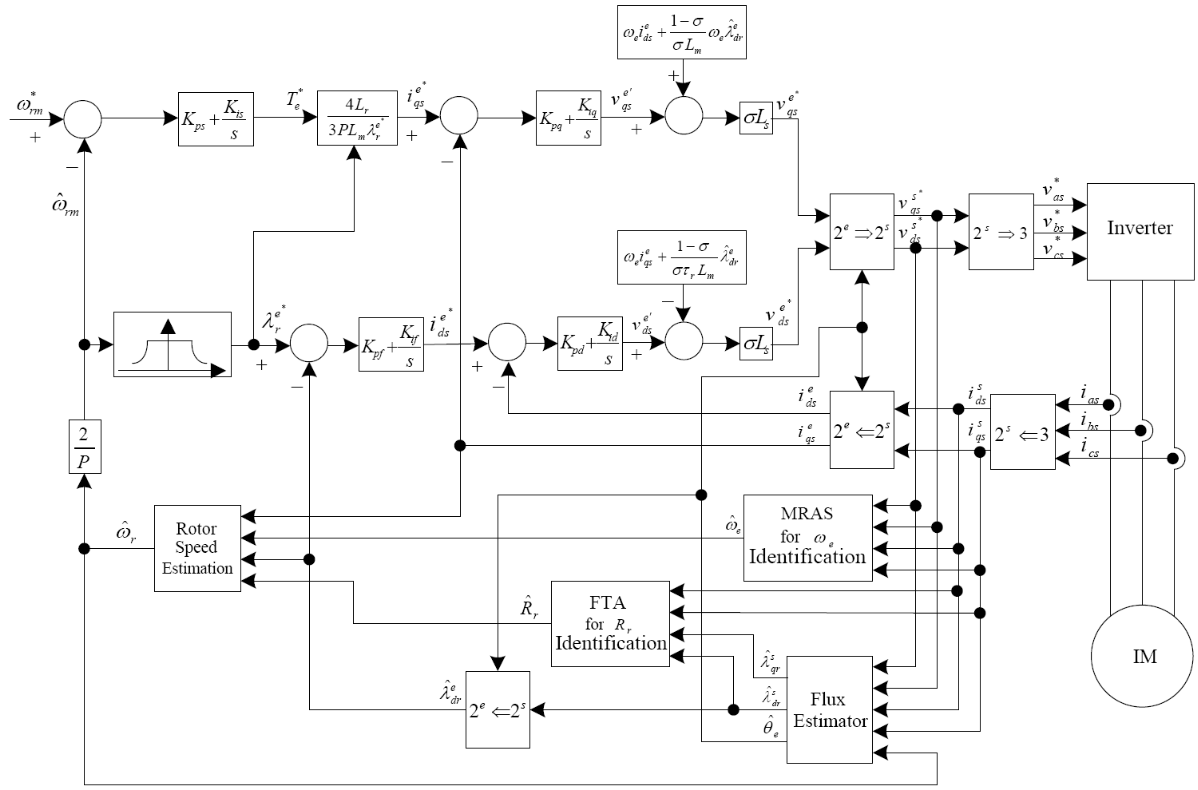

Figure 4. Speed estimation adaptive indirect RFVC IM drive scheme

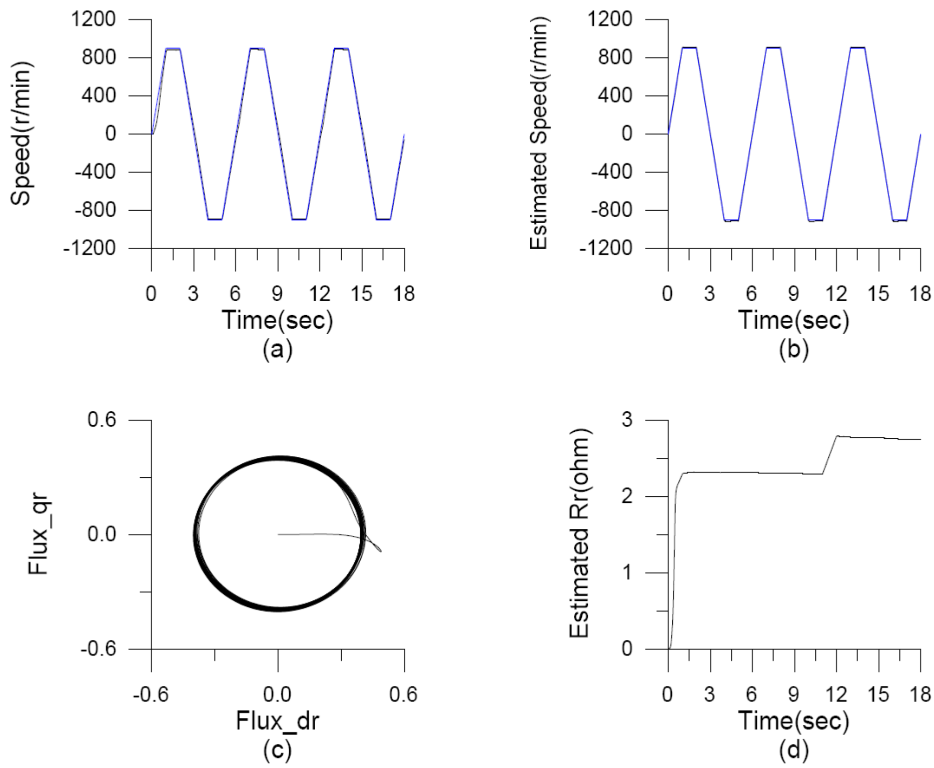

Figure 5. Simulated responses of the proposed system at reversible steady speed command 900 rpm with loading 2 N-m and the rotor resistance is increased 0.5Ω due to temperature-rising at $t = 11$ sec: (a) actual shaft speed, (b) estimated shaft speed, (c) rotor flux linkage locus, (d) estimated rotor resistance.

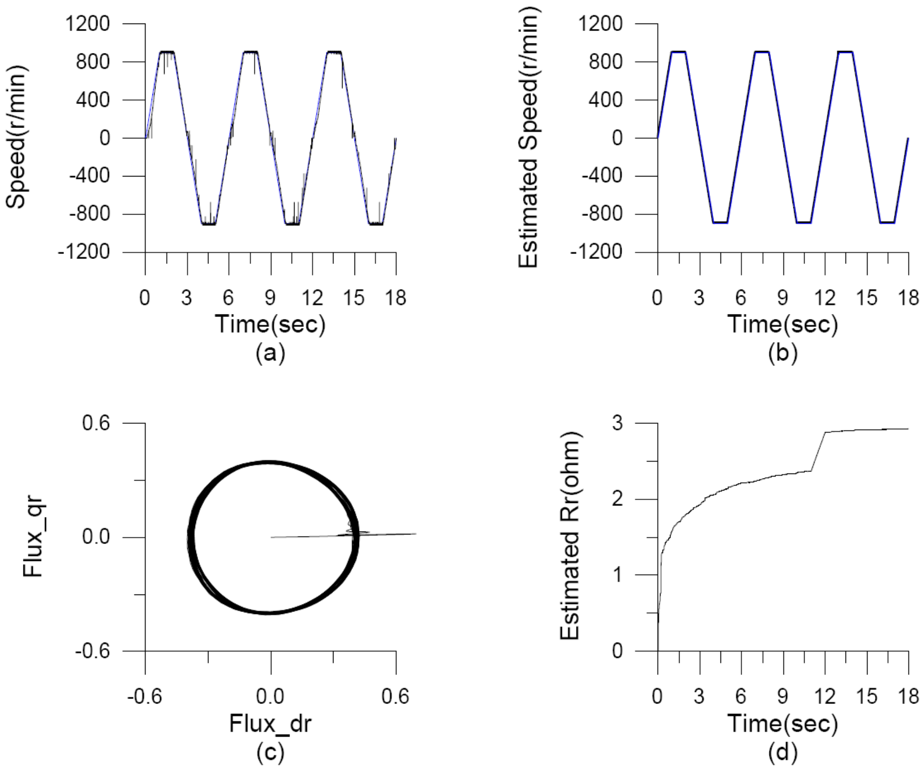

Figure 6. Measured responses of the proposed system at reversible steady speed command 900 rpm with loading 2 N-m and the rotor resistance is increased 0.5Ω due to temperature-rising at $t = 11$ sec: (a) actual shaft speed, (b) estimated shaft speed, (c) rotor flux linkage locus, (d) estimated rotor resistance.

responses with loading 2 N-m for reversible steady speed command ±900 rpm are shown in Figures 5 and 6, respectively.

Based on the simulated and experimental results shown in Figures 5 and 6, the accurate estimation rotor-shaft speed is attained, the correct coordinate transformation is validated by the circle shape rotor flux linkage locus, and the exact rotor resistance parameter adaptation for the resistance-temperature effect is verified, and these confirmed the proposed control strategy has shown that desired performance can be acquired.

5. **Conclusion.** A speed estimation adaptive indirect RFVC IM drive is proposed. The proper synchronous angle position for execution coordinate transformation is derived from the established serial current-and-voltage model-based rotor-flux estimator. The exact estimation synchronous speed is acquired by the designed reactive power based MRAS identification scheme, and FTA skill is applied to effectively modulating rotor resistance-temperature effect. The simulated and experimental responses confirmed the proposed approach to acquire superior performance for speed estimation adaptive indirect RFVC IM drive. Applying the field weakening skill to extending the available operation speed above the rated speed is the future extension research of this system.

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