Speed Estimation Rotor Flux Vector-Controlled Induction Motor Drive with Motor Resistance Parameter Identification

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ABSTRACT
In this study, a full-order flux observer-based speed estimation approach has been used to achieve rotor flux vector control (RFVC) of an induction motor (IM) drive. The RFVC IM drive was established by using stator current and rotor flux. A model reference adaptive system was utilized to identify the stator resistance parameter and the fixed trace algorithm was used to develop a rotor resistance parameter online adjustment scheme. Both proposed adaptive resistance parameter identification approaches can guarantee speed estimation and the coordinate transformation of an RFVC IM is unaffected by the motor resistance–temperature effect. The MATLAB/Simulink toolbox was used to simulate this system and all the control algorithms were realized using a 32 bit Renesas RX62T micro-control chip to generate PWM signals for the power stage to run the motor and to validate these approaches. Both simulation and experimental results verified the effectiveness of the proposed system.

1. Introduction
Modem intelligent factories demand superior motor drive precision to ensure the accuracy and quality of production. While DC motor drives have a high torque–current ratio and are easy to control, they are unsuitable for use in aggressive environments because the brushes and commutators are subject to damage. AC induction motors are cheaper, more robust, require less maintenance, and are suitable for use in dirty or even explosive environments. According to flux vector-controlled (FVC) theory [1], a coupled nonlinear and time-variant mathematical model of an IM can be transformed into torque–current and flux–current components by application of coordinate transformation. Both components are orthogonal and a superior torque–current ratio can be achieved. However, a rotor-shaft position sensor (such as an encoder) is required for implementation of an FVC IM drive, and the presence of such a sensor reduces the robustness of the drive. The development of a speed estimation method for an FVC IM drive is needed and a number of such methods have been proposed: speed identification using an adaptive control system [2–5], speed estimation using a neural network or fuzzy logic approach [6–8], speed adjustment
by flux estimation [9–11], and speed determination from an extended Kalman filter [12–15]. A few of these methods take proper account of deviation in speed estimation accuracy caused by variations in motor parameters.

Under heavy loads for a long time the stator and rotor resistance of an IM will be changed by the resistance–temperature effect, and if the allocation resistance parameters of the controller are not in coincidence with the actual motor resistances, the performance of the FVC IM drive will be degraded. Furthermore, variations in stator resistance also cause incorrect coordinate transformation. The reactive power-based MRAS along with online updating of rotor time constant scheme was used to estimate the rotor speed of a sensorless field-oriented controlled IM drive [16], it does not take account of the coordinate transformation implementation is affected by the stator resistance temperature effect. A fuzzy logic-based stator resistance parameter compensated technique was utilized to improve low-speed performance of the sensorless rotor flux vector-controlled IM drive [17], the estimated slip speed calculation is affected by the rotor resistance variation does not take into consideration.

The fixed-trace algorithm (FTA) method is an adaptive estimation scheme that evolved from the recursive least square (RLS) method, the forgetting factor is updated in FTA according to each estimation procedure and this factor is a constant in the RLS method. FTA is less affected by external noise and the divergence condition is avoided during the estimation procedure [18]. The model reference adaptive system (MRAS) is an adaptive identification approach that has the advantage of simple structure and easy implementation, it comprises both an adjustable model (requires identified parameters) and a reference model (without identified parameters). The difference between the two models through an adaptation mechanism regulates the identified parameters online [19]. In this study, the rotor resistance parameter online modulation was realized by an FTA scheme to acquire an accurate rotor time constant for estimated slip speed calculation, the stator resistance parameter identification was implemented by an MRAS scheme to achieve proper coordinate transformation, and these adaptive resistance parameters estimation approaches guarantees motor resistance unaffected by the resistance–temperature effect.

2. The Rotor Flux Vector-Controlled IM Drive

The stator and rotor voltage vector equations of an IM in the synchronous reference coordinate frame [20] are

\[
\vec{v}_s = R_s \vec{i}_s + j \omega_s \vec{\lambda}_s + p \vec{\lambda}_s
\]

\[0 = R_r \vec{i}_r + j \omega_r \vec{\lambda}_r + p \vec{\lambda}_r\]

where ‘j’ is the imaginary part, \(\vec{v}_s\) is the stator voltage vector, \(\vec{i}_s = i_{ds} + j i_{qs}\), and \(\vec{i}_r = i_{dr} + j i_{qr}\) are the stator and rotor current vectors, \(\vec{\lambda}_s = \lambda_{ds} + j \lambda_{qs}\) and \(\vec{\lambda}_r = \lambda_{dr} + j \lambda_{qr}\) are the stator and rotor flux linkage vectors, \(R_s\) and \(R_r\) are the stator and rotor resistance, \(\omega_s\) is speed of the synchronous reference coordinate frame, \(\omega_r\) is the rotor speed, \(\omega_p = \omega_e - \omega_r\) is the slip speed, and \(p\) is the differentiate operator.

The stator and rotor flux linkage vector are also expressed as

\[
\vec{\lambda}_s = L_s \vec{i}_s + L_m \vec{i}_r
\]

\[
\vec{\lambda}_r = L_r \vec{i}_r + L_m \vec{i}_s
\]

where \(L_s\) and \(L_r\) are the stator and rotor inductance, respectively, and \(L_m\) is the mutual inductance between the stator and rotor.

The developed electromagnetic torque of an IM is

\[
T_e = \frac{3P}{4} L_m (i_{dq} i_{dq} - i_{ds} i_{qr})
\]

where \(P\) is the number of motor poles.

The mechanical equation of the motor is

\[
J_m \ddot{\omega}_m + B_m \dot{\omega}_m = T_e - T_L
\]

where \(J_m\) is the inertia of the motor, \(B_m\) is the viscous friction coefficient, \(T_L\) is the load torque, and \(\omega_{rm} = (2/P) \omega_r\) is the mechanical speed of the motor shaft.

Under an RFVC condition [20], set \(\lambda_{qr} = 0\) in Equation (2), the estimated d-axis rotor flux linkage is derived as

\[
\hat{\lambda}_{dr} = \frac{L_m}{1 + \tau_s s} i_{ds}
\]

where \(s\) is the Laplace operator and ‘\&’ stands for estimated value.

The developed electromagnetic torque of an IM under an RFVC condition is also derived as

\[
T_e = \frac{3P}{4} L_m \hat{\lambda}_{dr} i_{qi}
\]

According to Equation (8), during the constant torque mode operation (below base speed), if the d-axis rotor estimated flux linkage is kept constant, then the developed electromagnetic torque of an IM is dominated by the q-axis stator current, and the maximum torque–current ratio can be acquired.

The two-axis voltage dynamic equations of an IM in the RFVC scheme is [20]
where \( \sigma = 1 - \frac{L_2^2}{L_1 L_r} \) is the leakage inductance coefficient and \( \tau_r = L_1 / R_s \) is the rotor time constant.

Examination of Equation (9) shows it to be coupled nonlinear and time-variant, linear control can be attained by utilization of feed-forward compensation. The linear output of the d-axis stator current controller is acquired as

\[
v'_d = (K_{pd} + K_{id}) (i^*_d - i_d)
\]

where \( K_{pd} \) and \( K_{id} \) are the proportion and integral gain constants of the d-axis stator current controller, respectively, \( i^*_d \) is the d-axis stator current command. The decoupling d-axis voltage dynamic equation of an IM is

\[
pv_d = -(\frac{R_s}{\sigma L_s} + \frac{1 - \sigma}{\sigma \tau_r}) i_d + v'_d
\]

Comparing Equation (11) with the first row of Equation (9), shows the decoupled d-axis stator current loop can be acquired by means of definition of the feed-forward voltage compensation as

\[
\sigma L_s (\omega_c i_q + \frac{1 - \sigma}{\sigma \tau_r L_m} \lambda_{dr})
\]

The output of the decoupled d-axis stator current loop is expressed as

\[
v^*_d = \sigma L_s (v'_d - \omega_c i_q - \frac{1 - \sigma}{\sigma \tau_r L_m} \lambda_{dr})
\]

where \( v^*_d \) is the d-axis stator voltage command. Similarly, the output of the decoupled q-axis stator current loop is also acquired as

\[
v^*_q = \sigma L_q (v'_q + \omega_c i_d + \frac{1 - \sigma}{\sigma L_m} \omega_c \dot{\lambda}_{dr})
\]

where \( v^*_q \) is the q-axis stator voltage command and \( v'_q \) is the linear output of the q-axis stator current controller.

The synchronous position angle for execution of coordinate transformation between the synchronous reference coordinate frame and the stationary reference coordinate frame is

\[
\dot{\theta}_e = \tan^{-1}\left(\frac{\dot{\lambda}_{qr}}{\lambda_{dr}}\right)
\]

### 3. A Speed Estimation Scheme for an RFVC IM Drive

The feedback speed is replaced by a speed estimation signal in the speed estimation RFVC IM drive scheme, and can be derived by the designed rotor flux observer.

#### 3.1. A Full-order Rotor Flux Observer

In the proposed speed estimation RFVC IM drive, the estimated rotor-shaft speed is derived from the estimated rotor flux, and the estimated rotor flux is acquired from the full-order rotor flux observer. The difference between actual stator current and estimated stator current through the observer gain matrix achieve online adjustment of the rotor speed. This also ensures the best performance of the speed estimation RFVC IM drive will be attained.

Substituting Equations (3) and (4) into Equations (2) and (1), in the stationary reference coordinate frame \( (\omega_e = 0) \), and using the variables of the stator current vector and rotor flux linkage vector, the state matrix is given by

![Figure 1. Rotor-shaft speed estimation-based full-order rotor flux observer scheme.](image-url)
4. Estimation of IM Resistance Parameters

The stator and rotor resistance parameters are required for the design of the full-order rotor flux observer. These resistances increase with a rise in temperature when an IM is under heavy load for long periods. If the allocated stator and rotor resistance parameters of the drive are not regulated with respect to temperature variation, the estimated rotor flux linkage and rotor speed will not be accurate.

In the proposed system, the rotor resistance parameter was adjusted by FTA and the stator resistance parameter was identified by utilizing MRAS and this ensured that the drive was not affected by variations in motor resistance.

4.1. Identification of the FTA Rotor Resistance Parameter

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

\[
\vec{v}_s = R_s \vec{i}_s + j \omega_r \vec{\lambda}_r \tag{18}\]

\[
0 = R_r \vec{i}_r + j \omega_r \vec{\lambda}_r \tag{19}\]

According to Equation (15), the full-order rotor flux observer is derived as

\[
P \begin{bmatrix} \frac{1}{\sigma L_s} (R_s + \frac{R_r L_s}{L_r}) & j \omega \frac{L_s}{L_r} - \frac{R_s}{L_r} \\ \frac{1}{\sigma L_r} & -\frac{R_r}{L_r} + j \omega \end{bmatrix} \begin{bmatrix} \tilde{i}_s \\ \tilde{\lambda}_r \end{bmatrix} + \begin{bmatrix} \frac{1}{\sigma L_s} \\ 0 \end{bmatrix} \tilde{v}_s = \begin{bmatrix} \frac{1}{\sigma L_s} \tilde{v} + G(\tilde{i}_s - \tilde{\lambda}_r) \end{bmatrix} \tag{16}\]

where \( G \) is the feedback gain matrix of the observer, \( \tilde{i}_s \) is the estimated stator current which is also the output variable of the observer. In accordance with the developed full-order rotor flux observer, the estimated rotor speed is acquired as

\[
\hat{\omega}_r = -(K_p + \frac{K_i}{s})(\tilde{i}_s - \tilde{\lambda}_r) \tag{17}\]

where \( K_p \) and \( K_i \) are the proportion and integral gain constants of the adaptation mechanism. The proposed rotor-shaft speed estimation based full-order rotor flux observer scheme is shown in Figure 1, where the measured stator voltage vector (\( \vec{V}_s \)) and current vector (\( \vec{i}_s \)) are obtained from an IM using the coordinate transformation 3-phase stationary to 2-axis stationary (\( 2^s \leftrightarrow 3^s \)), the estimated stator current vector \( \tilde{i}_s \) is derived from the developed full-order rotor flux observer, and the difference between \( \tilde{i}_s \) and \( \tilde{\lambda}_r \) is modulated by the observer gain matrix \( G \) to attain the estimated rotor-shaft speed \( \hat{\omega}_r \). Furthermore, the estimated rotor-shaft speed serves as a feedback speed signal to be delivered to the RFVC IM drive.
where \( \alpha[n] = -(\hat{\lambda}_{qr} i_{qr} + \hat{\lambda}_{dr} i_{dr}) \) is the denominator of Equation (22), \( \beta[n] = (\hat{\lambda}_{qr} s\hat{\lambda}_{qr} + \hat{\lambda}_{dr} s\hat{\lambda}_{dr}) \) is the numerator of Equation (22), and \( c > 0 \) is a gain factor. The current and flux linkage vectors of the rotor are used for on-line adjustment of the rotor resistance parameter for the FTA scheme, as shown in Figure 2.

4.2. Identification of the MRAS Stator Resistance Parameter

The proposed MRAS stator resistance parameter identification scheme was developed using the active power of an IM.

The d-axis and q-axis components of Equation (19) are

\[
0 = R_r i_{dr} + \omega_r \lambda_{qr} + p \lambda_{dr}
\]

(20)

\[
0 = R_r i_{qr} - \omega_r \lambda_{dr} + p \lambda_{qr}
\]

(21)

Utilization of Equations (19) and (21), the estimated rotor resistance is derived as

\[
\hat{R}_r = \frac{\hat{\lambda}_{qr} s\hat{\lambda}_{qr} + \hat{\lambda}_{dr} s\hat{\lambda}_{dr}}{(\hat{\lambda}_{qr} i_{qr} + \hat{\lambda}_{dr} i_{dr})}
\]

(22)

According to FTA skill [23], the recursive estimated rotor resistance is expressed as

\[
\hat{R}_r[n] = \hat{R}_r[n-1] + \frac{c\hat{R}_r[n]}{1 + c(\hat{R}_r[n])^2}(a[n]\hat{R}_r[n-1] - \beta[n])
\]

(23)

Figure 4. Block diagram of the proposed speed estimation RFVC IM drive with stator and rotor resistance parameter identification.

Figure 5. Experimental platform of the proposed system.
The d-axis and q-axis components of Equation (18) are
\[ v_{ds} = R_i i_{ds} + s\lambda_{ds} \]  
(24)
\[ v_{qs} = R_i i_{qs} + s\lambda_{qs} \]  
(25)
The active power of an IM absorbed from the power source is

\[ P_s = v_{ds}' i_{ds}' + v_{qs}' i_{qs}' \]  
(26)

Substituting Equations (24) and (25) into Equation (26), the absorbed active power of an IM can also be expressed as
\[ P'_s = \hat{R}_s (i_{ds}' + i_{qs}') + i_{ds}' s\lambda_{ds}' + i_{qs}' s\lambda_{qs}' \]  
(27)

According to MRAS theory [19], Equation (26) is selected as the reference model and Equation (27) as the adjustable model. The difference between the output of the reference and adjustable models through the adaptation mechanism identify the stator resistance parameter. No other parameters or speed signal are needed here, the identified stator resistance is unaffected by speed or other parameters. The advantages of this system are low parameter sensitivity, simple structure, and easy implementation. The MRAS stator resistance parameter identification scheme is as shown in Figure 3.

### Table 1. The parameters of the IM used in the experiment.

| Parameter       | Value       |
|-----------------|-------------|
| Base freq. (Hz) | 60          |
| Base speed (rpm)| 1680        |
| Poles           | 4           |
| \( R_s \) (Ω)   | 2.85        |
| \( R_r \) (Ω)   | 2.3433      |
| \( L_s \) (H)   | 0.1967      |
| \( L_r \) (H)   | 0.1967      |
| \( L_m \) (H)   | 0.1886      |
| \( J_m \) (Nt−s²/m) | 0.009 |
| \( B_m \) (Nt−s²/m²) | 0.00825 |

*Figure 6. Simulated responses of the RFVC IM drive with 2 N-m load at high steady-state speed command 300 rpm, where motor resistance varies with a rise in temperature over 3.5 ≤ t ≤ 7.5 s.*
experimental platform of the proposed system, shown in Figure 5, includes an RX62T control card, power stage, the 3-phase IM, a DC power supply, a D/A data acquisition card, and an oscilloscope. In a running cycle, the speed command is as follows: low speed (200 rpm) acceleration to higher speed (300 rpm or 1800 rpm) from $t = 0$ to $t = 1.5$ s; high steady-state speed operation over $1.5 \leq t \leq 3$ s; high speed braking operation to low speed over $3 \leq t \leq 4.5$ s; low steady-state speed operation over $4.5 \leq t \leq 6$ s. The simulated and measured responses of the first two running cycles are shown in Figures 6–9.

5. Simulation and Experimental

The block diagram of the proposed speed estimation RFVC IM drive with stator and rotor resistance parameter identification is shown in Figure 4, which includes MRAS stator resistance parameter identification, FTA rotor resistance parameter online tuning, the speed controller, flux controller, q-axis and d-axis stator current controllers, synchronous position angle calculation, voltage decoupling, coordinate transformation, and the full-order rotor flux observer.

A standard 3-phase, 220 V, 0.75 kW, Δ-connected, squirrel-cage IM was used in the experiments to confirm the effectiveness of the proposed speed estimation drive, the parameters of the IM are listed in Table 1. The experimental platform of the proposed system, shown in Figure 5, includes an RX62T control card, power stage, the 3-phase IM, a DC power supply, a D/A data acquisition card, and an oscilloscope. In a running cycle, the speed command is as follows: low speed (200 rpm) acceleration to higher speed (300 rpm or 1800 rpm) from $t = 0$ to $t = 1.5$ s; high steady-state speed operation over $1.5 \leq t \leq 3$ s; high speed braking operation to low speed over $3 \leq t \leq 4.5$ s; low steady-state speed operation over $4.5 \leq t \leq 6$ s. The simulated and measured responses of the first two running cycles are shown in Figures 6–9. Each figure contains six responses: (a) Command speed (dotted line) and actual shaft speed (solid line), (b) command speed (dotted line) and estimated actual shaft speed.
The steady-state percentage errors of the estimation rotor speed, estimation rotor resistance, and estimation stator resistance are about 2.5, 4.5, and 4%, respectively. Based on the simulated and measured results for different operation conditions as shown in Figures 6–9, the estimation of rotor-shaft speed and electromagnetic torque attained better response, the validity of the identified motor resistance–temperature effect was confirmed, the circular shape of the estimated rotor flux linkage locus verified the estimated rotor flux position angle for execution coordinate transformation to be exact. Hence, the proposed speed estimations RFVC IM drive with stator and rotor resistance parameter identification showed that the desired performance could be achieved.

Figure 8. Measured responses of the RFVC IM drive with 2 N-m load at high steady-state speed command 300 rpm, where stator resistance was increased by 1Ω at 6 s.

(solid line), (c) actual rotor resistance (dotted line) and estimated rotor resistance (solid line), (d) actual stator resistance (dotted line) and estimated stator resistance (solid line), (e) estimated electromagnetic torque, (f) rotor flux linkage locus. The simulated responses with 2 N-m load and motor resistance is varied with rising temperature over 3.5 ≤ t ≤ 7.5 s for high steady-state speed command at 300 rpm and 1800 rpm are shown in Figures 6 and 7. The measured responses with 2 N-m load and the stator resistance is increased by 1Ω at 6 s for high steady-state speed command at 300 rpm and 1800 rpm are shown in Figures 8 and 9. The percentage error states for the estimation rotor speed, estimation rotor resistance, and estimation stator resistance are shown in Figures 10–12, respectively.
Figure 9. Measured responses of the RFVC IM drive with 2 N-m load at high steady-state speed command 1800 rpm, where stator resistance was increased by 1Ω at 6 s.

Figure 10. Estimation rotor speed percentage error state.

Figure 11. Estimation rotor resistance percentage error state.
6. Conclusions

A rotor-shaft speed online estimation scheme based on a full-order rotor flux observer has been proposed for speed estimation of an RFVC IM drive. To function correctly the flux observer only needs to know the output difference between the estimated and actual stator current. This difference allows the adaptation mechanism to determine the estimated rotor-shaft speed. The MRAS stator resistance parameter identification and FTA rotor resistance parameter modulation schemes that guarantee the designed full-order rotor flux observer is unaffected by motor resistance–temperature variation. This is also validated by the attainment of correct estimated rotor flux position angle for proper coordinate transformation. The effectiveness of the proposed approach was confirmed by both simulation and experiment at different steady-state speed commands.

Disclosure Statement

No potential conflict of interest was reported by the authors.

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