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Speed Sensorless Fault-Tolerant Drive System of 3-Phase Induction Motor Using Switching Extended Kalman Filter

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Abstract

Speed sensorless vector control of 3-phase induction motor under open-phase fault (faulty 3-phase induction motor) based on Indirect Rotor Field-Oriented Control (IRFOC) is proposed in this paper. To ensure high performance FOC of induction motor drives, the estimation of the rotor speed is necessary. However, the algorithm used to estimate the rotor speed for a 3-phase induction motor cannot be used directly for a faulty 3-phase induction motor. This is because the faulty induction motor model is different from the healthy 3-phase induction motor. To overcome this problem, in this paper a new switching Extended Kalman Filter (EKF) is proposed to update online the rotor speed. The proposed algorithm can be used for estimation of rotor speed in both healthy and faulty conditions. MATLAB simulation results are carried out to show the capability of the proposed drive system. The results show the activity of the proposed method at wide range speed operation.

Keywords: *3-phase induction motor, IRFOC, EKF, rotor speed estimation, fault-tolerant drive system*

1. Introduction

Recently, 3-phase induction motors have received a greet attention for drive applications. 3-phase induction motor has several advantages for example high reliability and robustness. Open-phase fault is one of familiar failures in the 3-phase induction motor stator windings. Mechanical shaking, opening of coils, and etc. causes this fault. In the existing literature, different methods have been presented to detect stator winding faults in induction motors [1-3]. All of these techniques provide immediate open stator winding detection and are supposed in this study.

Field-Oriented Control (FOC) method for induction motors are broadly adopted to obtain high dynamic performance in drive systems. In the fault condition (open-phase fault), if a conventional FOC technique is applied to the faulty induction motor, oscillations in the motor torque and speed can be observed [4-10]. Several methods have been conducted to study on the vector control of faulty 3-phase or 2-phase induction motor based on FOC [4-14]. It was shown in [4-14] that by using some modifications to the conventional FOC for 3-phase induction motor, the FOC of unbalanced or faulty induction motor is possible.

FOC method requires the acknowledgment of the motor speed; however, the speed sensors have some drawbacks such as system complexity, machine cost and size. Different algorithms are studied for speed sensorless of the 2-phase induction motors (single-phase induction motor with two windings) [15-19]. In Refs [15, 16], Model Reference Adaptive System (MRAS) have been proposed for rotor speed estimation in 2-phase induction motors. This technique does not have excellent results in the low speed range and also sensitive to the resistance variations. In [8], [17-19], speed sensorless vector control of 2-phase induction motor based on motor model has been proposed. The suggested techniques for rotor speed estimation using a motor model fed by stator quantities are parameter dependent; consequently, parameter errors can result in the performance of speed control.

Extended Kalman Filter (EKF) is one of the most useful algorithms which is used for parameters estimation for example speed, flux, load and resistance in electrical machines. This

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algorithm is a form of observer that considers the nonlinearity of the machine model filters the system and measured noises and estimates the states variables [20]. In this research, a contribution to the issue of speed sensorless Indirect Rotor Field-Oriented Control (IRFOC) of fault-tolerant drive system for 3-phase induction motor based on [6] is proposed. The published paper [6] investigates the IRFOC of fault-tolerant drive system for 3-phase induction motor. In this paper, an EKF is used to estimate the motor speed for IRFOC scheme. The proposed switching EKF in this paper can be employed for estimation of induction motor speed in both healthy and faulty conditions. Finally, the dynamics and the performance characteristics of the proposed drive system are evaluated and verified using MATLAB software. Promising results showed that the switching EKF based sensorless vector control of fault-tolerant system for 3-phase induction motor drive with a good performance is achievable at low and high speed operations.

2. d-q Model of Induction Motor

The dynamic model for induction motor in a stationary reference frame (superscript ‘‘*s*’’) can be described by the following equations [6]:

$$v_{ds}^{s} = r_s i_{ds}^{s} + \frac{d\lambda_{ds}^{s}}{dt} \tag{1}$$

$$v_{qs}^{s} = r_s i_{qs}^{s} + \frac{d\lambda_{qs}^{s}}{dt} \tag{2}$$

$$0 = r_r i_{dr}^{s} + \frac{d\lambda_{dr}^{s}}{dt} + \omega_r \lambda_{qr}^{s} \tag{3}$$

$$0 = r_r i_{qr}^{s} + \frac{d\lambda_{qr}^{s}}{dt} - \omega_r \lambda_{dr}^{s} \tag{4}$$

$$\tau_e = \frac{P}{2}\left(M_q i_{qs}^{s} i_{dr}^{s} - M_d i_{ds}^{s} i_{qr}^{s}\right) \tag{5}$$

$$\tau_e - \tau_l = \frac{2}{P}\left(J\frac{d\omega_r}{dt} + F\omega_r\right) \tag{6}$$

Where,

$$\lambda_{ds}^{s} = L_{ds} i_{ds}^{s} + M_d i_{dr}^{s} \tag{7}$$

$$\lambda_{qs}^{s} = L_{qs} i_{qs}^{s} + M_q i_{qr}^{s} \tag{8}$$

$$\lambda_{dr}^{s} = M_d i_{ds}^{s} + L_r i_{dr}^{s} \tag{9}$$

$$\lambda_{qr}^{s} = M_q i_{qs}^{s} + L_r i_{qr}^{s} \tag{10}$$

In (1)-(10), v^s_{ds}, v^s_{qs} are the stator d-q axes voltages i^s_{ds}, i^s_{qs} are the stator d-q axes currents i^s_{dr}, i^s_{qr} are the rotor d-q axes currents λ^s_{ds}, λ^s_{qs} are the stator d-q axes fluxes and λ^s_{dr} and λ^s_{qr} are the rotor d-q axes fluxes in the stator reference frame. r_s and r_r are the stator and rotor resistances, respectively. L_{ds}, L_{qs}, L_r, M_d and M_q denote the stator, the rotor self and mutual inductances. ω_r is the motor speed. τ_e and τ_l are electromagnetic torque and load torque and P, J and F are the number of poles, moment of inertia and viscous friction coefficient respectively. It can be noted that, equations (1)-(10) are the general forms of induction motor equations. By substituting M_d=M_q=M=3/2L_{ms} and L_{ds}=L_{qs}=L_s=L_{ls}+3/2L_{ms} in (1)-(10), we can obtain the equations of healthy 3-phase induction motor and by substituting M_d=3/2L_{ms}, M_q=√3/2L_{ms}, L_{ds}=L_{ls}+3/2L_{ms} and L_{qs}=L_{ls}+1/2L_{ms} in (1)-(10), equations of 3-phase induction motor under open-phase fault are obtained [6].

3. Fault-tolerant Drive System of 3-phase Induction Motor

Because of the unbalanced structure of faulty 3-phase induction motor model ($M_d \neq M_q$ and $L_{ds} \neq L_{qs}$), classical FOC algorithm for healthy 3-phase induction motor cannot be employed for faulty motor. To solve this problem, similar technique as proposed in [6] will be used here. In paper [6], based on using transformation matrices, a new method for RFOC of faulty or unbalanced induction motors was proposed. These transformation matrices are given by (11) and (12).

$$\begin{bmatrix} i_{ds}^{e} \\ i_{qs}^{e} \end{bmatrix} = \left[T_{is}^{e}\right] \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} = \begin{bmatrix} \frac{M_d}{M_q}\cos\theta_e & \sin\theta_e \\ -\frac{M_d}{M_q}\sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} \tag{11}$$

$$\begin{bmatrix} v_{ds}^{e} \\ v_{qs}^{e} \end{bmatrix} = \left[T_{vs}^{e}\right] \begin{bmatrix} v_{ds}^{s} \\ v_{qs}^{s} \end{bmatrix} = \begin{bmatrix} \frac{M_q}{M_d}\cos\theta_e & \sin\theta_e \\ -\frac{M_q}{M_d}\sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} v_{ds}^{s} \\ v_{qs}^{s} \end{bmatrix} \tag{12}$$

In (11) and (12), θ_e is the angle between the stationary reference frame and the rotor field-oriented reference frame. Moreover, the superscript "*e*" indicates the variables are in the rotating reference frame. In [6], it was shown by using these transformation matrices, the unbalanced equations of faulty 3-phase induction motor change into balanced equations. Using (11) and (12) and by considering $L_{ds}/L_{qs}=(M_d/M_q)^2$, RFOC equations of 3-phase induction motor under open-phase fault are obtained as following equations (in RFOC technique, the rotor flux vector is aligned with d-axis; $\lambda_{dr}^{e}=|\lambda_r|$, $\lambda_{qr}^{e}=0$):

Stator voltage equations:

$$\begin{aligned} \left[T_{vs}^{e}\right]\begin{bmatrix} v_{ds}^{s} \\ v_{qs}^{s} \end{bmatrix} &= \left[T_{vs}^{e}\right]\begin{bmatrix} r_s + L_{ds}\frac{d}{dt} & 0 \\ 0 & r_s + L_{qs}\frac{d}{dt} \end{bmatrix}\left[T_{is}^{e}\right]^{-1}\left[T_{is}^{e}\right]\begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} \\ &+ \left[T_{vs}^{e}\right]\begin{bmatrix} M_d\frac{d}{dt} & 0 \\ 0 & M_q\frac{d}{dt} \end{bmatrix}\left[T_{s}^{e}\right]^{-1}\left[T_{s}^{e}\right]\begin{bmatrix} i_{dr}^{s} \\ i_{qr}^{s} \end{bmatrix} \end{aligned} \tag{13}$$

Rotor voltage equations:

$$\begin{aligned} \left[T_{s}^{e}\right]\begin{bmatrix} 0 \\ 0 \end{bmatrix} &= \left[T_{s}^{e}\right]\begin{bmatrix} M_d\frac{d}{dt} & \omega_r M_q \\ -\omega_r M_d & M_q\frac{d}{dt} \end{bmatrix}\left[T_{is}^{e}\right]^{-1}\left[T_{is}^{e}\right]\begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} \\ &+ \left[T_{s}^{e}\right]\begin{bmatrix} r_r + L_r\frac{d}{dt} & \omega_r L_r \\ -\omega_r L_r & r_r + L_r\frac{d}{dt} \end{bmatrix}\left[T_{s}^{e}\right]^{-1}\left[T_{s}^{e}\right]\begin{bmatrix} i_{dr}^{s} \\ i_{qr}^{s} \end{bmatrix} \end{aligned} \tag{14}$$

Torque equation:

$$\begin{aligned}\tau_e &= \frac{P}{2}(M_q i_{qs}^s i_{dr}^s - M_d i_{ds}^s i_{qr}^s) \\ &= \frac{P}{2}\begin{bmatrix} i_{dr}^s & i_{qr}^s \end{bmatrix}\begin{bmatrix} 0 & M_q \\ -M_d & 0 \end{bmatrix}\begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} \\ &= \left(\frac{P}{2}\begin{bmatrix} i_{dr}^s & i_{qr}^s \end{bmatrix}\left[T_s^e\right]^T\left(\left[T_s^e\right]^{-1}\right)^T \right. \\ &\left. \begin{bmatrix} 0 & M_q \\ -M_d & 0 \end{bmatrix}\left[T_{ns}^e\right]^{-1}\left[T_{ns}^e\right]\begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} \right)\end{aligned} \tag{15}$$

Where: $\left[T_s^e\right] = \begin{bmatrix} \cos\theta_e & \sin\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix}$, after simplifying (13)-(15), following equations are obtained:

$$\omega_e = \omega_r + \frac{M_q i_{qs}^e}{T_r|\lambda_r|} \tag{16}$$

$$|\lambda_r| = \frac{M_q i_{ds}^e}{1 + T_r d/dt} \tag{17}$$

$$\tau_e = \frac{P}{2}\frac{M_q}{L_r}|\lambda_r| i_{qs}^e \tag{18}$$

$$v_{ds}^e = v_{ds}^d + v_{ds}^{ref} + v_{ds}^{-e} \tag{19}$$

$$v_{qs}^e = v_{qs}^d + v_{qs}^{ref} + v_{qs}^{-e} \tag{20}$$

Where,

$$v_{ds}^d = -\omega_e i_{qs}^e (L_{qs} - \frac{M_q^2}{L_r}) + (\frac{M_q}{L_r})(\frac{M_q i_{ds}^e - |\lambda_r|}{T_r}) \tag{21}$$

$$v_{qs}^d = \omega_e i_{ds}^e (L_{qs} - \frac{M_q^2}{L_r}) + \omega_e M_q \frac{|\lambda_r|}{L_r} \tag{22}$$

$$v_{ds}^{ref} = (\frac{r_s M_q^2 + r_s M_d^2}{2M_d^2}) i_{ds}^e + (L_{qs} - \frac{M_q^2}{L_r})\frac{di_{ds}^e}{dt} \tag{23}$$

$$v_{qs}^{ref} = (\frac{r_s M_q^2 + r_s M_d^2}{2M_d^2}) i_{qs}^e + (L_{qs} - \frac{M_q^2}{L_r})\frac{di_{qs}^e}{dt} \tag{24}$$

$$v_{ds}^{-e} = \left(\frac{r_s M_q^2 - r_s M_d^2}{2M_d^2}\right)\left(\cos 2\theta_e i_{ds}^e - \sin 2\theta_e i_{qs}^e\right) \tag{25}$$

$$v_{qs}^{-e} = \left(\frac{r_s M_q^2 \quad r_s M_d^2}{2M_d^2}\right)\left(\quad \sin 2\theta_e i_{ds}^e \quad \cos 2\theta_e i_{qs}^e\right) \tag{26}$$

Where, $T_r=L_r/r_r$ *is* rotor time constant. As mentioned before, by employing transformation matrices (equations (11) and (12)), RFOC equations of 3-phase induction motor under open-phase fault become like RFOC of healthy 3-phase induction motor. It can be seen that the only difference between these equations and healthy 3-phase induction motor equations is that for healthy 3-phase induction motor, we have r_s, $M=3/2L_{ms}$ and $L_s=L_{ls}+3/2L_{ms}$ [21], but for faulty 3-phase induction motor: $r_s=(r_sM_q^2+r_sM_d^2)/2M_d^2=2/3r_s$, $M=M_q=\sqrt{3/2}L_{ms}$, $L_s=L_{qs}=L_{ls}+1/2L_{ms}$ and we have: v_{ds}^{-e}, v_{qs}^{-e}.

4. Speed Estimation in the Fault-tolerant Drive System Based on EKF

To improve the performance of the presented controller, in this paper, estimation of rotor speed using EKF is done. The conventional EKF for motor speed estimation in 3-phase induction motors cannot be employed for faulty motor because of the different models that are used to describe a balanced and unbalanced 3-phase induction motor. In this research, an EKF with two different parameters is proposed to estimate the motor speed for both healthy and faulty 3-phase induction motor in associated with IRFOC. The changes of these parameters are done after the fault detection and by a switch. In the proposed switching EKF and for healthy motor, $M_d=M_q=3/2L_{ms}$ and $L_{ds}=L_{qs}=L_{ls}+3/2L_{ms}$ are used in the EKF algorithm. When the fault happens, the values are substituted with, $M_d=3/2L_{ms}$, $M_q=\sqrt{3/2}L_{ms}$, $L_{ds}=L_{ls}+3/2L_{ms}$ and $L_{qs}=L_{ls}+1/2L_{ms}$.

For the purpose of motor speed estimation, the stator d-q axes currents (i^s_{ds}, i^s_{qs}), the stator d-q axes fluxes (λ^s_{ds}, λ^s_{qs}), motor speed (ω_r) and load torque (τ_l) are chosen as the state variables. Using these state variables, it is possible to express the state space model of the induction motor in the form of Equation (27) and (28):

$$\dot{x} = Ax + Bu \tag{27}$$

$$y = Cx \tag{28}$$

Equation (27) and (28), in the form of discrete state equations can be re-written as following equations:

$$x(n+1) = \underbrace{(I + Adt)}_{A(n)}x(n) + \underbrace{(Bdt)}_{B(n)}u(n) + w(n) \tag{29}$$

$$y(n) = C(n)x(n) + v(n) \tag{30}$$

In these equations, *A*, *B* and *C* are the system, input and output matrices respectively. *x*, *y* and *u* are the system state matrix, system output matrix and system input matrix respectively. *w*(*n*) and *v*(*n*) is the system noise and measurement noise. The matrices *x*(*n*), *y*(*n*) and *u*(*n*) are given as:

$$x(n) = \begin{bmatrix} i_{ds}(n) & i_{qs}(n) & \lambda_{ds}(n) & \lambda_{qs}(n) & \omega_r(n) & \tau_l(n) \end{bmatrix}^T \tag{31}$$

$$u(n) = \begin{bmatrix} v_{ds}(n) & v_{qs}(n) \end{bmatrix}^T \tag{32}$$

$$y(n) = \begin{bmatrix} i_{ds}(n) & i_{qs}(n) \end{bmatrix}^T \tag{33}$$

Moreover, The matrices of $A(n)$, $B(n)$ and $C(n)$ in equations (29) and (30) are given as follows:

$$A(n)=\begin{bmatrix} 1-\frac{1}{k_1}\left(r_s+\frac{M_d^2 r_r}{L_r^2}\right)dt & 0 & \frac{M_d r_r}{k_1 L_r^2}dt & \frac{M_d r_r}{k_1 L_r}dt & 0 & 0 \\ 0 & 1-\frac{1}{k_2}\left(r_s+\frac{M_q^2 r_r}{L_r^2}\right)dt & \frac{-M_q r_r}{k_2 L_r}dt & \frac{M_q r_r}{k_2 L_r^2}dt & 0 & 0 \\ \frac{M_d r_r}{L_r}dt & 0 & 1-\frac{r_r}{L_r}dt & -r_r dt & 0 & 0 \\ 0 & \frac{M_q r_r}{L_r}dt & r_r dt & 1-\frac{r_r}{L_r}dt & 0 & 0 \\ \frac{1.5P^2 M_d \lambda_{qr}^s}{2JL_r}dt & \frac{1.5P^2 M_q \lambda_{dr}^s}{2JL_r}dt & 0 & 0 & 1 & \frac{1}{J} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (34)$$

$$B(n)=\begin{bmatrix} \frac{1}{k_1}dt & 0 \\ 0 & \frac{1}{k_2}dt \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad (35)$$

$$C(n)=\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (36)$$

Where:

$$k_1 = L_{ds} - \frac{M_d^2}{L_r}$$
$$k_2 = L_{qs} - \frac{M_q^2}{L_r} \quad (37)$$

The steps of the EKF algorithm can be formulated as Equation (37)-(40) [20]:
1-Estimation of the Error Covariance Matrix:

$$P(n+1)=\Gamma(n)P(n)\Gamma^T(n)+Q \quad (38)$$

2-Computation of Kalman Filter Gain:
$$K(n)=P(n+1)\Delta^T(n)[\Delta(n)P(n+1)\Delta(n)+R]^{-1} \quad (39)$$

3-Update of the Error Covariance Matrix:
$$P(n)=[1-K(n)\Delta(n)]P(n+1) \quad (40)$$

4-State Estimation:
$$\hat{x}(n+1)=\hat{x}(n)+K(n)[z(n+1)-h(\hat{x}(n+1))] \quad (41)$$

In these equations, *Q* and *R* are the covariance matrices of the noises. The initial values of matrices *P*, *Q* and *R* for estimation of rotor speed are obtained from the trial and error process. Based on (16)-(26) and (31)-(41), the structure of the fault-tolerant drive system based on IRFOC with the proposed switching EKF-based rotor speed estimator is as Figure 1.

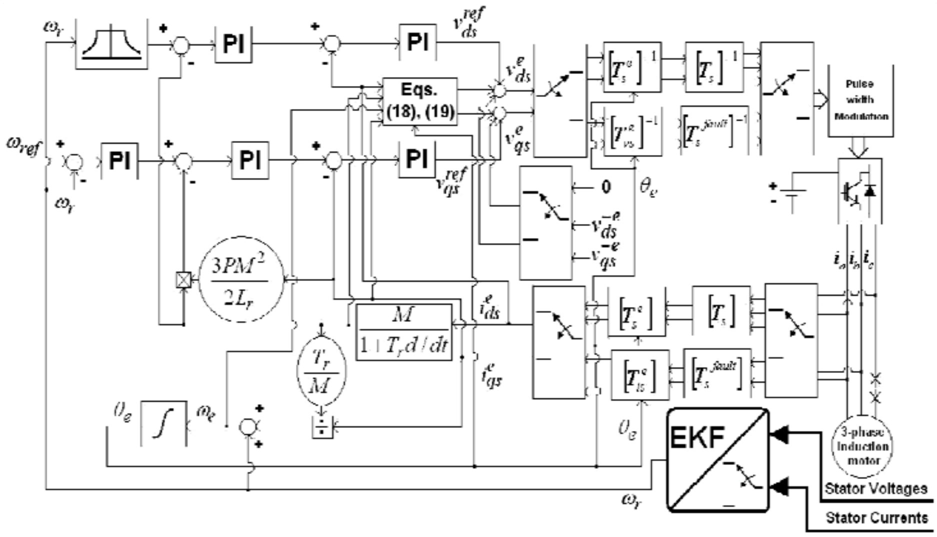

Figure 1. Scheme of the Fault-tolerant Drive System Based on IRFOC with the Proposed Switching EKF-based Rotor Speed Estimator

In Figure 1:

$$[T_s]=\sqrt{\frac{2}{3}}\begin{bmatrix} +1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \quad (41)$$

$$[T_s^{fault}]=\frac{\sqrt{2}}{2}\begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \quad (42)$$

5. Simulation Results

Simulation works are carried out on the 3-phase induction motor to prove the effectiveness of the proposed drive system. The simulations are performed using the MATLAB software. The parameters of the 3-phase induction motor are listed as follows:

$$v=125V\ ,\ f=50HZ\ ,\ P=4\ ,\ r_s=20.6\Omega\ ,\ r_r=19.15\Omega$$
$$L_{ls}=0.0814\ ,\ L_{lr}=0.0814H\ ,\ L_{ms}=0.851H\ ,\ power=475W$$

To evaluate the proposed drive system performance, two different cases are simulated:

Case (1): comparison between classical FOC and fault-tolerant dive system based on Figure 1 and without rotor speed estimator

In Figure 3, the reference speed is assumed as Figure 2. The load torque is increased steeply from 0N.m to 0.5N.m at t=1.5s and removed at t=2s. A phase cut-off fault is introduced at the starting (t=0s). Based on Figure 3, the simulation results of the presented controller show that the actual speed can follow and trace well the reference speed even under load. Compared to the classical FOC, the motor speed of the proposed scheme contains very low ripples. The results ensure the high performance of the presented fault-tolerant drive system at wide range speed operation.

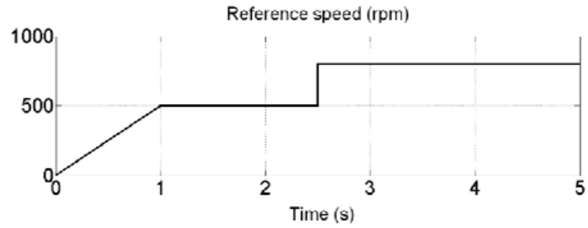

Figure 2. Variation of Rotor Speed

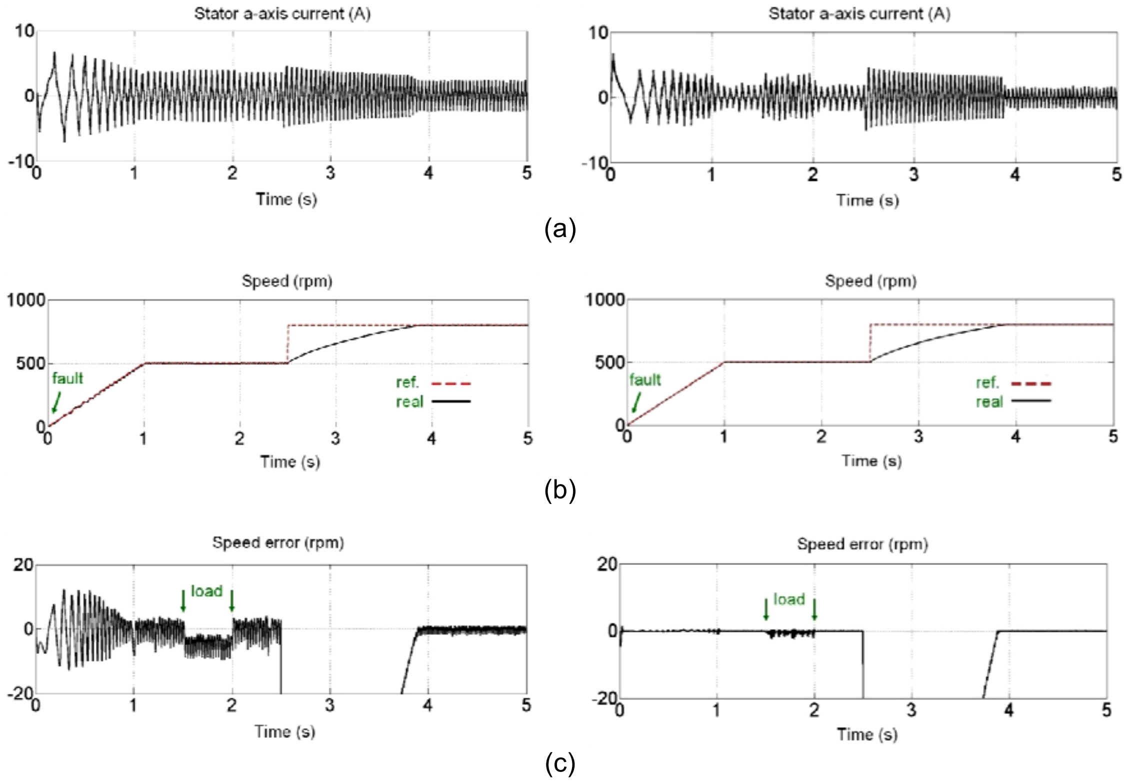

Figure 3. Simulation Results of the Comparison between Classical FOC (left) and Fault-tolerant Dive System Based on Figure 1 (right) and without Rotor Speed Estimator, (a) Stator current, (b) Speed response, (c) Speed error

Case (2): fault-tolerant dive system based on Figure 1 and with rotor speed estimator

The responses of the stator currents, electromagnetic torque, actual and estimated rotor speed and speed error (the error between reference and actual speed) of the proposed speed sensorless IRFOC of fault-tolerant drive system are shown in Figure 4. In this Figure, a phase cut-off fault is introduced at t=0.3s (from t=0s to t=0.3s, the induction motor work in the balanced condition then at t=0.3s, one of the stator phases (phase “c”) is opend). As shown, the phase current waveform is enlarged to show that the induction motor current is nearly sinusoidal in both healthy and faulty conditions. It is shown that the estimated and actual speeds are identical. Moreover, Figure 4 illustrates that the electromagnetic torque waveforms contain low ripples even at the faulty mode. In addition, the error between the reference and actual rotor speed is very low. The results of the proposed controller shows that the actual and reference speeds are aligned and can track well the trajectory of the reference speed.

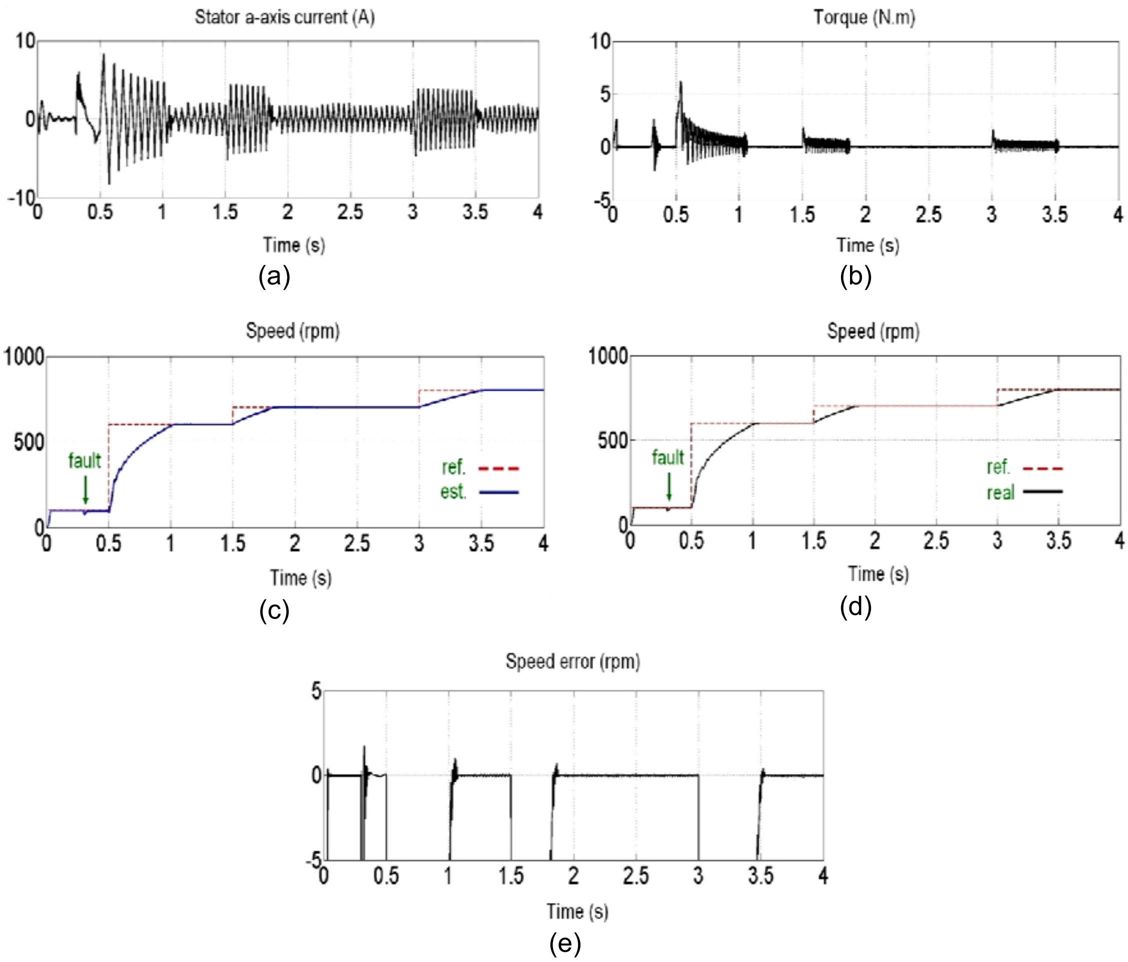

Figure 4. Simulation Results of the Fault-tolerant Dive System Based on Figure 1 and with Rotor Speed Estimator, (a) Stator current, (b) Torue response (b) Speed response, (c) Speed response, (d) Speed error

6. Conclusion

In this paper, speed sensorless control based on IRFOC of the fault-tolerant 3-phase induction motor is studied. The rotor speed which required for FOC is estimated based on the EKF. To overcome the problem of the rotor speed mismatch, especially at the open-phase fault, a switching EKF is designed to estimate the motor speed. This aspect of the study is an extension of the authors' previous research presented in Reference [4-9]. Simulation works are carried out to assess the proposed system performance at different operating conditions. The results prove that the proposed switching EKF is able to update the rotor speed online at any operating speed as well as in balanced and unbalanced conditions.

References

[1] RM Tallam, TG Habetler, RG Harley, DJ Gritter, BH Burton. *Neural network based on-line stator winding turn fault detection for induction motors*. Industrial Application Conference. 2000; 375-380.
[2] M Ghazal, J Poshtan. *Robust stator winding fault detection in induction motors*. In Power Electronics, Drive Systems and Technologies Conference. 2011; 163-168.
[3] TM Wolbank, R Wohrnschimmel. On-*line stator winding fault detection in induction motors by stator current reconstruction*. In Proc. ICEM'99. 1999; 253-257.
[4] M Jannati, E Fallah. *Modeling and Vector Control of Unbalanced induction motors (faulty three phase or single phase induction motors)*. 1st. Conference on Power Electronic & Drive Systems & Technologies (PEDSTC). 2010; 208-211.

[5] M Jannati, NRN Idris, MJA Aziz. *A new method for RFOC of Induction Motor under open-phase fault*. In Industrial Electronics Society, IECON. 2013; 2530-2535.
[6] M Jannati, NRN Idris, Z Salam. *A New Method for Modeling and Vector Control of Unbalanced Induction Motors*. IEEE Energy Conversion Congress and Exposition. 2012; 3625-3632.
[7] M Jannati, A Monadi, NRN Idris, MJA Aziz, AAM Faudzi. Vector Control of Faulty Three-Phase Induction Motor with an Adaptive Sliding Mode Control. *Prz Elektrotech*. 2013; 89(12): 116-120.
[8] M Jannati, A Monadi, NRN Idris, MJA Aziz. Speed Sensorless Vector Control of Unbalanced Three-Phase Induction Motor with Adaptive Sliding Mode Control. *International Journal of Power Electronics and Drive Systems (IJPEDS)*. 2014; 4(3): 406-418.
[9] M Jannati, NRN Idris, MJA Aziz. Indirect Rotor Field-Oriented Control of Fault-Tolerant Drive System for Three-Phase Induction Motor with Rotor Resistance Estimation Using EKF. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2014; 12(9).
[10] M Jannati, NRN Idris, MJA Aziz. IFOC of Faulty Single-Phase IMs. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2014; 12(10).
[11] M Jannati, A Monadi, SA Anbaran, NRN Idris, MJA Aziz. An Exact Model for Rotor Field-Oriented Control of Single-Phase Induction Motors. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2014; 12(7): 5110-5120.
[12] M Jannati, NRN Idris, MJA Aziz, A Monadi, AAM Faudzi. A Novel Scheme for Reduction of Torque and Speed Ripple in Rotor Field Oriented Control of Single Phase Induction Motor Based on Rotational Transformations. *Research Journal of Applied Sciences, Engineering and Technology*. 2014; 7(16): 3405-3409.
[13] M Jannati, E Fallah. *A New Method for Speed Sensorless Vector Control of Single-Phase Induction Motor Using Extended Kalman Filter*. Conf. Proc. Of ICEE. 2011; 1-5.
[14] M Jannati, SH Asgari, NRN Idris, MJA Aziz. Speed Sensorless Direct Rotor Field-Oriented Control of Single-Phase Induction Motor Using Extended Kalman Filter. *International Journal of Power Electronics and Drive Systems (IJPEDS)*. 2014; 4(4).
[15] HB Azza, M Jemli, M Boussak, M Gossa. Implementation of sensorless speed control for two-phase induction motor drive using ISFOC strategy. *Transactions of Electrical Engineering*. 2011; 35(E1): 63–74.
[16] HB Azza, N Zaidi, M Jemli, M Boussak. Development and Experimental Evaluation of a Sensorless Speed Control of SPIM Using Adaptive Sliding Mode-MRAS Strategy. *IEEE Journal of Emerging and Selected Topics in Power Electronics*. 2014; 2(2): 319-328.
[17] S Vaez-Zadeh, A Payman. Design and analysis of sensorless torque optimization for single phase induction motors. *Energy conversion and management*. 2006; 47(11): 1464-1477.
[18] M Jemli, HB Azza, M Boussak. Sensorless Indirect Stator Field Orientation Speed Control for Single-Phase Induction Motor Drive. *IEEE Transactions on Power Electronics*. 2009; 24(6): 1618-1627.
[19] MBR Corrêa, CB Jacobina, PM dos Santos, EC dos Santos, AMN Lima. *Sensorless IFOC for single-phase induction motor drive system*. International Conference on Electric Machines and Drives. 2005; 162-166.
[20] M Barut, S Bogosyan, M Gokasan. Speed-sensorless estimation for induction motors using extended Kalman filters. *IEEE Trans Indust Electron.* 2007; 54(1): 272-280.
[21] P Vas. Sensorless vector and direct torque control. Oxford University Press. 1998.