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A Novel Method for Vector Control of Faulty Three-Phase IM Drives Based on FOC Method

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ABSTRACT

This paper proposes a novel method for vector control of faulty three-phase Induction Motor (IM) drives based on Field-Oriented Control (FOC) method. The performance characteristics of the presented drive system are investigated at healthy and open-phase fault conditions. The simulation of the case study is carried out by using the Matlab/M-File software for a star-connected three-phase IM. The results show the better performance of the proposed drive system especially in reduction of motor speed and torque oscillations during open-phase fault operating.

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1. INTRODUCTION

The Field-Oriented Control (FOC) method is widely used for implementing high performance vector control of three-phase Induction Motor (IM) drives. The FOC technique divides IM stator currents into flux and torque producing components. The torque is proportional to the product of these two perpendicular components and they can be treated separately. This means that the control of three-phase IM is transformed into a control system similar to the control of DC machine. Generally, there are two possibilities for the FOC technique. They are: Rotor Field-Oriented Control (RFOC) and Stator Field-Oriented Control (SFOC) [1].

In some industrial applications, such as in electric vehicle, space exploration, and etc the control of faulty electrical machines is very important [2]. These applications need a fault-tolerant control method whereby the operation of the drive system cannot be interrupted by a faulty condition mostly for safety reasons. The control of faulted machine, however, is clearly different from the control of healthy machine. By using the standard control strategies to faulted machine, significant oscillations in the motor speed and torque output will be developed [3]-[5].

In case of open-phase fault, in [6]-[12], some methods to control faulted multi-phase IMs and faulted permanent magnet synchronous motors have been proposed. These methods are limited to these customized or specialized machines and applications. In [5], [13] two techniques for FOC of three-phase IM under open-phase fault have been presented. These techniques are only applicable to vector-controlled motor drives based on current-controlled Voltage Source Inverter (VSI). In [14], [15] different methods based on voltage controller for vector control of three-phase IM under open-phase fault have been proposed. The drawback of these techniques is that these methods are not good for high performance vector control applications as in these techniques due to the using two different transformation matrices, the drive system is sensitive to motor parameters variations.

This study shows the three-phase IM equations under open-phase fault can be modeled as two balanced forward and backward equations. Based on this, a novel FOC method for three-phase IM under open-phase is presented. The configuration of the used converter for feeding three-phase IM during open-phase fault is shown in Figure 1. During fault condition as shown in this figure, the mid-point of DC-link voltage should be connected to the neutral point of the machine as discussed in [16]. This paper is organized as follows: After introduction in section 1, in section 2, d-q model of healthy and faulty three-phase IMs is presented. Next, section 3 describes the development of the FOC algorithm, followed by presenting proposed scheme. The performance of the presented method is analyzed and checked using Matlab software in section 4 and section 5 concludes the paper.

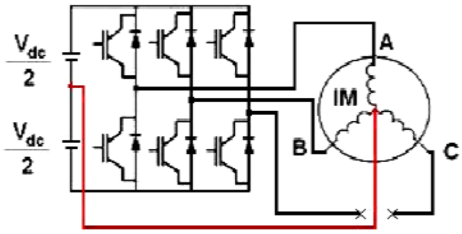

Figure 1. Configuration of the used converter for feeding three-phase IM during open-phase fault

2. MODELING OF HEALTHY AND FAULTY THREE-PHASE IMs

The d-q model of healthy and faulty three-phase IMs in the stationary reference frame (superscript "s") can be described by the following equations [13]:

$$\begin{aligned}
& v_{ds}^{s} = r_{ds} i_{ds}^{s} + \frac{d\lambda_{ds}^{s}}{dt} \quad , \quad v_{qs}^{s} = r_{qs} i_{qs}^{s} + \frac{d\lambda_{qs}^{s}}{dt} \\
& 0 - r_r i_{dr}^{s} + \frac{d\lambda_{dr}^{s}}{dt} + \omega_r \lambda_{qr}^{s} \quad , \quad 0 - r_r i_{qr}^{s} + \frac{d\lambda_{qr}^{s}}{dt} - \omega_r \lambda_{dr}^{s} \\
& \lambda_{ds}^{s} = L_{ds} i_{ds}^{s} + M_d i_{dr}^{s} \quad , \quad \lambda_{qs}^{s} = L_{qs} i_{qs}^{s} + M_q i_{qr}^{s} \\
& \lambda_{dr}^{s} = M_d i_{ds}^{s} + L_r i_{dr}^{s} \quad , \quad \lambda_{qr}^{s} = M_q i_{qs}^{s} + L_r i_{qr}^{s} \\
& \tau_e = \frac{Pole}{2} (M_q i_{qs}^{s} i_{dr}^{s} - M_d i_{ds}^{s} i_{qr}^{s}) \\
& \frac{Pole}{2} (\tau_e - \tau_l) - J \frac{d\omega_r}{dt} + F\omega_r
\end{aligned} \tag{1}$$

In (1), 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}, λ^s_{qr} are the rotor d-q axes fluxes. r_{ds}, r_{qs}, r_r indicate the stator and rotor d-q axes resistances. L_{ds}, L_{qs}, L_r, M_d, M_q denote the stator and rotor d-q axes self and mutual inductances. ω_r is the motor speed. τ_e, τ_l are electromagnetic torque and load torque. J, F are the moment of inertia and viscous friction coefficient respectively. It can be noted that Equation (1) can be described healthy three-phase IM if, $r_{ds}=r_{qs}=r_s$, $L_{ds}=L_{qs}=L_s=L_{ls}+1.5L_{ms}$, $M_d=M_q=1.5L_{ms}$ and three-phase IM under open-phase fault if, $r_{ds}=r_{qs}=r_s$, $L_{ds}=L_{ls}+1.5L_{ms}$, $L_{qs}=L_{ls}+0.5L_{ms}$, $M_d=1.5L_{ms}$, $M_q=\sqrt{3}/2L_{ms}$ [13] (L_{ls} and L_{ms} are leakage and mutual inductances respectively).

3. PROPOSED METHOD FOR VECTOR CONTROL OF HEALTHY AND FAULTY IMs

In this section, a method for vector control of three-phase IM based on extended model of IM as shown in (1) is presented. It is obvious this method can be used for healthy machine if, $r_{ds}=r_{qs}=r_s$, $L_{ds}=L_{qs}=L_s=L_{ls}+1.5L_{ms}$, $M_d=M_q=1.5L_{ms}$ and faulty machine if, $r_{ds}=r_{qs}=r_s$, $L_{ds}=L_{ls}+1.5L_{ms}$, $L_{qs}=L_{ls}+0.5L_{ms}$, $M_d=1.5L_{ms}$, $M_q=\sqrt{3}/2L_{ms}$. The proposed method is based on indirect RFOC and direct RFOC methods.

In RFOC strategy it is necessary that the motor equations transfer to the rotating reference frame. For this purpose, the transformation matrix as shown in (2) is used [1]:

$$\left[T_s^e\right]=\begin{bmatrix}\cos\theta_e & \sin\theta_e\\ -\sin\theta_e & \cos\theta_e\end{bmatrix} \tag{2}$$

In (2), superscript "e" indicates the equations are in the rotating reference frame. Also, "θ_e" is the angle between the stationary reference frame and rotating reference frame. Using (2), the equations of IM (Equation (1)), can be obtained as (3) and (4):

$$\begin{bmatrix}v_{ds}^e\\ v_{qs}^e\\ 0\\ 0\end{bmatrix}=\underbrace{\begin{bmatrix}\frac{(r_{ds}+r_{qs})}{2}+\frac{(L_{ds}+L_{qs})}{2}\frac{d}{dt} & -\omega_e\frac{(L_{ds}+L_{qs})}{2} & \frac{(M_d+M_q)}{2}\frac{d}{dt} & -\omega_e\frac{(M_d+M_q)}{2}\\ \omega_e\frac{(L_{ds}+L_{qs})}{2} & \frac{(r_{ds}+r_{qs})}{2}+\frac{(L_{ds}+L_{qs})}{2}\frac{d}{dt} & \omega_e\frac{(M_d+M_q)}{2} & \frac{(M_d+M_q)}{2}\frac{d}{dt}\\ \frac{(M_d+M_q)}{2}\frac{d}{dt} & -(\omega_e-\omega_r)\frac{(M_d+M_q)}{2} & r_r+L_r\frac{d}{dt} & -(\omega_e-\omega_r)L_r\\ (\omega_e-\omega_r)\frac{(M_d+M_q)}{2} & \frac{(M_d+M_q)}{2}\frac{d}{dt} & (\omega_e-\omega_r)L_r & r_r+L_r\frac{d}{dt}\end{bmatrix}\begin{bmatrix}i_{ds}^{+e}\\ i_{qs}^{+e}\\ i_{dr}^{+e}\\ i_{qr}^{+e}\end{bmatrix}}_{\begin{bmatrix}v_{ds}^{+e}\\ v_{qs}^{+e}\\ v_{dr}^{+e}\\ v_{qr}^{+e}\end{bmatrix}}$$

$$+\underbrace{\begin{bmatrix}\frac{(r_{ds}-r_{qs})}{2}+\frac{(L_{ds}-L_{qs})}{2}\frac{d}{dt} & \omega_e\frac{(L_{ds}-L_{qs})}{2} & \frac{(M_d-M_q)}{2}\frac{d}{dt} & \omega_e\frac{(M_d-M_q)}{2}\\ \omega_e\frac{(L_{ds}-L_{qs})}{2} & -\frac{(r_{ds}-r_{qs})}{2}-\frac{(L_{ds}-L_{qs})}{2}\frac{d}{dt} & \omega_e\frac{(M_d-M_q)}{2} & -\frac{(M_d-M_q)}{2}\frac{d}{dt}\\ \frac{(M_d-M_q)}{2}\frac{d}{dt} & (\omega_e-\omega_r)\frac{(M_d-M_q)}{2} & 0 & 0\\ (\omega_e-\omega_r)\frac{(M_d-M_q)}{2} & -\frac{(M_d-M_q)}{2}\frac{d}{dt} & 0 & 0\end{bmatrix}\begin{bmatrix}i_{ds}^{-e}\\ i_{qs}^{-e}\\ i_{dr}^{-e}\\ i_{qr}^{-e}\end{bmatrix}}_{\begin{bmatrix}v_{ds}^{-e}\\ v_{qs}^{-e}\\ v_{dr}^{-e}\\ v_{qr}^{-e}\end{bmatrix}} \tag{3}$$

Where,

$$\begin{bmatrix}i_{ds}^{+e}\\ i_{qs}^{+e}\\ i_{ds}^{-e}\\ i_{qs}^{-e}\end{bmatrix}=\begin{bmatrix}\cos\theta_e & \sin\theta_e & 0 & 0\\ -\sin\theta_e & \cos\theta_e & 0 & 0\\ \cos\theta_e & -\sin\theta_e & 0 & 0\\ \sin\theta_e & \cos\theta_e & 0 & 0\end{bmatrix}\begin{bmatrix}i_{ds}^s\\ i_{qs}^s\\ i_{dr}^s\\ i_{qr}^s\end{bmatrix}$$
$$\begin{bmatrix}i_{dr}^{+e}\\ i_{qr}^{+e}\\ i_{dr}^{-e}\\ i_{qr}^{-e}\end{bmatrix}=\begin{bmatrix}0 & 0 & \cos\theta_e & \sin\theta_e\\ 0 & 0 & -\sin\theta_e & \cos\theta_e\\ 0 & 0 & \cos\theta_e & -\sin\theta_e\\ 0 & 0 & \sin\theta_e & \cos\theta_e\end{bmatrix}\begin{bmatrix}i_{ds}^s\\ i_{qs}^s\\ i_{dr}^s\\ i_{qr}^s\end{bmatrix} \tag{4}$$

In (3), "ω_e" is the angular velocity of the rotor field oriented reference frame. As it is seen from (3), in general, Equation (3) includes two set of equations (forward equations: superscript "+e" and backward equations: superscript "-e"). Each of equations represents an equation where rotates in the forward or backward direction as shown in Figure 2.

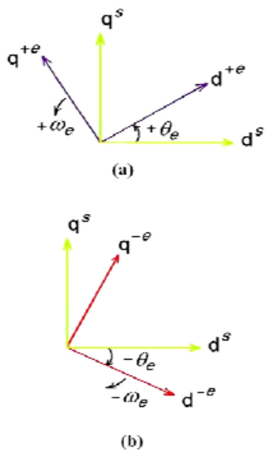

Figure 2. (a): Forward and stationary reference frames (superscript "+*e*": forward, superscript "*s*": stationary), (b): Backward and stationary reference frames (superscript "-*e*": backward, superscript "*s*": stationary)

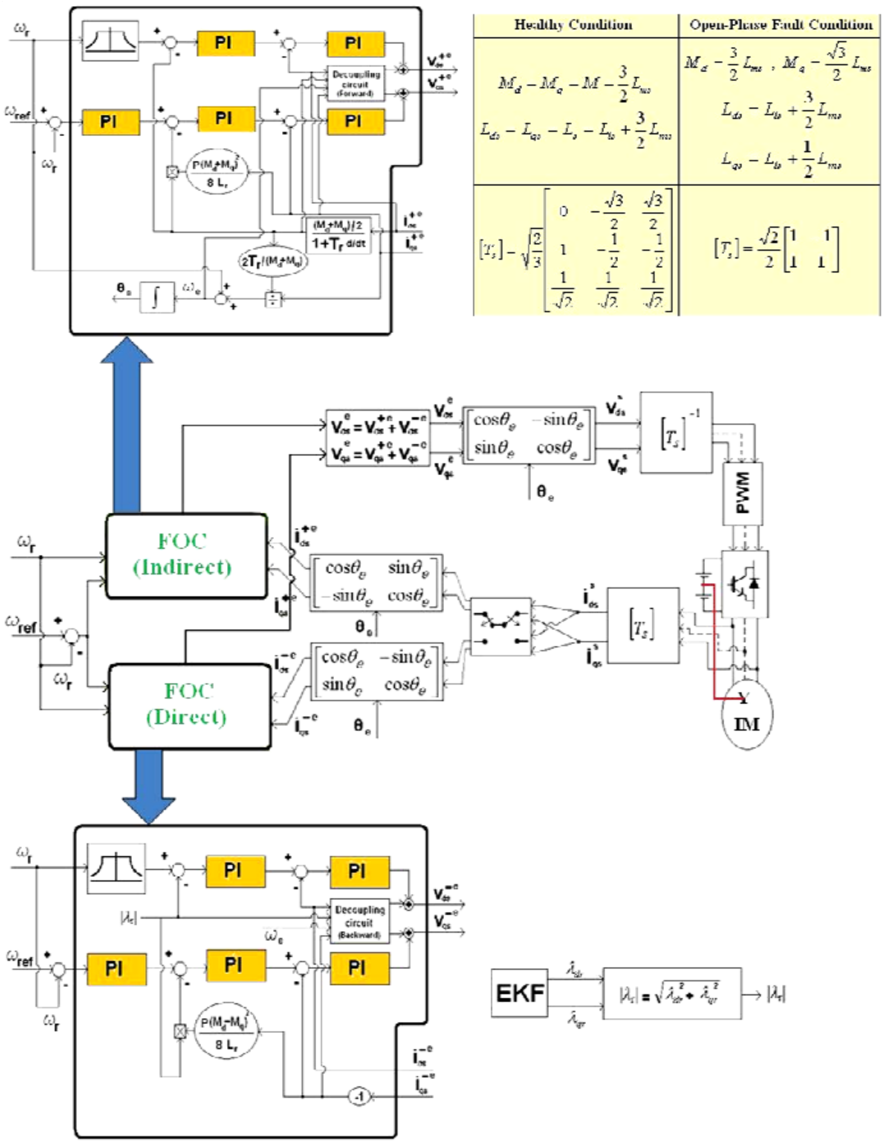

Figure 3. Block diagram of proposed method for vector control of healthy and faulty machines

As it is seen from (3), the structure of the forward and backward equations are similar to the RFOC equations of healthy three-phase IM. Consequently, it is possible to control faulty machine using two developed RFOC algorithms. The block diagram of proposed RFOC for vector control of faulty machine is shown in Figure 3. In this figure, an indirect RFOC algorithm and a direct RFOC algorithm are used to control faulty IM (indirect RFOC algorithm to control forward equations and direct RFOC algorithm to control backward equations). In Figure 3, in order to alternately switched between the forward and backward states, a switch is used whereby this switch will consecutively change positions in each sampling time. It can be noted that this figure can be used for both healthy and faulty three-phase IMs. The parameters of motor which are needed to be changed from healthy mode to faulty mode are shown in Figure 3.

In the proposed scheme for vector control of faulty machine an Extended Kalman Filter (EKF) is used to estimate the rotor flux in the direct RFOC. For the purpose of rotor flux estimation, the d-axis and q-axis of stator currents as well as d-axis and q-axis of rotor fluxes are chosen as the state variables. Using these state variables, it is possible to express the state space model in the form of Equation (5) and (6):

$$\dot{x} = Ax + Bu \tag{5}$$

$$y = Cx \tag{6}$$

In these equations, x, y and u are the system state matrix, system output matrix and system input matrix. Also, A, B and C are the system, input and output matrices respectively. The matrices of x, y, u, A, B and C in equations (5) and (6) are given as follows:

$$x = \begin{bmatrix} i_{ds} & i_{qs} & \lambda_{dr} & \lambda_{qr} \end{bmatrix}^T \tag{7a}$$

$$y = \begin{bmatrix} i_{ds} & i_{qs} \end{bmatrix}^T \tag{7b}$$

$$u = \begin{bmatrix} v_{ds} & v_{qs} \end{bmatrix}^T \tag{7c}$$

$$A = \begin{bmatrix} 1 & -\omega_r dt & 0 & 0 \\ \omega_r dt & 1 & 0 & 0 \\ 0 & -\omega_r \frac{(M_d - M_q)}{2} dt & 1 & 0 \\ \omega_r \frac{(M_d - M_q)}{2} dt & 0 & 0 & 1 \end{bmatrix} \tag{7d}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}^T \tag{7e}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{7f}$$

The steps of the EKF algorithm can be formulated as [15]:

1) Estimation of the Error Covariance Matrix:

$$P(n+1) = \Gamma(n)P(n)\Gamma^T(n) + Q \tag{8}$$

2) Computation of Kalman Filter Gain:

$$K(n) = P(n+1)\Delta^T(n)\left[\Delta(n)P(n+1)\Delta(n) + R\right]^{-1} \tag{9}$$

3) Update of the Error Covariance Matrix:

$$P(n) = \left[1 - K(n)\wedge(n)\right]P(n+1) \tag{10}$$

4) State Estimation:

$$\hat{x}(n+1) = \hat{x}(n) + K(n)\left[z(n+1) - h(\hat{x}(n+1))\right] \tag{11}$$

In these equations, *P*, *Q* and *R* are the covariance matrices of the noises. To begin the calculation, the initial values of the state variables and error covariance matrices need to be identified. In this work, the initial values of matrices *P*, *Q* and *R* for estimation of rotor flux are obtained from the trial and error process.

4. SIMULATION RESULTS AND COMPARISIONS

In this section simulation results for 475Watt star-connected three-phase IM is carried out to validate the proposed control strategy. The simulation investigation is mainly focused on the motor speed and torque responses. Two different cases using Matlab/M-File software are simulated:

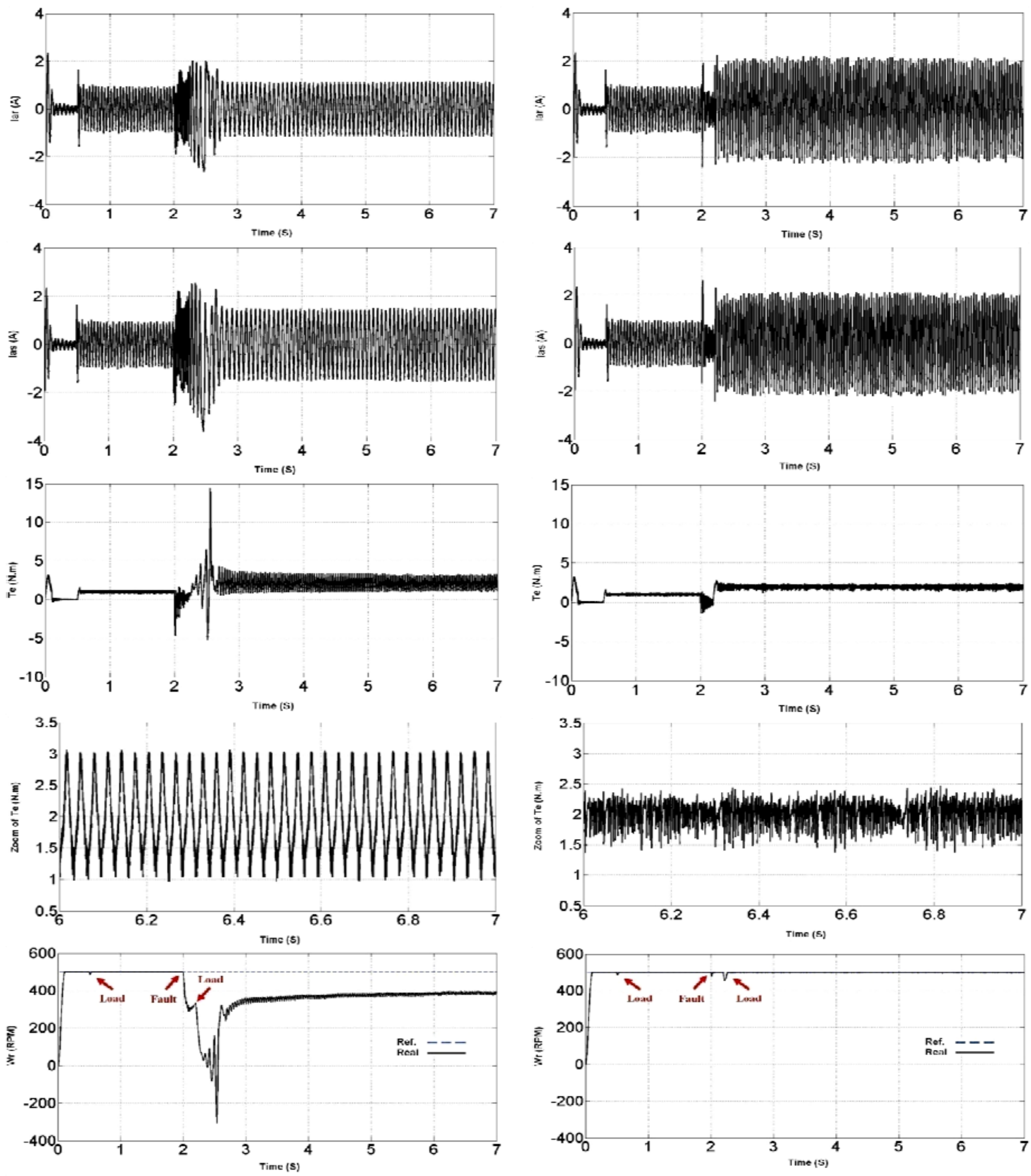

Figure 4. Simulation results of the conventional (left) and proposed (right) methods for vector control of healthy and faulty three-phase IMs; from top to bottom: Rotor a-axis current, Stator a-axis current, Electromagnetic torque, Zoom of electromagnetic torque, Speed

1) Figure 4(left): vector control of healthy and faulty three-phase IMs drive based on conventional IRFOC (the conventional IRFOC method based on voltage controller has been fully discussed in [1]).
2) Figure 4(right): vector control of healthy and faulty three-phase IMs drive based on Figure 3 (proposed FOC).

Runge–Kutta algorithm is used for solving the healthy and faulty three-phase IMs dynamic equations. An IM is fed from a Sine Pulse Width Modulation (SPWM) VSI. In the simulation the reference speed is 500rpm. In this paper it is assumed an immediate open-phase fault detection. The ratings and parameters of the simulated motor are:

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

In Figure 4, it is supposed that the open-phase fault happened at t=2s (from t=0s to t=2s→healthy condition and from t=2s to t=7s→faulty condition). In this test, the value of the load is: from t=0s to t=0.5s, T_l=0N.m; from t=0.5s to t=2s, T_l=1N.m; from t=2s to t=2.2s, T_l=0N.m; from t=2.2s to t=7s, T_l=2N.m. Based on Figure 4(left), simulation results of the conventional controller confirm that the conventional controller is unable to control the faulty IM correctly. It can be seen that from the presented simulation results that the dynamic performance of the proposed fault-tolerant controller is acceptable. As can be seen from Figure 4(right), the proposed FOC method produces fewer ripples in the speed and torque responses. As can be seen by using conventional controller, the electromagnetic torque oscillation at steady state is about 1N.m at an average amount of 2N.m but by using proposed controller, the electromagnetic torque oscillation reduced notably by about 0.3N.m at an average amount of 2N.m. Simulation results show the better performance of the proposed technique for vector control of faulted machine in both transient and steady state.

5. CONCLUSION

In this paper, a vector control strategy for star-connected three-phase IM drives under open-phase fault based on RFOC is proposed and simulated. It was shown that the faulty machine equations in the rotating reference frame can be classified as two set of balanced equations (forward and backward equations). Based on this, a novel vector control technique using two developed RFOC algorithms was proposed. The results show the good performance of the proposed drive system

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