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Modelling of Faulty Three Phase Induction Motor by Field Orientation

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Abstract

This study investigates the simple vector control of a 3-phase squirrel cage Induction Motor (IM) under open-circuit fault (faulty 3-phase IM). It was shown that it is needed to supply the stator windings with unbalanced currents to remove the oscillating term of the machine electromagnetic torque. The vector control system is based upon Field-Oriented Control (FOC) that has been adapted for this type of machine. Simulation results are provided to show the operation of the proposed drive system.

***Keywords**: squirrel cage 3-phase IM, FOC, open- circuit fault, simple method, simulation results*

1. Introduction

Recently, 3-phase Induction Motors (IMs) have received a greet attention for electrical drive applications [1-5]. Squirrel cage 3-phase IMs have several advantages for example high reliability and robustness. Open-circuit fault is one of familiar failures in the 3-phase IM stator windings. This abnormal condition happens because of the failure of one stator phase connection, inverter faults mitigated by using fuses or many other reasons.

The conventional vector control systems which is used for healthy IMs drive cannot be able to work during fault situations, in practice, they fail in the presence of such faults as open-phase fault (if a conventional vector control system is applied to the faulty IM, oscillations in the motor torque and speed can be observed [6-14]). For this, a suitable control algorithm is needed to ensure proper operation of the drive both in healthy and faulty conditions. Most of the different solutions proposed in the past to improve the performance of the 3-phase IM or unbalaced 2-phase IM drives under open-circuit fault [6-18]. In general, these methods are based on using transformation matrices which are obtained from machine model (in [6-18], several techniques for FOC of faulty 3-phase IM (open-phase fault), single-phase IM (unbalanced 2-phase IM) and high performance FOC of these machines using Extended Kalman Filter (EKF), adaptive sliding mode and etc have been proposed). These transformation matrices are used to modify the controlling system due to the fault. It is clear the use of transformation matrices in the drive syastems leads to system complixity.

The main contribution of this paper is to expand vector control method based on FOC (Field-Oriented Control) for 3-phase IM which can be also adopted for faulty 3-phase IM. Differently from the previous methods for vector control of faulty IM (e.g., [6-18]), the proposed method in this paper donot used transformation matrices. This research is organized as follows: In part 2, model of healthy and faulty 3-phase IM based on d-q model is presented. After that, a brief overview on vector control equations for healthy 3-phase IM based on FOC are presented in part 3. Besides, the main idea of the proposed method for vector control of 3-phase IM under open-circuit fault is expounded in this section. The simulation results and copmarisions are shown in part 4 and part 5 concludes the paper.

2. Machine model

The dynamic model of 3-phase IM can be shown as following equations [19, 20]:

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$$\begin{bmatrix} v_{ds}^s \\ v_{qs}^s \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_s + \left(L_{ls} + \frac{3}{2}L_{ms}\right)\frac{d}{dt} & 0 & \left(\frac{3}{2}L_{ms}\right)\frac{d}{dt} & 0 \\ 0 & r_s + \left(L_{ls} + \frac{3}{2}L_{ms}\right)\frac{d}{dt} & 0 & \left(\frac{3}{2}L_{ms}\right)\frac{d}{dt} \\ \left(\frac{3}{2}L_{ms}\right)\frac{d}{dt} & \omega_r\left(\frac{3}{2}L_{ms}\right) & r_r + L_r\frac{d}{dt} & \omega_r L_r \\ -\omega_r\left(\frac{3}{2}L_{ms}\right) & \left(\frac{3}{2}L_{ms}\right)\frac{d}{dt} & -\omega_r L_r & r_r + L_r\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \\ i_{dr}^s \\ i_{qr}^s \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} \lambda_{ds}^s \\ \lambda_{qs}^s \\ \lambda_{dr}^s \\ \lambda_{qr}^s \end{bmatrix} = \begin{bmatrix} \left(L_{ls} + \frac{3}{2}L_{ms}\right) & 0 & \frac{3}{2}L_{ms} & 0 \\ 0 & \left(L_{ls} + \frac{3}{2}L_{ms}\right) & 0 & \frac{3}{2}L_{ms} \\ \frac{3}{2}L_{ms} & 0 & L_r & 0 \\ 0 & \frac{3}{2}L_{ms} & 0 & L_r \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \\ i_{dr}^s \\ i_{qr}^s \end{bmatrix} \tag{2}$$

$$\tau_e = \frac{Pole}{2}\left(\frac{3}{2}L_{ms}\right)\left(i_{qs}^s i_{dr}^s - i_{ds}^s i_{qr}^s\right) \tag{3}$$

$$\frac{Pole}{2}\left(\tau_e - \tau_l\right) = J\frac{d\omega_r}{dt} + F\omega_r \tag{4}$$

Where, v^s_{ds}, v^s_{qs}, i^s_{ds}, i^s_{qs}, i^s_{dr}, i^s_{qr}, λ^s_{ds}, λ^s_{qs}, λ^s_{dr} and λ^s_{qr} are the d-q axes voltages, currents, and fluxes of the stator and rotor in the stator reference frame (superscript "*s*"). r_s and r_r denote the stator and rotor resistances. L_{ls} and L_{ms} denote the stator leakage and mutual inductances. ω_r is the machine speed. τ_e, τ_l, J and F are electromagnetic torque, load torque, inertia and viscous friction coefficient. The equations that present the dynamic model for 3-phase IM under open-circuit fault are also as following equations [9]:

$$\begin{bmatrix} v_{ds}^s \\ v_{qs}^s \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_s + \left(L_{ls} + \frac{3}{2}L_{ms}\right)\frac{d}{dt} & 0 & \left(\frac{3}{2}L_{ms}\right)\frac{d}{dt} & 0 \\ 0 & r_s + \left(L_{ls} + \frac{1}{2}L_{ms}\right)\frac{d}{dt} & 0 & \left(\frac{\sqrt{3}}{2}L_{ms}\right)\frac{d}{dt} \\ \left(\frac{3}{2}L_{ms}\right)\frac{d}{dt} & \omega_r\left(\frac{\sqrt{3}}{2}L_{ms}\right) & r_r + L_r\frac{d}{dt} & \omega_r L_r \\ -\omega_r\left(\frac{3}{2}L_{ms}\right) & \left(\frac{\sqrt{3}}{2}L_{ms}\right)\frac{d}{dt} & -\omega_r L_r & r_r + L_r\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \\ i_{dr}^s \\ i_{qr}^s \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} \lambda_{ds}^s \\ \lambda_{qs}^s \\ \lambda_{dr}^s \\ \lambda_{qr}^s \end{bmatrix} = \begin{bmatrix} \left(L_{ls} + \frac{3}{2}L_{ms}\right) & 0 & \frac{3}{2}L_{ms} & 0 \\ 0 & \left(L_{ls} + \frac{1}{2}L_{ms}\right) & 0 & \frac{\sqrt{3}}{2}L_{ms} \\ \frac{3}{2}L_{ms} & 0 & L_r & 0 \\ 0 & \frac{\sqrt{3}}{2}L_{ms} & 0 & L_r \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \\ i_{dr}^s \\ i_{qr}^s \end{bmatrix} \tag{6}$$

$$\tau_e = \frac{Pole}{2}\left(\left(\frac{\sqrt{3}}{2}L_{ms}\right)i_{qs}^s i_{dr}^s - \left(\frac{3}{2}L_{ms}\right)i_{ds}^s i_{qr}^s\right) \tag{7}$$

$$\frac{Pole}{2}\left(\tau_e - \tau_l\right) = J\frac{d\omega_r}{dt} + F\omega_r \tag{8}$$

The model of faulty 3-phase IM was obtained using an approach like that used to obtain the model for a healthy 3-phase IM (the model of faulty 3-phase IM is fully discussed in Reference [9]).

3. Rotor Field-Oriented Control (RFOC)

In this section the conventional RFOC of healthy 3-phase IM and proposed method for RFOC of 3-phase IM under open-circuit fault is discussed.

3.1. RFOC of Healthy 3-phase IM

In RFOC method, it is necessary the machine equations transfer from stator reference frame (superscript "*s*") to the rotating reference frame (superscript "*e*") [21]. Equation of 3-phase IM voltages, fluxes and electromagnetic torque in the rotating reference frame can be express as follows (in this paper, superscript "*e*" indicates that the equations are in the rotating reference frame. Moreover, in (9), ω_e is the angular velocity of the Rotor Field-Oriented frame) [21]:

$$\begin{bmatrix} v_{ds}^e \\ v_{qs}^e \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_s + \left(L_{ls} + \frac{3}{2}L_{ms}\right)\frac{d}{dt} & -\omega_e\left(L_{ls} + \frac{3}{2}L_{ms}\right) & \left(\frac{3}{2}L_{ms}\right)\frac{d}{dt} & -\omega_e\left(\frac{3}{2}L_{ms}\right) \\ \omega_e\left(L_{ls} + \frac{3}{2}L_{ms}\right) & r_s + \left(L_{ls} + \frac{3}{2}L_{ms}\right)\frac{d}{dt} & \omega_e\left(\frac{3}{2}L_{ms}\right) & \left(\frac{3}{2}L_{ms}\right)\frac{d}{dt} \\ \left(\frac{3}{2}L_{ms}\right)\frac{d}{dt} & -(\omega_e - \omega_r)\left(\frac{3}{2}L_{ms}\right) & r_r + L_r\frac{d}{dt} & -(\omega_e - \omega_r)L_r \\ (\omega_e - \omega_r)\left(\frac{3}{2}L_{ms}\right) & \left(\frac{3}{2}L_{ms}\right)\frac{d}{dt} & (\omega_e - \omega_r)L_r & r_r + L_r\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{ds}^e \\ i_{qs}^e \\ i_{dr}^e \\ i_{qr}^e \end{bmatrix} \tag{9}$$

$$\begin{bmatrix} \lambda_{dr}^e \\ \lambda_{qr}^e \end{bmatrix} = \begin{bmatrix} \frac{3}{2}L_{ms} & 0 \\ 0 & \frac{3}{2}L_{ms} \end{bmatrix} \begin{bmatrix} i_{ds}^e \\ i_{qs}^e \end{bmatrix} + \begin{bmatrix} L_r & 0 \\ 0 & L_r \end{bmatrix} \begin{bmatrix} i_{dr}^e \\ i_{qr}^e \end{bmatrix} \tag{10}$$

$$\tau_e = \frac{Pole}{L_r}\left(\frac{3}{2}L_{ms}\right)\left(i_{qs}^e \lambda_{dr}^e - i_{ds}^e \lambda_{qr}^e\right) \tag{11}$$

In RFOC system, the rotor flux vector is aligned with d-axis ($\lambda_{dr}^e = |\lambda_r|$ and $\lambda_{qr}^e = 0$). With this supposition Equation (10) can be written as Equation (12):

$$\begin{bmatrix} |\lambda_r| \\ 0 \end{bmatrix} = \begin{bmatrix} \frac{3}{2}L_{ms} & 0 \\ 0 & \frac{3}{2}L_{ms} \end{bmatrix} \begin{bmatrix} i_{ds}^e \\ i_{qs}^e \end{bmatrix} + \begin{bmatrix} L_r & 0 \\ 0 & L_r \end{bmatrix} \begin{bmatrix} i_{dr}^e \\ i_{qr}^e \end{bmatrix} \tag{12}$$

From (12), the equation between rotor currents and stator currents are obtained as following equations:

$$i_{dr}^e = \frac{|\lambda_r|}{L_r} - \left(\frac{3L_{ms}}{2L_r}\right) i_{ds}^e \tag{13}$$

$$i_{qr}^e = -\left(\frac{3L_{ms}}{2L_r}\right) i_{qs}^e \tag{14}$$

Based on (9)-(14) and after simplifying RFOC equations for healthy 3-phase IM are obtained as following equations [21]:

$$|\lambda_r| = \left(\frac{3}{2}L_{ms}\right)\left(\frac{1}{1 + T_r \frac{d}{dt}}\right) i_{ds}^e \tag{15}$$

$$\omega_e = \omega_r + \left(\frac{3}{2}L_{ms}\right)\left(\frac{1}{T_r |\lambda_r|}\right) i_{qs}^e \tag{16}$$

$$\tau_e = \frac{Pole}{2}\left(\frac{3}{2}L_{ms}\right)\left(\frac{|\lambda_r|}{L_r}\right) i_{qs}^e \tag{17}$$

In above equations, T_r is rotor time constant. Based on (15)-(17), conventional block diagram of healthy 3-phase IM based on Indirect RFOC (IRFOC) is as Figure 1 (the simplest way to implement the FOC is to use hysteresis current controllers which is used in this study).

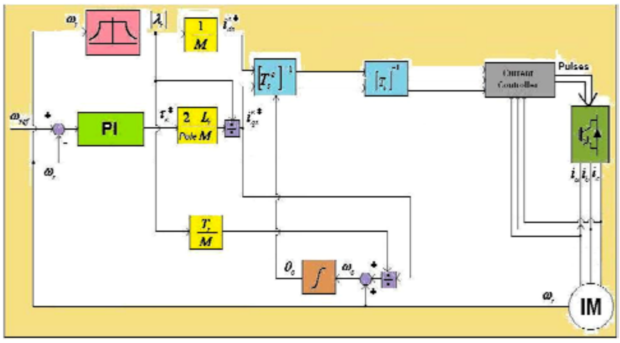

Figure 1. Conventional block diagram of healthy 3-phase IM based on IRFOC

In Figure 1, i_{ds}^{e*}, i_{qs}^{e*} and τ_e^* represent the reference stator d-axis current, reference stator q-axis current and reference torque, respectively. Moreover, M=3/2L_{ms}. The block $[T_s^e]^{-1}$ performs signal transformations from the rotating reference frame to the stationary reference frame. Furthermore, the block $[T_s]^{-1}$ is 2 to 3 transformation for the stator current variables (Park transformation). In Figure 1, 3-phase IM is fed from a conventional 3-leg Voltage Source Inverter (VSI) as shown in Figure 2. $[T_s^e]$ and $[T_s]$ are difined as follows [21]:

$$\begin{bmatrix} i_{ds}^e \\ i_{qs}^e \end{bmatrix} = \left[T_s^e\right] \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} = \begin{bmatrix} \cos\theta_e & \sin\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} \tag{18}$$

$$\begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} = \left[T_s\right] \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} +1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} \tag{19}$$

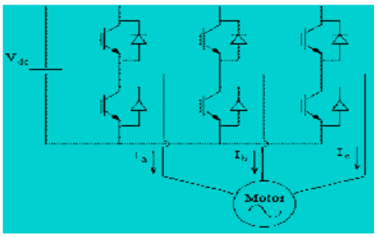

Figure 2. 3-leg Voltage Source Inverter (VSI)

3.2. RFOC of faulty 3-phase IM

Because of the asymmetry of stator windings in the faulty 3-phase IM, the use of conventional FOC needs a special attention. The asymmetry in the faulty IM model is a result of different d-q parameters. This asymmetry causes an oscillating term in the machine torque. It is possible to remove the oscillating term of faulty machine torque by means of a suitable control of the stator q-axis current. Based on the RFOC model for healthy 3-phase IM which is derived previously, it is possible to employ the RFOC principles for vector control of faulty 3-phase IM. Assuming that the stator q-axis current can be imposed as:

$$i_{qs}^s = \sqrt{3} I_{QS}^s \tag{20}$$

By substituting (20), the faulty machine model can be re-written as:
Rotor flux equations:

$$\begin{bmatrix} \lambda_{dr}^{s} \\ \lambda_{qr}^{s} \end{bmatrix} = \begin{bmatrix} \left(\frac{3}{2}L_{ms}\right) & 0 \\ 0 & \left(\frac{3}{2}L_{ms}\right) \end{bmatrix} \begin{bmatrix} i_{ds}^{s} \\ I_{QS}^{s} \end{bmatrix} + \begin{bmatrix} L_r & 0 \\ 0 & L_r \end{bmatrix} \begin{bmatrix} i_{dr}^{s} \\ i_{qr}^{s} \end{bmatrix} \quad (21)$$

Electromagnetic torque equation:

$$\tau_e = \frac{Pole}{2}\left(\frac{3}{2}L_{ms}\right)\left(I_{QS}^{s} i_{dr}^{s} - i_{ds}^{s} i_{qr}^{s}\right) \quad (22)$$

Equation (21) and (22) is equivalent to that of the healthy 3-phase IM in which the oscillating term does not exist in steady state. Using the stator q-axis current compensation given by (20), a novel vector control model can be developed for 3-phase IM under open-circuit fault. From the proposed results (equations (10) and (11)), it is possible to adopt the IRFOC scheme, as presented in Figure 3.

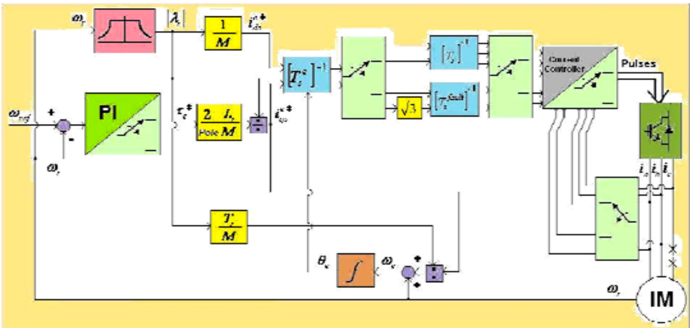

Figure 3. Proposed block diagram of healthy and faulty 3-phase IM based on IRFOC

In Figure 3, the block $[T_s^{fault}]^{-1}$ is 2 to 2 transformation for the stator current variables in the faulty condition which is difined as [9] (in this paper it is assumed a cut-off fault is occured in phase "c"):

$$\begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} = \left[T_s^{fault}\right] \begin{bmatrix} i_{as} \\ i_{bs} \end{bmatrix} \frac{\sqrt{2}}{2} \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \end{bmatrix} \quad (23)$$

With the aim of switched between the two conditions, five switches are used in Figure 3. These switches change positions once the fault is detected (in this paper, an immediate open stator winding detection is supposed as considered in [6-14]).

4. Simulation Results

To show the usefulness of the proposed algorithm (Figure 3), MATLAB/M-FILE simulation are carried out. At the same time, a controlling system based on Figure 2 for healthy and faulty 3-phase IM is also simulated. In simulations the reference motor speed (ω_{ref}) and load torque (T_l) are considered as Figure 4 and Figure 5 respectively. The simulated 3-phase IM parameters are listed as follows:

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

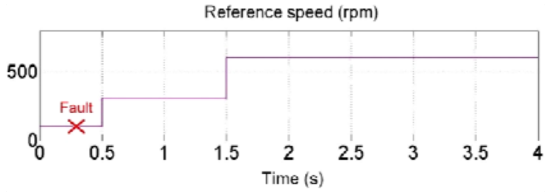

Figure 4. Variation of rotor speed

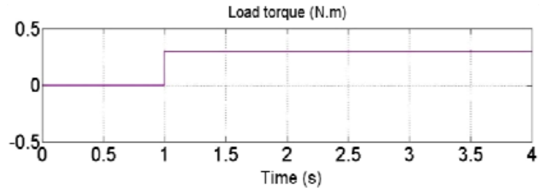

Figure 5. Variation of load torque

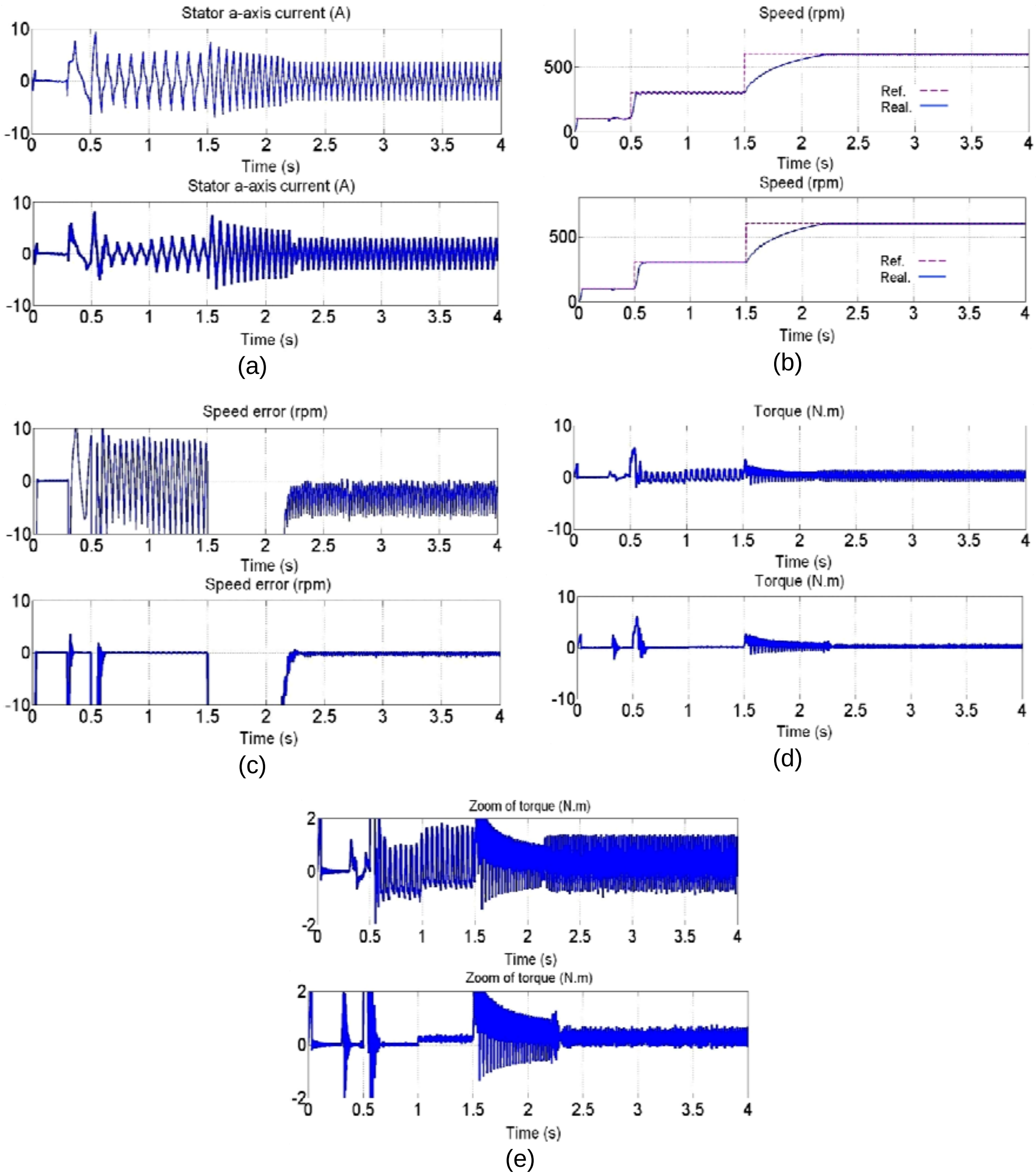

Figure 6. Simulation results of the comparison between conventional IRFOC (left) and proposed IRFOC(right) for vector control of healthy and faulty 3-phase IM, (a) Stator a-axis current, (b) Speed, (c) Speed error, (d) Torque, (e) Zoom of torque

Two cases are simulated; Case (1): conventional IRFOC method for healthy and faulty 3-phase IM based on Figure 2 (the simulation results of this case is shown in Figure 6(left)) and Case (2): proposed IRFOC method for healthy and faulty 3-phase IM based on Figure 3 (the simulation results of this case is shown in Figure 6(right)). In both cases, the 3-phase IM started in the healthy condition and without load torque, and then at t=0.3s a phase cut-off fault is happened in phase "c". After that at t=1s a step load torque equal to 0.3N.m is applied. As expected in the healthy condition, the conventional and roposed controller exhibit good tracking performance and fast response without steady-state error. Simulation results of Figure 6(right) shows that that the actual motor speed can follow and trace well the reference speed even under load (see Figure 6(right-b)). Compared to the conventional IRFOC algorithm, the motor speed of the proposed scheme contains very low speed ripples (see Figure 6(left-c) and see Figure 6(right-c)). Moreover, using proposed controller, the electromagnetic torque waveforms contain low ripples even at the faulty mode (see Figure 6 (right-e)). The stator current waveform is enlarged to show that the IM current is nearly sinusoidal in both healthy and faulty conditions (see Figure 6(right-a)). It is shown that the proposed IRFOC algorithm for vector control of healthy and faulty 3-phase IM has a good speed conrol and adequate vector control characteristics at wide range speed operation.

5. Conclusion

A simple Indirect Rotor-Field Oriented Control (IRFOC) of a squirrel cage 3-phase motor under open-circuit fault was simulated in the MATLAB environment. It was shown that it is essential to supply the stator q-axis motor winding with unbalanced current to remove the oscillating term of the electromagnetic torque. Furthermore, this unbalanced control is essential to realize a balanced IRFOC which enables vector control to be applied to the faulty IM. Based on the presented results in this paper it is possible to implement high-performance AC drive systems with a faulty 3-phase IM. A prospective application of the proposed method is its use as an scheme for the single-phase IM drive systems (the structure of single-phase IM with two different windings is similar to the 3-phase IM under open-circuit fault). In future works, experimental tests will be conducted to emphasize the simulation results, which are so far very promising.

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