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A Novel Method for IRFOC of Three-Phase Induction Motor under Open-Phase Fault

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ABSTRACT

This paper investigates the vector control of a star-connected three-phase Induction Motor (IM) under stator winding open-phase fault. The used vector control method is based upon indirect rotor field-orientation concepts that have been adapted for this type of machine. Beside the implementation of this method in critical industrial applications, the proposed method in this paper can be used for vector control of unbalanced 2-phase or single-phase IM with two main and auxiliary windings. Simulation results are provided to show the operation of the proposed drive system.

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1. INTRODUCTION

Three-phase Induction Motor (IM) drives are one of the most common types of AC drives used in industrial applications [1]-[3]. In some applications where continuous operation is desirable or critical, such as in military, electric vehicle, aircraft, and etc having a fault-tolerant control system is necessary. Generally the classification of faults in three-phase IM drives can be listed as follows: faults in the inverter [4], faults in the mechanical or electrical sensors [5] and [7] and also faults in electrical machine [7]-[11]. Faults that is related to electrical machine is broadly discussed in the literatures, these include stator faults and rotor faults.

Nowadays Field-Oriented Control (FOC) method for IMs is broadly adopted to obtain high performance control of IM drive systems. The FOC represents a better solution to convince industrial requirements. In the literature, several approaches have been presented for vector control of three-phase IM under open-phase fault [12]-[20]. In [12] and [13] scalar and vector control techniques to control Δ-connected three-phase IM under open-phase fault using current controller have been proposed. In [14] another method for FOC of Δ-connected three-phase IM in case of open-phase fault based on voltage controller has been presented. It was discussed in [14], during open-phase fault, the limitation due to maximum permissible torque is about 30% of the rated torque of the IM. In [15]-[18], several techniques for FOC of star-connected three-phase motor under open-phase fault were proposed. However, the results in [15]-[18] due to using two different transformation matrices for stator voltage and current variables are sensitive to variations of motor parameters. In [19] the analysis of the star-connected three-phase IM in the open-phase fault indicates that, to compensate torque pulsations, odd harmonic voltages of the magnitude and phase angle can be injected at the machine terminal. These methods have been applied and implemented to a volts/hertz controlled IM.

This paper investigates the use of the scheme in Figure 1 for feeding a three-phase IM under open-phase fault. This paper presents a vector control strategy based on Indirect Rotor FOC (IRFOC) for three-phase IM under open-phase fault. It investigates the design and use of the RFO vector control in detail. The presented drive system enable to control three-phase IM under normal and open-phase fault conditions. This paper is organized as follows; after the introduction in section 1, section 2 gives the mathematical model of three-phase IM under stator winding open-phase fault. Next, section 3 describes the development of the FOC algorithm, followed by presenting proposed scheme for vector control of three-phase IM under open-phase fault. The performance of the proposed approach is tested by simulations with the results presented in section 4 and finally, conclusions are listed in section 5.

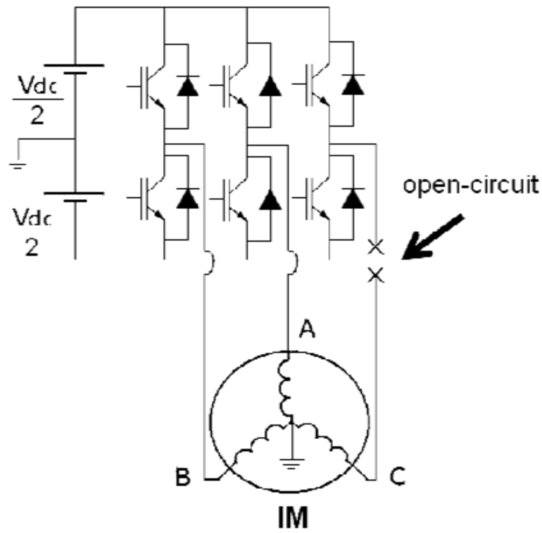

Figure 1. Three-phase IM drive with one opened phase

2. FAULTY THREE-PHASE IM MODEL

The d-q model of the start-connected three-phase IM under stator winding open-phase fault can be described by the following equations [20]:

Stator voltage equations:

$$\begin{bmatrix} v_{ds}^s \\ v_{qs}^s \end{bmatrix} = \begin{bmatrix} r_s + L_{ds}p & 0 \\ 0 & r_s + L_{qs}p \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} + \begin{bmatrix} M_{ds}p & 0 \\ 0 & M_{qs}p \end{bmatrix} \begin{bmatrix} i_{dr}^s \\ i_{qr}^s \end{bmatrix} \tag{1}$$

Rotor voltage equations:

$$\begin{bmatrix} v_{dr}^s \\ v_{qr}^s \end{bmatrix} = \begin{bmatrix} M_{ds}p & \omega_r M_{qs} \\ -\omega_r M_{ds} & M_{qs}p \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} + \begin{bmatrix} r_r + L_r p & \omega_r L_r \\ -\omega_r L_r & r_r + L_r p \end{bmatrix} \begin{bmatrix} i_{dr}^s \\ i_{qr}^s \end{bmatrix} \tag{2}$$

Stator flux equations:

$$\begin{bmatrix} \lambda_{ds}^s \\ \lambda_{qs}^s \end{bmatrix} = \begin{bmatrix} L_{ds} & 0 \\ 0 & L_{qs} \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} + \begin{bmatrix} M_{ds} & 0 \\ 0 & M_{qs} \end{bmatrix} \begin{bmatrix} i_{dr}^s \\ i_{qr}^s \end{bmatrix} \tag{3}$$

Rotor flux equations:

$$\begin{bmatrix} \lambda_{dr}^{s} \\ \lambda_{qr}^{s} \end{bmatrix} = \begin{bmatrix} M_{ds} & 0 \\ 0 & M_{qs} \end{bmatrix} \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} + \begin{bmatrix} L_{r} & 0 \\ 0 & L_{r} \end{bmatrix} \begin{bmatrix} i_{dr}^{s} \\ i_{qr}^{s} \end{bmatrix} \tag{4}$$

Torque equations:

$$\begin{aligned} T_e &= \frac{pole}{2}\left(M_{qs} i_{qs}^{s} i_{dr}^{s} - M_{ds} i_{ds}^{s} i_{qr}^{s}\right) \\ T_e - T_l &= \frac{2}{pole}\left(Jp\omega_r + B\omega_r\right) \end{aligned} \tag{5}$$

where:

$$\begin{aligned} M_{ds} &= \frac{3}{2} L_{ms}, M_{qs} = \frac{\sqrt{3}}{2} L_{ms} \\ L_{ds} &= L_{ls} + \frac{3}{2} L_{ms}, L_{qs} = L_{ls} + \frac{1}{2} L_{ms}, p = \frac{d}{dt} \end{aligned} \tag{6}$$

In (1)-(6), 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 stationary reference frame (superscript "s"). r_s and r_r indicate the stator and rotor resistances. L_{ds}, L_{qs}, L_r, M_{ds} and M_{qs} denote the stator and rotor d-q axes self and mutual inductances. ω_r is the motor speed. T_e and T_l are electromagnetic torque and load torque. J and B are the moment of inertia and viscous friction coefficient respectively. Note that (1)-(5) are general equations for the three-phase IM. In other words, they may represent either a healthy three-phase IM if $L_{ds}=L_{qs}=L_s=L_{ls}+3/2L_{ms}$ and $M_{ds}=M_{qs}=M=3/2L_{ms}$ or a faulty three-phase IM (three-phase IM under stator winding open-phase fault) if $L_{ds}=L_{ls}+3/2L_{ms}$, $L_{qs}=L_{ls}+1/2L_{ms}$, $M_{ds}=3/2L_{ms}$ and $M_{qs}=\sqrt{3}/2L_{ms}$.

3. FIELD-ORIENTED CONTROL OF FAULTY THREE-PHASE IM

3.1. Problem

Among the various types of the vector control techniques, FOC method is more convenient. In conventional Rotor FOC method and in normal condition, the IM equations are transformed to the rotating reference frame. For this purpose, the following transformation matrix is used [21]:

$$\begin{bmatrix} i_{ds}^{mr} \\ i_{qs}^{mr} \end{bmatrix} = \left[T_s^{mr}\right] \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} = \begin{bmatrix} \cos\theta_{mr} & \sin\theta_{mr} \\ -\sin\theta_{mr} & \cos\theta_{mr} \end{bmatrix} \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} \tag{7}$$

In (7), θ_{mr} is the angle between the stationary reference frame and the rotating reference frame (in this paper superscript "mr" indicates that the variables are in the rotating reference frame). Since the IM studied is asymmetrical, the use of field-orientation principles needs a special attention. The asymmetry is a result of different d and q axis parameters in the faulty IM model. This asymmetry causes an oscillating term in the faulty machine torque [20]. It is possible to remove the oscillating term in the faulty machine electromagnetic torque by using an appropriate control of the stator currents.

3.2. Proposed Method (using Transformation Matrix for Stator Current Variables)

Using following substitutions,

$$\begin{cases} i_{DS} = i_{ds} - j i_{qs} \\ i_{QS} = j\dfrac{M_{ds}}{M_{qs}} i_{ds} + \dfrac{M_{ds}}{M_{qs}} i_{qs} \end{cases} \tag{8}$$

The electromagnetic torque equation of faulty machine can be written as (9):

$$T_e = \frac{pole}{2}\left(jM_{ds} i_{DS} i_{dr} + M_{ds} i_{QS} i_{dr} - M_{ds} i_{DS} i_{qr} - jM_{ds} i_{QS} i_{qr}\right) \tag{9}$$

which gives,

$$T_e = \frac{pole}{2}\left(M_{ds} i_{QS} i_{dr} - M_{ds} i_{DS} i_{qr}\right) \tag{10}$$

As can be seen from (10), faulty machine torque equation becomes similar healthy machine torque equation. Equation (8) can be written as (11):

$$\begin{bmatrix} i_{DS} \\ i_{QS} \end{bmatrix} = \begin{bmatrix} 1 & -j \\ j\dfrac{M_{ds}}{M_{qs}} & \dfrac{M_{ds}}{M_{qs}} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} \tag{11}$$

Using following substitutions,

$$\left.\begin{matrix} 1 \to \cos\theta_{mr} & j \to \sin\theta_{mr} \\ i_{DS} \to i_{ds}^{s} & i_{ds} \to i_{ds}^{mr} \\ i_{QS} \to i_{qs}^{s} & i_{qs} \to i_{qs}^{mr} \end{matrix}\right\} \tag{12}$$

The transformation matrices for the current can be written as (13).

$$\begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} = \begin{bmatrix} \cos\theta_{mr} & -\sin\theta_{mr} \\ \dfrac{M_{ds}}{M_{qs}}\sin\theta_{mr} & \dfrac{M_{ds}}{M_{qs}}\cos\theta_{mr} \end{bmatrix} \begin{bmatrix} i_{ds}^{mr} \\ i_{qs}^{mr} \end{bmatrix} \tag{13}$$

The inverse of (13) gives the proposed transformation matrix for stator current variables:

$$\begin{bmatrix} i_{ds}^{mr} \\ i_{qs}^{mr} \end{bmatrix} = \left[T_{is}^{mr}\right] \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} = \begin{bmatrix} \cos\theta_{mr} & \dfrac{M_{qs}}{M_{ds}}\sin\theta_{mr} \\ -\sin\theta_{mr} & \dfrac{M_{qs}}{M_{ds}}\cos\theta_{mr} \end{bmatrix} \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} \tag{14}$$

Using (14), the new mathematical model can be written as (15) and (16):

Rotor voltage equations:

$$\begin{aligned} \left[T_s^{mr}\right] \begin{bmatrix} v_{dr}^{s} \\ v_{qr}^{s} \end{bmatrix} &= \left[T_s^{mr}\right] \begin{bmatrix} M_{ds} p & \omega_r M_{qs} \\ -\omega_r M_{qs} & M_{qs} p \end{bmatrix} \left[T_{is}^{mr}\right]^{-1} \left[T_{is}^{mr}\right] \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} \\ &+ \left[T_s^{mr}\right] \begin{bmatrix} r_r + L_r p & \omega_r L_r \\ -\omega_r L_r & r_r + L_r p \end{bmatrix} \left[T_s^{mr}\right]^{-1} \left[T_s^{mr}\right] \begin{bmatrix} i_{dr}^{s} \\ i_{qr}^{s} \end{bmatrix} \end{aligned} \tag{15}$$

Torque equation:

$$
\begin{aligned}
T_e &= \frac{pole}{2}(M_{qs} i_{qs}^s i_{dr}^s - M_{ds} i_{ds}^s i_{qr}^s) \\
&= \frac{pole}{2}\begin{bmatrix} i_{dr}^s & i_{qr}^s \end{bmatrix}\begin{bmatrix} 0 & M_{qs} \\ -M_{ds} & 0 \end{bmatrix}\begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} \\
&= \left(\frac{pole}{2}\begin{bmatrix} i_{dr}^s & i_{qr}^s \end{bmatrix}\left[T_s^{mr}\right]^T \left(\left[T_s^{mr}\right]^{-1}\right)^T \right. \\
&\left. \begin{bmatrix} 0 & M_{qs} \\ -M_{ds} & 0 \end{bmatrix}\left[T_{is}^{mr}\right]^{-1}\left[T_{is}^{mr}\right]\begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} \right)
\end{aligned}
\tag{16}
$$

which gives,

Rotor voltage equations:

$$
\begin{aligned}
\begin{bmatrix} 0 \\ 0 \end{bmatrix} &= \begin{bmatrix} M_{ds} p & -(\omega_{mr} - \omega_r) M_{ds} \\ (\omega_{mr} - \omega_r) M_{ds} & M_{ds} p \end{bmatrix}\begin{bmatrix} i_{ds}^{mr} \\ i_{qs}^{mr} \end{bmatrix} \\
&+ \begin{bmatrix} r_r + L_r p & (\omega_{mr} - \omega_r) L_r \\ (\omega_{mr} - \omega_r) L_r & r_r + L_r p \end{bmatrix}\begin{bmatrix} i_{dr}^{mr} \\ i_{qr}^{mr} \end{bmatrix}
\end{aligned}
\tag{17}
$$

Torque equation:

$$T_e = \frac{pole}{2}(M_{ds} i_{qs}^{mr} i_{dr}^{mr} - M_{ds} i_{ds}^{mr} i_{qr}^{mr}) \tag{18}$$

where, ω_{mr} is the angular velocity of the rotor field-oriented reference frame. From (17) and (18), it can be seen that the rotor voltage and the torque equations are similar to the healthy three-phase IM equations. Consequently, it is possible to control faulty machine by the some modifications in the conventional RFO vector control.

3.3. RFOC Equations of Faulty IM

The rotor FOC equations of faulty IM based on equations (17) and (18) can be written as (19)-(21) (to obtain these equations the assumption $\lambda_{dr}^{mr}=|\lambda_r|$ and $\lambda_{qr}^{mr}=0$ has been considered):

Rotor flux equation:

$$|\lambda_r| = \frac{M_{ds} i_{ds}^{mr}}{1 + T_r p} \tag{19}$$

Torque equation:

$$T_e = \frac{pole}{2}\frac{M_{ds}}{L_r}|\lambda_r| i_{qs}^{mr} \tag{20}$$

Speed equation:

$$\omega_{mr} = \omega_r + \frac{M_{ds} i_{qs}^{mr}}{T_r |\lambda_r|} \tag{21}$$

In these equations, T_r is the rotor time constant ($T_r=L_r/r_r$). As can be seen from (19)-(21) the structure of the equations of proposed vector control for faulty three-phase IM is the same as equations of the vector control for healthy three-phase IM. In summery the comparison between conventional and proposed vector control equations is listed in Table 1.

Table 1. The Comparison between Conventional and Proposed Vector Control Equations

	Healthy IM	Faulty IM
Flux equation	$\lvert\lambda_r\rvert = \dfrac{M i_{ds}^{mr}}{1+T_r p}$	$\lvert\lambda_r\rvert = \dfrac{M_{ds} i_{ds}^{mr}}{1+T_r p} = \dfrac{M i_{ds}^{mr}}{1+T_r p}$
Torque equation	$T_e = \dfrac{pole}{2}\dfrac{M}{L_r}\lvert\lambda_r\rvert i_{qs}^{mr}$	$T_e = \dfrac{pole}{2}\dfrac{M_{ds}}{L_r}\lvert\lambda_r\rvert i_{qs}^{mr} = \dfrac{pole}{2}\dfrac{M}{L_r}\lvert\lambda_r\rvert i_{qs}^{mr}$
Speed equation	$\omega_{mr} = \omega_r + \dfrac{M i_{qs}^{mr}}{T_r\lvert\lambda_r\rvert}$	$\omega_{mr} = \omega_r + \dfrac{M_{ds} i_{qs}^{mr}}{T_r\lvert\lambda_r\rvert} = \dfrac{pole}{2}\dfrac{M}{L_r}\lvert\lambda_r\rvert i_{qs}^{mr}$

3.4. Block Diagram of Proposed IRFOC for Faulty Three-Phase IM

From the results of (19)-(21), it is possible to adopt the indirect field-oriented control scheme for faulty three-phase IM using current controller as shown in Figure 2. In Figure 2, the switches are changed from balanced mode to unbalanced mode after fault is happened.

It can be noted that 2 to 2 transformation for stator currents during fault condition as is [20]:

$$\begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} = \frac{\sqrt{2}}{2}\begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix}\begin{bmatrix} i_{as} \\ i_{bs} \end{bmatrix} \tag{22}$$

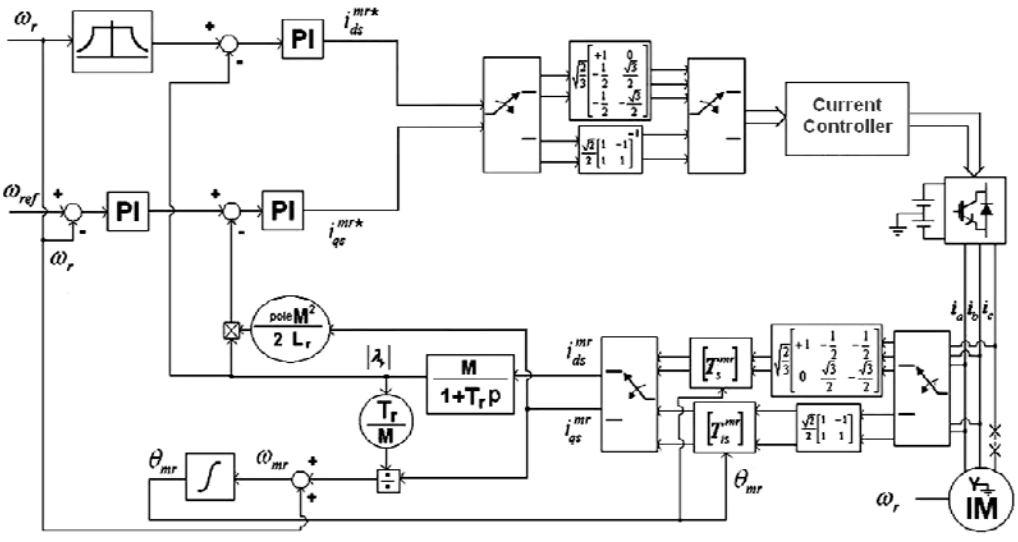

Figure 2. Block diagram of proposed IRFOC of healthy and faulty three-phase IM

4. RESULTS AND COMPARISONS

To verify the effectiveness of the proposed method, different cases using MATLAB software are simulated. Runge-Kutta algorithm is used for solving the healthy and faulty IM dynamic equations. An IM is fed from a SPWM VSI. In this paper it is assumed an immediate open stator winding detection. The ratings and parameters of the simulated motor are as follows:

$v = 125V$, $f = 50HZ$, $P = 4$, $r_s = 20.6\Omega$, $r_r = 19.15\Omega$

$L_{ls} = 0.0814$, $L_{lr} = 0.0814H$, $L_{ms} = 0.851H$, $power = 475W$

Figure 3 shows the comparison between conventional controller and proposed IRFOC (Figure 3 (left): conventional and Figure 3 (right): proposed). In this figure, the IM is starting in the balanced condition. Then a phase cut-off fault is introduced at t=0.5s and the IM becomes unbalanced. Simulation results of the conventional and proposed controller illustrate that the conventional FOC was unable to control the faulty IM correctly. Especially, significant oscillations in the IM torque and speed are observed. It can be seen from Figure 3 that the dynamic performance of the proposed FOC in both healthy and faulty conditions is satisfactory.

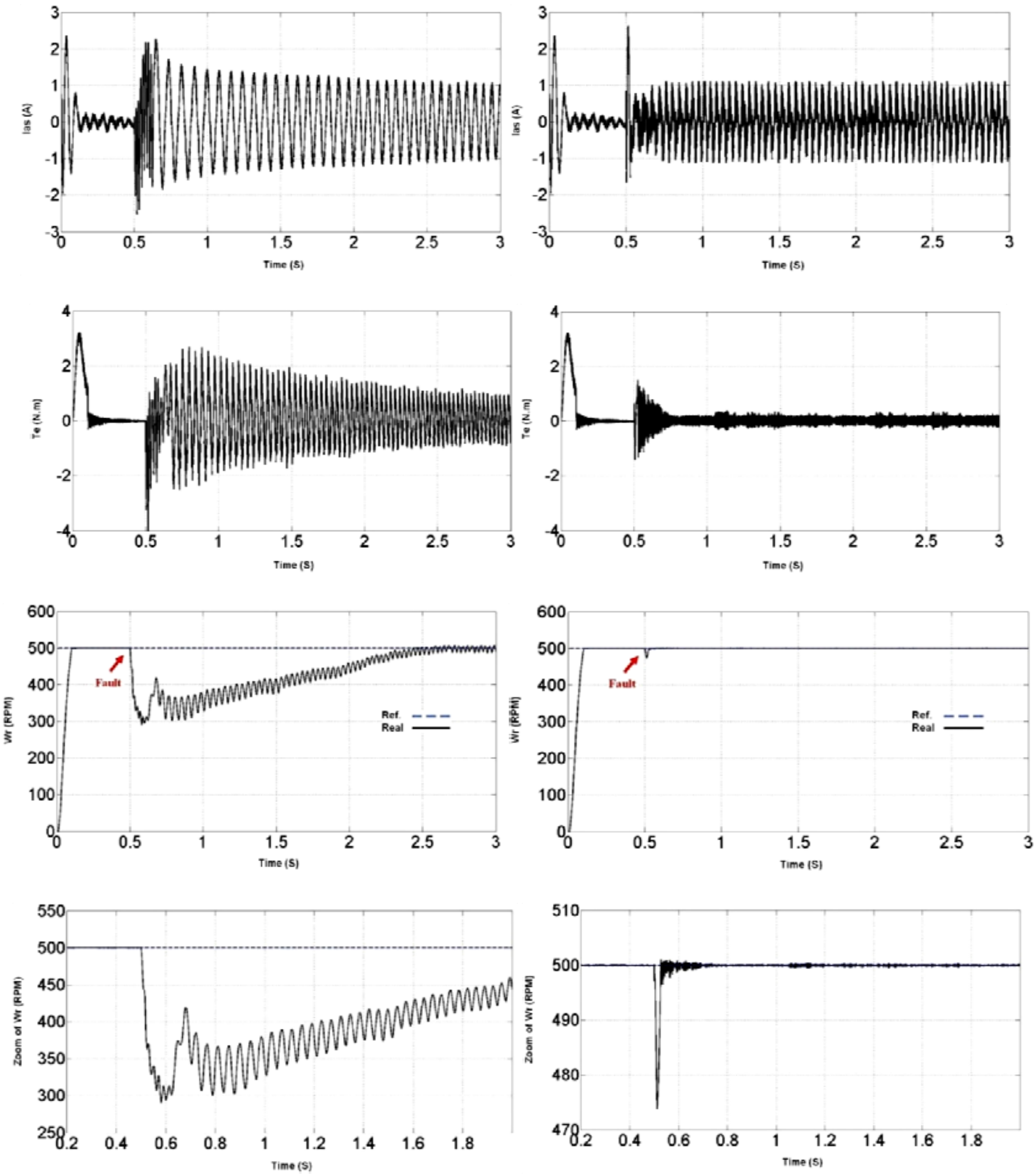

Figure 3. Simulation results of the conventional IRFOC (left) and proposed IRFOC (right); from top to bottom: stator a-axis current, electromagnetic torque, speed and zoom of speed

In Figure 4, two drive systems are tested under the same operating conditions as follows: a phase cut-off fault is introduced at t=2s, the value of the load is increased from zero to 1N.m at t=0.5s and from 1N.m to 1.3N.m at t=2s. Simulation results show that the conventional vector controller cannot control the unbalanced IM properly (see Figure 4 (left)). As can be seen from Figure 4 (left), in the fault condition, significant oscillation is seen in the electromagnetic torque and motor speed (in this case and using conventional controller the oscillation of electromagnetic torque at steady state is about 0.9N.m around the average amount of 1.3N.m). Based on Figure 4 (right) the proposed controller is able to control both healthy and faulty three-phase IM even under load variations. Simulation results of Figure 4 (right) show that the proposed controller reduces the torque oscillation considerably (in this case and using proposed controller the oscillation of electromagnetic torque at steady state is about 0.3N.m).

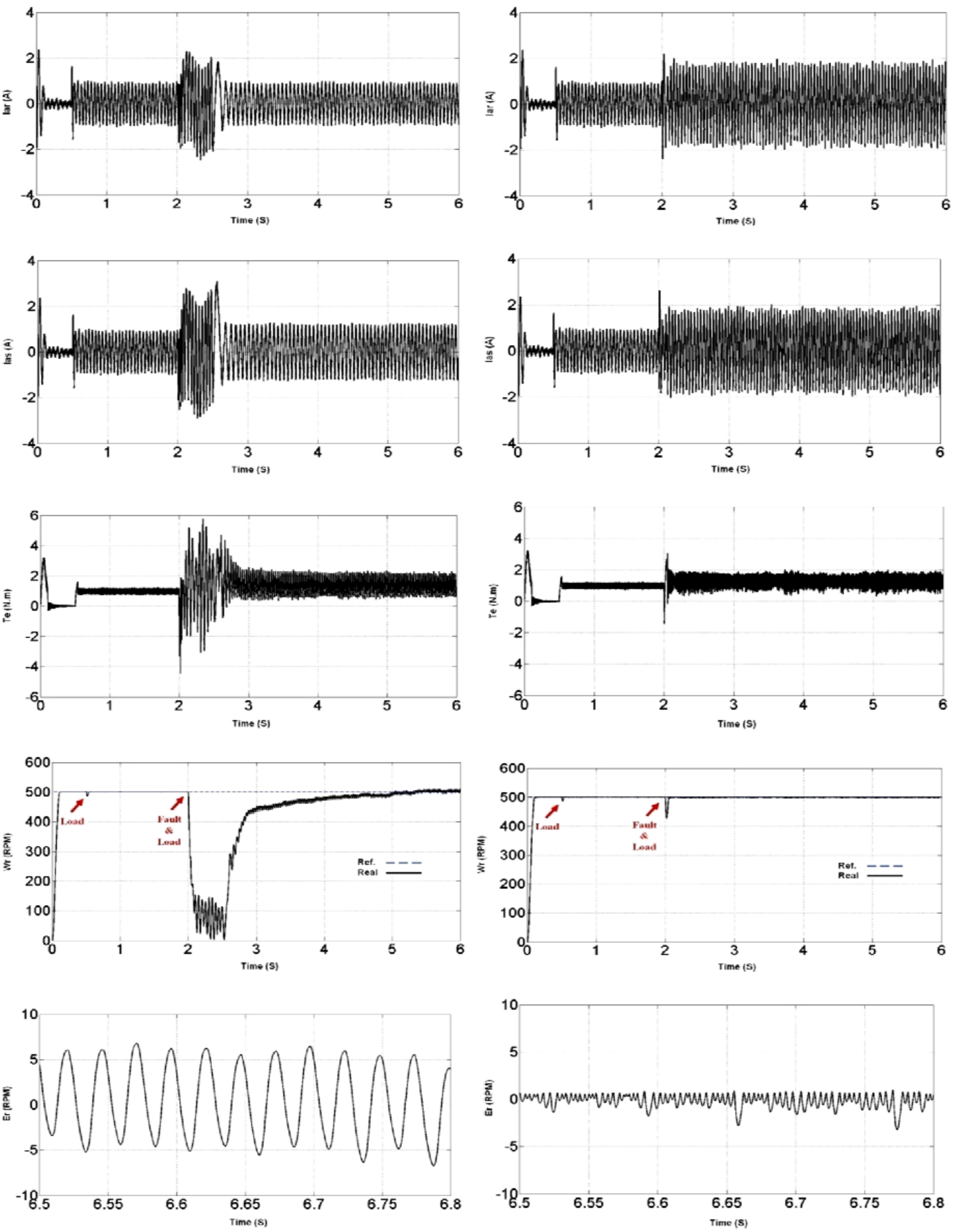

Figure 4. Simulation results of the conventional IRFOC (left) and proposed IRFOC (right); from top to bottom: rotor a-axis current, stator a-axis current, electromagnetic torque, speed and speed error

Figure 5 shows simulation results of the proposed method for healthy and faulty IM in the different values of reference speed (zero/low speed and high speed). In Figure 5, a phase cut-off fault is occurred at t=3s. It is evident from Figure 5 that using proposed technique the three-phase IM during normal and open-phase fault conditions can follow the reference speed without any overshoot and steady-state error. It can be seen from the presented simulation results that the dynamic performance of the proposed fault-tolerant control of three-phase IM drive is acceptable.

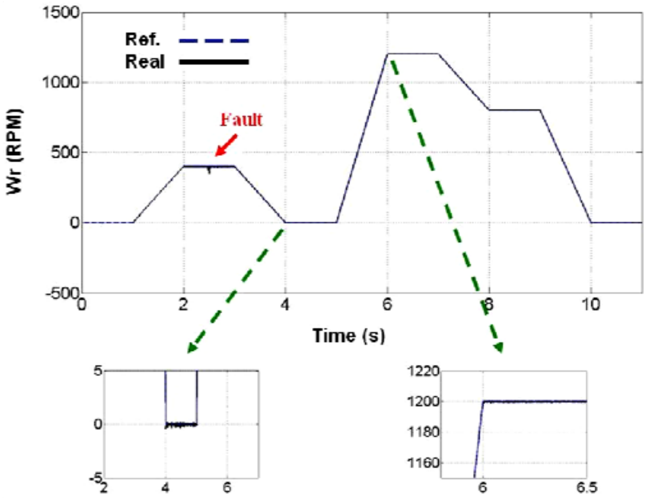

Figure 5. Simulation result of the speed response using proposed IRFOC

5. CONCLUSION

The rotor flux-oriented control of a faulty three-phase IM (three-phase IM under open-phase fault) was presented in this paper. The design of proposed controller for faulty machine was discussed in detail. It was shown that to control three-phase IM under stator winding open-phase fault it is required to use unbalanced transformation matrix for stator current variables to eliminate the oscillating term of the electromagnetic torque. This paper has shown that with some modifications in the structure of conventional RFO controller for healthy three-phase IM it is possible to implement conventional controller for three-phase IM under open-phase fault. Simulation results show that the performance of the proposed vector controller is satisfactory. The applications of the proposed drive system are its use as an emergency scheme for critical industrial applications and vector control of single-phase IM with two main and auxiliary windings.

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