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Novel Method of FOC to Speed Control in Three-Phase IM under Normal and Faulty Conditions

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ABSTRACT

This paper proposes a novel method for speed control of three-phase induction motor (IM) which can be used for both healthy three-phase IM and three-phase IM under open-phase fault. The proposed fault-tolerant control system is derived from conventional field-oriented control (FOC) algorithm with minor changes on it. The presented drive system is based on using an appropriate transformation matrix for the stator current variables. The presented method in this paper can be also used for speed control of single-phase IMs with two windings. The feasibility of the proposed strategy is verified by simulation results.

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1. INTRODUCTION

Recently, the safety and reliability of electric motor drive systems, especially in critical applications, have drawn the attention of many researchers. Fault-tolerant control strategies, which aim to keep a system running continuously after faults have happened, have become a very active research field. A lot of researches have been published on the fault-tolerant control techniques of electrical machines [1]-[20].

Generally, there are three types of faults in three-phase Induction Motor (IM) drive systems: motor faults (such as open-phase fault in stator windings, short-circuit fault in stator windings, broken bar(s), cracked end-ring and etc) [2],[6],[8],[11]-[20], inverter faults (such as open-circuit and short-circuit) [1] and sensor faults (mechanical and electrical) [3]. Open-phase fault is one of the most common problems in industrial applications. Conventional control methods such as Field-Oriented Control (FOC) and Direct Torque Control (DTC) which have been designed based on healthy machine model cannot be directly used to control faulty machine. If conventional controller techniques are applied to the faulty machine, significant oscillations in the machine torque and speed can be observed [11],[12],[15]-[20]. In case of open-phase fault for three-phase IM, the most common technique is to utilize current controller [6],[11],[12],[20]. However, using current controller has problem in light load condition. From [15]-[18], it can be seen that based on voltage controller, two different transformation matrices are needed. The drawback of these strategies is that using two different transformation matrices for stator variables is not good for high performance control applications as in this condition the drive system is sensitive to variations of motor parameters. From the research analyzed above, it can be seen that the fault-tolerant control approaches in three-phase IM drives still remains a challenging task for researchers.

This paper focuses on a novel method for speed control of star-connected three-phase IM under open-phase fault based voltage controller. In the proposed fault-tolerant control system which is based on indirect rotor FOC, a new transformation matrix for stator current variables is introduced and applied. The configuration of the used Voltage Source Inverter (VSI) fed three-phase IM drive system during open-phase fault is shown in Figure 1. During open-phase fault condition as it can be seen from Figure 1, the mid-point of DC-link voltage should be connected to the neutral point of the machine. The rest of this paper is organized as follows. In section 2, the mathematical model of three-phase IM under stator winding open-phase fault is presented. The proposed fault-tolerant control method based FOC algorithm for a three-phase IM is shown in section 3. In order to validate theory and to investigate the performance of the proposed method, simulation results are presented in section 4. Conclusions and remarkable points are listed in section 5.

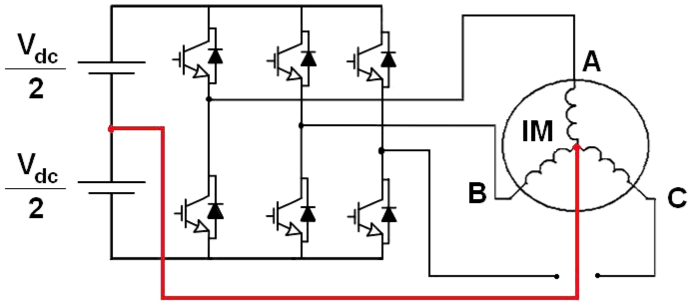

Figure 1. Faulty three-phase IM drive

2. THREE-PHASE IM MODEL UNDER OPEN-PHASE FAULT

The model of three-phase IM under stator winding open-phase fault can be described by the following equations [18]:

Stator voltage equations:

$$\begin{bmatrix} v_{sd}^s \\ v_{sq}^s \end{bmatrix} = \begin{bmatrix} r_s + L_{sd}\frac{d}{dt} & 0 \\ 0 & r_s + L_{sq}\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{sd}^s \\ i_{sq}^s \end{bmatrix} + \begin{bmatrix} M_{sd}\frac{d}{dt} & 0 \\ 0 & M_{sq}\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{rd}^s \\ i_{rq}^s \end{bmatrix} \tag{1}$$

Rotor voltage equations:

$$\begin{bmatrix} v_{rd}^s \\ v_{rq}^s \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} M_{sd}\frac{d}{dt} & \omega_r M_{sq} \\ -\omega_r M_{sd} & M_{sq}\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{sd}^s \\ i_{sq}^s \end{bmatrix} + \begin{bmatrix} r_r + L_r\frac{d}{dt} & \omega_r L_r \\ -\omega_r L_r & r_r + L_r\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{rd}^s \\ i_{rq}^s \end{bmatrix} \tag{2}$$

Torque equations:

$$T_e = \frac{pole}{2}\left(M_{sq} i_{sq}^s i_{rd}^s - M_{sd} i_{sd}^s i_{rq}^s\right)$$
$$T_e - T_l = \frac{2}{pole}\left(J\frac{d}{dt}\omega_r + B\omega_r\right) \tag{3}$$

where:

$$M_{sd} = \frac{3}{2}L_{sm}\ ,\ M_{sq} = \frac{\sqrt{3}}{2}L_{sm}\ ,\ L_{sd} = L_{sl} + \frac{3}{2}L_{sm}\ ,\ L_{sq} = L_{sl} + \frac{1}{2}L_{sm}\ ,\ L_r = L_{rl} + \frac{3}{2}L_{rm} \tag{4}$$

In (1)-(4), v^s_{sd}, v^s_{sq} are the stator d-q axes voltages, v^s_{rd}, v^s_{rq} are the rotor d-q axes voltages, i^s_{sd}, i^s_{sq} are the stator d-q axes currents, i^s_{rd}, i^s_{rq} are the rotor d-q axes currents in the stationary reference frame (superscript "*s*"). r_s and r_r are the stator and rotor resistances. L_{sd}, L_{sq}, L_r, L_{sl}, L_{sm}, L_{rl}, L_{rm}, M_{sd} and M_{sq} indicate the stator and rotor d-q axes self, mutual and leakage inductances. ω_r is the motor electrical speed. T_e and T_l show electromagnetic torque and load torque. *J* and *B* are the moment of inertia and viscous friction coefficient respectively.

3. PROPOSED FOC METHOD FOR THREE-PHASE IM UNDER OPEN-PHASE FAULT

Among the various vector based control methods, FOC technique is more convenient. However, due to the unsymmetrical structure of three-phase IM model under open-phase fault, the conventional FOC method cannot be employed for faulty machine. This asymmetry causes oscillations in the motor electromagnetic torque. It is possible to remove the asymmetrical term in the faulty three-phase IM by using a suitable transformation matrix for the stator current variables as follows:

$$\left[T^e_{si}\right]=\begin{bmatrix}\cos\theta_e & \dfrac{M_{sq}}{M_{sd}}\sin\theta_e \\ -\sin\theta_e & \dfrac{M_{sq}}{M_{sd}}\cos\theta_e\end{bmatrix} \tag{5}$$

where, θ_e is the angle between the stationary reference frame and the rotating reference frame. Using (5), the new mathematical model for three-phase IM under open-phase fault can be written as (6)-(9):

Stator voltage equations:

$$\left[T^e_s\right]\begin{bmatrix}v^s_{sd}\\ v^s_{sq}\end{bmatrix}=\left[T^e_s\right]\begin{bmatrix}r_s+L_{sd}\dfrac{d}{dt} & 0\\ 0 & r_s+L_{sq}\dfrac{d}{dt}\end{bmatrix}\left[T^e_{si}\right]^{-1}\left[T^e_{si}\right]\begin{bmatrix}i^s_{sd}\\ i^s_{sq}\end{bmatrix}+\left[T^e_s\right]\begin{bmatrix}M_{sd}\dfrac{d}{dt} & 0\\ 0 & M_{sq}\dfrac{d}{dt}\end{bmatrix}\left[T^e_s\right]^{-1}\left[T^e_s\right]\begin{bmatrix}i^s_{rd}\\ i^s_{rq}\end{bmatrix} \tag{6}$$

Rotor voltage equations:

$$\begin{bmatrix}0\\0\end{bmatrix}=\left[T^e_s\right]\begin{bmatrix}M_{sd}\dfrac{d}{dt} & \omega_r M_{sq}\\ -\omega_r M_{sq} & M_{sq}\dfrac{d}{dt}\end{bmatrix}\left[T^e_{si}\right]^{-1}\left[T^e_{si}\right]\begin{bmatrix}i^s_{sd}\\ i^s_{sq}\end{bmatrix}+\left[T^e_s\right]\begin{bmatrix}r_r+L_r\dfrac{d}{dt} & \omega_r L_r\\ -\omega_r L_r & r_r+L_r\dfrac{d}{dt}\end{bmatrix}\left[T^e_s\right]^{-1}\left[T^e_s\right]\begin{bmatrix}i^s_{rd}\\ i^s_{rq}\end{bmatrix} \tag{7}$$

Torque equation:

$$\begin{aligned}T_e&=\frac{pole}{2}(M_{sq}i^s_{sq}i^s_{rd}-M_{sd}i^s_{sd}i^s_{rq})=\frac{pole}{2}\begin{bmatrix}i^s_{rd} & i^s_{rq}\end{bmatrix}\begin{bmatrix}0 & M_{sq}\\ -M_{sd} & 0\end{bmatrix}\begin{bmatrix}i^s_{sd}\\ i^s_{sq}\end{bmatrix}\\ &=\left(\frac{pole}{2}\begin{bmatrix}i^s_{rd} & i^s_{rq}\end{bmatrix}\left[T^e_s\right]^T\left(\left[T^e_s\right]^{-1}\right)^T\begin{bmatrix}0 & M_{sq}\\ -M_{sd} & 0\end{bmatrix}\left[T^e_{si}\right]^{-1}\left[T^e_{si}\right]\begin{bmatrix}i^s_{sd}\\ i^s_{sq}\end{bmatrix}\right)\end{aligned} \tag{8}$$

where,

$$\left[T^e_s\right]=\begin{bmatrix}\cos\theta_e & \sin\theta_e\\ -\sin\theta_e & \cos\theta_e\end{bmatrix} \tag{9}$$

(6)-(8) gives,

Stator voltage equations:

$$\begin{bmatrix} v_{sd}^{e} \\ v_{sq}^{e} \end{bmatrix} = \begin{bmatrix} r_s + \left(\frac{L_{sd}+L_{sq}}{2}\right)\frac{d}{dt} & -\omega_e\left(\frac{L_{sd}+L_{sq}}{2}\right) \\ \omega_e\left(\frac{L_{sd}+L_{sq}}{2}\right) & r_s + \left(\frac{L_{sd}+L_{sq}}{2}\right)\frac{d}{dt} \end{bmatrix}\begin{bmatrix} i_{sd}^{e} \\ i_{sq}^{e} \end{bmatrix} + \begin{bmatrix} \left(\frac{M_{sd}^2+M_{sq}^2}{2M_{sq}}\right)\frac{d}{dt} & -\omega_e\left(\frac{M_{sd}^2+M_{sq}^2}{2M_{sq}}\right) \\ \omega_e\left(\frac{M_{sd}^2+M_{sq}^2}{2M_{sq}}\right) & \left(\frac{M_{sd}^2+M_{sq}^2}{2M_{sq}}\right)\frac{d}{dt} \end{bmatrix}\begin{bmatrix} i_{rd}^{e} \\ i_{rq}^{e} \end{bmatrix} \quad (10)$$

$$+\begin{bmatrix} \left(\frac{L_{sd}-L_{sq}}{2}\right)\frac{d}{dt} & \omega_e\left(\frac{L_{sd}-L_{sq}}{2}\right) \\ \omega_e\left(\frac{L_{sd}-L_{sq}}{2}\right) & -\left(\frac{L_{sd}-L_{sq}}{2}\right)\frac{d}{dt} \end{bmatrix}\begin{bmatrix} i_{sd}^{-e} \\ i_{sq}^{-e} \end{bmatrix} + \begin{bmatrix} \left(\frac{M_{sd}^2-M_{sq}^2}{2M_{sq}}\right)\frac{d}{dt} & \omega_e\left(\frac{M_{sd}^2-M_{sq}^2}{2M_{sq}}\right) \\ \omega_e\left(\frac{M_{sd}^2-M_{sq}^2}{2M_{sq}}\right) & -\left(\frac{M_{sd}^2-M_{sq}^2}{2M_{sq}}\right)\frac{d}{dt} \end{bmatrix}\begin{bmatrix} i_{rd}^{-e} \\ i_{rq}^{-e} \end{bmatrix}$$

Rotor voltage equations:

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} M_{sd}\frac{d}{dt} & -(\omega_e-\omega_r)M_{sd} \\ (\omega_e-\omega_r)M_{sd} & M_{sd}\frac{d}{dt} \end{bmatrix}\begin{bmatrix} i_{sd}^{e} \\ i_{sq}^{e} \end{bmatrix} + \begin{bmatrix} r_r + L_r\frac{d}{dt} & (\omega_e-\omega_r)L_r \\ (\omega_e-\omega_r)L_r & r_r + L_r\frac{d}{dt} \end{bmatrix}\begin{bmatrix} i_{rd}^{e} \\ i_{rq}^{e} \end{bmatrix} \quad (11)$$

Torque equation:

$$T_e = \frac{pole}{2}(M_{sd}i_{sq}^{e}i_{rd}^{e} - M_{sd}i_{sd}^{e}i_{rq}^{e}) \quad (12)$$

where,

$$\begin{bmatrix} i_{sd}^{-e} \\ i_{sq}^{-e} \end{bmatrix} = \begin{bmatrix} \cos\theta_e & -\frac{M_{sq}}{M_{sd}}\sin\theta_e \\ \sin\theta_e & \frac{M_{sq}}{M_{sd}}\cos\theta_e \end{bmatrix}\begin{bmatrix} i_{sd}^{s} \\ i_{sq}^{s} \end{bmatrix} \quad (13a)$$

$$\begin{bmatrix} i_{rd}^{-e} \\ i_{rq}^{-e} \end{bmatrix} = \begin{bmatrix} \cos\theta_e & -\frac{M_{sq}}{M_{sd}}\sin\theta_e \\ \sin\theta_e & \frac{M_{sq}}{M_{sd}}\cos\theta_e \end{bmatrix}\begin{bmatrix} i_{rd}^{s} \\ i_{rq}^{s} \end{bmatrix} \quad (13b)$$

In these equations, ω_e is the angular velocity of the rotor field-oriented reference frame. From (10)-(12), it can be seen that the stator voltages, rotor voltages and the torque equations are similar to the healthy three-phase IM equations. However, the stator voltage equation (equation (10)) has an extra term (superscript "e"). Consequently, it is possible to control three-phase IM by the some modifications in the conventional controller.

In summery the comparison between healthy three-phase IM equations and equations (10)-(12) is listed in Table 1.

Table 1. The Comparison between Three-Phase IM Equations and Equations (10)-(12)

	Three-phase IM	Equations (10)-(12)
Stator voltage equations	$\begin{bmatrix} v_{sd}^e \\ v_{sq}^e \end{bmatrix} = \begin{bmatrix} r_s + L_{sd}\frac{d}{dt} & -\omega_e L_{sd} \\ \omega_e L_{sd} & r_s + L_{sd}\frac{d}{dt} \end{bmatrix}\begin{bmatrix} i_{sd}^e \\ i_{sq}^e \end{bmatrix} + \begin{bmatrix} M_{sd}\frac{d}{dt} & -\omega_e M_{sd} \\ \omega_e M_{sd} & M_{sd}\frac{d}{dt} \end{bmatrix}\begin{bmatrix} i_{rd}^e \\ i_{rq}^e \end{bmatrix}$	$\begin{bmatrix} v_{sd}^e \\ v_{sq}^e \end{bmatrix} = \begin{bmatrix} r_s + \left(\frac{L_{sd}+L_{sq}}{2}\right)\frac{d}{dt} & -\omega_e\left(\frac{L_{sd}+L_{sq}}{2}\right) \\ \omega_e\left(\frac{L_{sd}+L_{sq}}{2}\right) & r_s + \left(\frac{L_{sd}+L_{sq}}{2}\right)\frac{d}{dt} \end{bmatrix}\begin{bmatrix} i_{sd}^e \\ i_{sq}^e \end{bmatrix} + \begin{bmatrix} \left(\frac{M_{sd}^2+M_{sq}^2}{2M_{sq}}\right)\frac{d}{dt} & -\omega_e\left(\frac{M_{sd}^2+M_{sq}^2}{2M_{sq}}\right) \\ \omega_e\left(\frac{M_{sd}^2+M_{sq}^2}{2M_{sq}}\right) & \left(\frac{M_{sd}^2+M_{sq}^2}{2M_{sq}}\right)\frac{d}{dt} \end{bmatrix}\begin{bmatrix} i_{rd}^e \\ i_{rq}^e \end{bmatrix} + \begin{bmatrix} \left(\frac{L_{sd}-L_{sq}}{2}\right)\frac{d}{dt} & \omega_e\left(\frac{L_{sd}-L_{sq}}{2}\right) \\ \omega_e\left(\frac{L_{sd}-L_{sq}}{2}\right) & -\left(\frac{L_{sd}-L_{sq}}{2}\right)\frac{d}{dt} \end{bmatrix}\begin{bmatrix} i_{sd}^{-e} \\ i_{sq}^{-e} \end{bmatrix} + \begin{bmatrix} \left(\frac{M_{sd}^2-M_{sq}^2}{2M_{sq}}\right)\frac{d}{dt} & \omega_e\left(\frac{M_{sd}^2-M_{sq}^2}{2M_{sq}}\right) \\ \omega_e\left(\frac{M_{sd}^2-M_{sq}^2}{2M_{sq}}\right) & -\left(\frac{M_{sd}^2-M_{sq}^2}{2M_{sq}}\right)\frac{d}{dt} \end{bmatrix}\begin{bmatrix} i_{rd}^{-e} \\ i_{rq}^{-e} \end{bmatrix}$
Rotor voltage equations	$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} M_{sd}\frac{d}{dt} & -(\omega_e-\omega_r)M_{sd} \\ (\omega_e-\omega_r)M_{sd} & M_{sd}\frac{d}{dt} \end{bmatrix}\begin{bmatrix} i_{sd}^e \\ i_{sq}^e \end{bmatrix} + \begin{bmatrix} r_r + L_r\frac{d}{dt} & (\omega_e-\omega_r)L_r \\ (\omega_e-\omega_r)L_r & r_r + L_r\frac{d}{dt} \end{bmatrix}\begin{bmatrix} i_{rd}^e \\ i_{rq}^e \end{bmatrix}$	$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} M_{sd}\frac{d}{dt} & -(\omega_e-\omega_r)M_{sd} \\ (\omega_e-\omega_r)M_{sd} & M_{sd}\frac{d}{dt} \end{bmatrix}\begin{bmatrix} i_{sd}^e \\ i_{sq}^e \end{bmatrix} + \begin{bmatrix} r_r + L_r\frac{d}{dt} & (\omega_e-\omega_r)L_r \\ (\omega_e-\omega_r)L_r & r_r + L_r\frac{d}{dt} \end{bmatrix}\begin{bmatrix} i_{rd}^e \\ i_{rq}^e \end{bmatrix}$
Torque equation	$T_e = \frac{pole}{2}(M_{sd}i_{sq}^e i_{rd}^e - M_{sd}i_{sd}^e i_{rq}^e)$	$T_e = \frac{pole}{2}(M_{sd}i_{sq}^e i_{rd}^e - M_{sd}i_{sd}^e i_{rq}^e)$

Based on equations (10)-(12), the rotor FOC equations of three-phase IM can be written as (14)-(15g) (to obtain these equations the assumption $\lambda_{rd}^e=|\lambda_r|$ and $\lambda_{rq}^e=0$ has been considered):

$$|\lambda_r| = \frac{M_{sd}i_{sd}^e}{1+\frac{L_r}{r_r}\frac{d}{dt}} \quad , \quad T_e = \frac{pole}{2}\frac{M_{sd}}{L_r}|\lambda_r| i_{sq}^e \quad , \quad \omega_e = \omega_r + \frac{M_{sd}i_{sq}^e}{\frac{L_r}{r_r}|\lambda_r|}$$
$$v_{sd}^e = v_{sd}^{ref} + v_{sd}^d + v_{sd}^{-e} \quad , \quad v_{sq}^e = v_{sq}^{ref} + v_{sq}^d + v_{sq}^{-e} \tag{14}$$

where,

$$v_{sd}^{ref} = r_s i_{sd}^e + \left[\left(\frac{L_{sd}+L_{sq}}{2}\right) - \frac{\left(\frac{M_{sd}^2+M_{sq}^2}{2M_{sq}}\right)^2}{L_r}\right]\frac{d}{dt}i_{sd}^e \tag{15a}$$

$$v_{sd}^{d}=-\omega_e\left[\left(\frac{L_{sd}+L_{sq}}{2}\right)-\frac{\left(\frac{M_{sd}^2+M_{sq}^2}{2M_{sq}}\right)^2}{L_r}\right]i_{sq}^{e}+\left(\frac{\left(\frac{M_{sd}^2+M_{sq}^2}{2M_{sq}}\right)}{L_r}\right)\left(\frac{\left(\frac{M_{sd}^2+M_{sq}^2}{2M_{sq}}\right)i_{sd}^{e}-|\lambda_r|}{\frac{L_r}{r_r}}\right) \quad (15b)$$

$$v_{sd}^{-e}=\left(\frac{L_{sd}-L_{sq}}{2}\right)\frac{d}{dt}i_{sd}^{-e}+\omega_e\left(\frac{L_{sd}-L_{sq}}{2}\right)i_{sq}^{-e}+\left(\frac{M_{sd}^2-M_{sq}^2}{2M_{sq}}\right)\frac{d}{dt}i_{rd}^{-e}+\omega_e\left(\frac{M_{sd}^2-M_{sq}^2}{2M_{sq}}\right)i_{rq}^{-e} \quad (15c)$$

$$v_{sq}^{ref}=r_s i_{sq}^{e}+\left[\left(\frac{L_{sd}+L_{sq}}{2}\right)-\frac{\left(\frac{M_{sd}^2+M_{sq}^2}{2M_{sq}}\right)^2}{L_r}\right]\frac{d}{dt}i_{sq}^{e} \quad (15d)$$

$$v_{sq}^{d}=\omega_e\left[\left(\frac{L_{sd}+L_{sq}}{2}\right)-\frac{\left(\frac{M_{sd}^2+M_{sq}^2}{2M_{sq}}\right)^2}{L_r}\right]i_{sd}^{e}+\omega_e\frac{\left(\frac{M_{sd}^2+M_{sq}^2}{2M_{sq}}\right)|\lambda_r|}{L_r} \quad (15e)$$

$$v_{sq}^{-e}=\omega_e\left(\frac{L_{sd}-L_{sq}}{2}\right)i_{sd}^{-e}-\left(\frac{L_{sd}-L_{sq}}{2}\right)\frac{d}{dt}i_{sq}^{-e}+\omega_e\left(\frac{M_{sd}^2-M_{sq}^2}{2M_{sq}}\right)i_{rd}^{-e}-\left(\frac{M_{sd}^2-M_{sq}^2}{2M_{sq}}\right)\frac{d}{dt}i_{rq}^{-e} \quad (15f)$$

$$\begin{bmatrix} i_{rd}^{-e} \\ i_{rq}^{-e} \end{bmatrix}=\begin{bmatrix} \cos\theta_e & -\frac{M_{rq}}{M_{rd}}\sin\theta_e \\ \sin\theta_e & \frac{M_{rq}}{M_{rd}}\cos\theta_e \end{bmatrix}\left(\begin{bmatrix} \cos\theta_e & \sin\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix}\right)^{-1}\begin{bmatrix} \frac{|\lambda_r|}{L_r}-\frac{M_{sd}}{L_r}i_{sd}^{e} \\ -\frac{M_{sd}}{L_r}i_{sq}^{e} \end{bmatrix} \quad (15g)$$

From the equations (14)-(15g), it is possible to adopt the indirect rotor FOC scheme for three-phase IM under open-phase fault as shown in Figure 2. It can be noted that Figure 2 can be used for both healthy and faulty three-phase IM. The necessary blocks in Figure 2 which should be changed from healthy mode to faulty mode are shown in red. These changes are given in Table 2. Moreover, the block diagram of Decoupling Circuit in Figure 2 is shown in Figure 3.

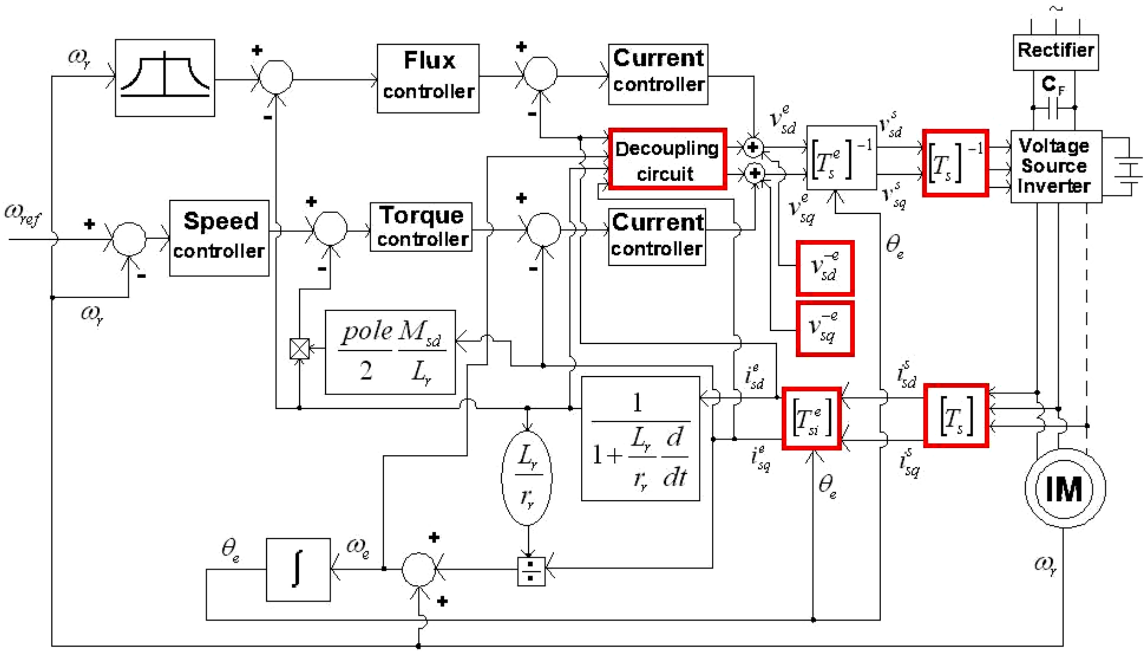

Figure 2. Block diagram of indirect rotor FOC of healthy and faulty three-phase IM

Table 2. The Necessary Changes in Figure 2 from Healthy Mode to Faulty Mode

Normal condition	Faulty condition
3 to 2 transformation for the stator currents [21]	2 to 2 transformation for the stator currents [18]
$[T_s]=\sqrt{\frac{2}{3}}\begin{bmatrix} +1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}$	$[T_s]=\frac{\sqrt{2}}{2}\begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix}$
Transformation matrix for the stator currents [21]	Transformation matrix for the stator currents
$[T_{si}^e]=\begin{bmatrix} \cos\theta_e & \sin\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix}$	$[T_{si}^e]=\begin{bmatrix} \cos\theta_e & \frac{M_{sq}}{M_{sd}}\sin\theta_e \\ -\sin\theta_e & \frac{M_{sq}}{M_{sd}}\cos\theta_e \end{bmatrix}$
Stator self and mutual inductances used in Decoupling Circuit block [21]	Stator self and mutual inductances used in Decoupling Circuit block
$L_s = L_{sl} + \frac{3}{2}L_{sm}, M = \frac{3}{2}L_{sm}$	$L_s = \left(\frac{L_{sd}+L_{sq}}{2}\right), \; M = \left(\frac{M_{sd}^2+M_{sq}^2}{2M_{sq}}\right)$
Extra terms in the stator voltage equations	Extra terms in the stator voltage equations
--------------------	$v_{sd}^{-e} = \left(\frac{L_{sd}-L_{sq}}{2}\right)\frac{d}{dt}i_{sd}^{-e} + \omega_e\left(\frac{L_{sd}-L_{sq}}{2}\right)i_{sq}^{-e} + \left(\frac{M_{sd}^2-M_{sq}^2}{2M_{sq}}\right)\frac{d}{dt}i_{rd}^{-e} + \omega_e\left(\frac{M_{sd}^2-M_{sq}^2}{2M_{sq}}\right)i_{rq}^{-e}$ $v_{sq}^{-e} = \omega_e\left(\frac{L_{sd}-L_{sq}}{2}\right)i_{sd}^{-e} - \left(\frac{L_{sd}-L_{sq}}{2}\right)\frac{d}{dt}i_{sq}^{-e} + \omega_e\left(\frac{M_{sd}^2-M_{sq}^2}{2M_{sq}}\right)i_{rd}^{-e} - \left(\frac{M_{sd}^2-M_{sq}^2}{2M_{sq}}\right)\frac{d}{dt}i_{rq}^{-e}$

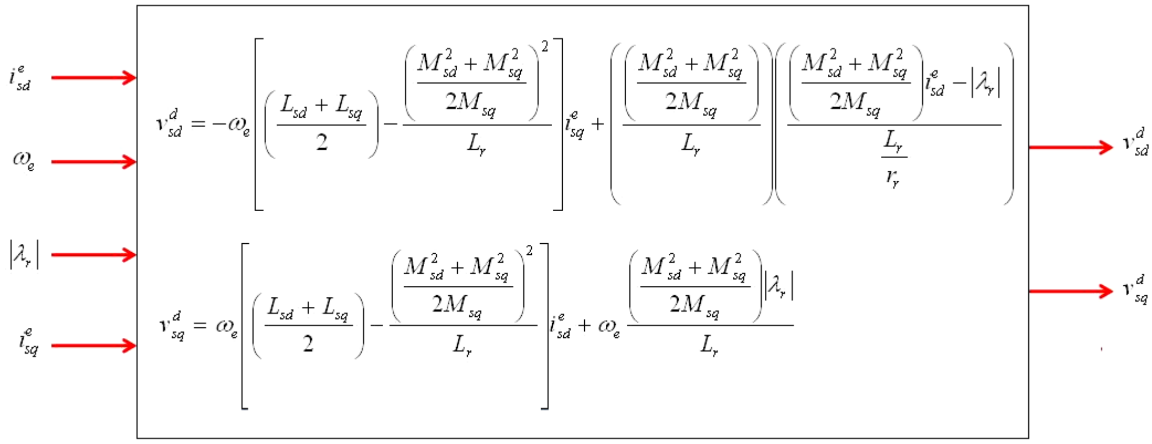

Figure 3. Block diagram of Decoupling Circuit

4. SIMULATION RESULTS

To verify the effectiveness of the proposed fault-tolerant control strategy, different simulations using MATLAB (M-File) software are carried out. A star-connected three-phase IM is fed from a SPWM VSI. In this paper it is assumed an immediate open-phase fault detection. The ratings and parameters of the simulated IM 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 4 shows simulation results of the proposed technique for speed control of healthy and faulty three-phase IM in different values of reference speed (in this test from t=0s to t=2s, ω_{ref}=500RPM. From t=2s to t=4s, ω_{ref}=600RPM. From t=4s to t=5s, ω_{ref}=300RPM). In Figure 4, the three-phase IM is starting in the balanced (healthy) condition then a phase cut-off fault occurred at t=1s. Moreover, the value of the load is 0.5N.m (load is applied from starting). It is evident from Figure 4 that using proposed FOC method, the three-phase IM under various conditions and open-phase fault can follow the reference speed without any overshoot and steady-state errors. Also, using proposed technique the motor currents in both healthy and faulty conditions are sinusoidal. It can be seen from the presented simulation results that the dynamic performance of the proposed fault-tolerant control drive system is acceptable.

Figure 5 show simulation results of the proposed dive system for indirect rotor FOC of healthy and faulty three-phase IM in high reference speed (ω_{ref}=1500RPM). In Figure 5, a phase cut-off fault is occurred at the start (t=0s). Furthermore, in this figure the value of the load is changed from 0N.m to 0.5N.m at t=2s. Based on Figure 5, simulation results of the proposed controller confirm that the introduced controller is able to control the faulty IM correctly. The difference between the real and reference speeds remains very small even during open-phase fault. As can be seen from Figure 5, the proposed method produces a reasonable ripple in the speed and torque responses. It is seen that from Figure 5 that the dynamic performance of the proposed strategy for vector control of both healthy and faulty machines is satisfactory.

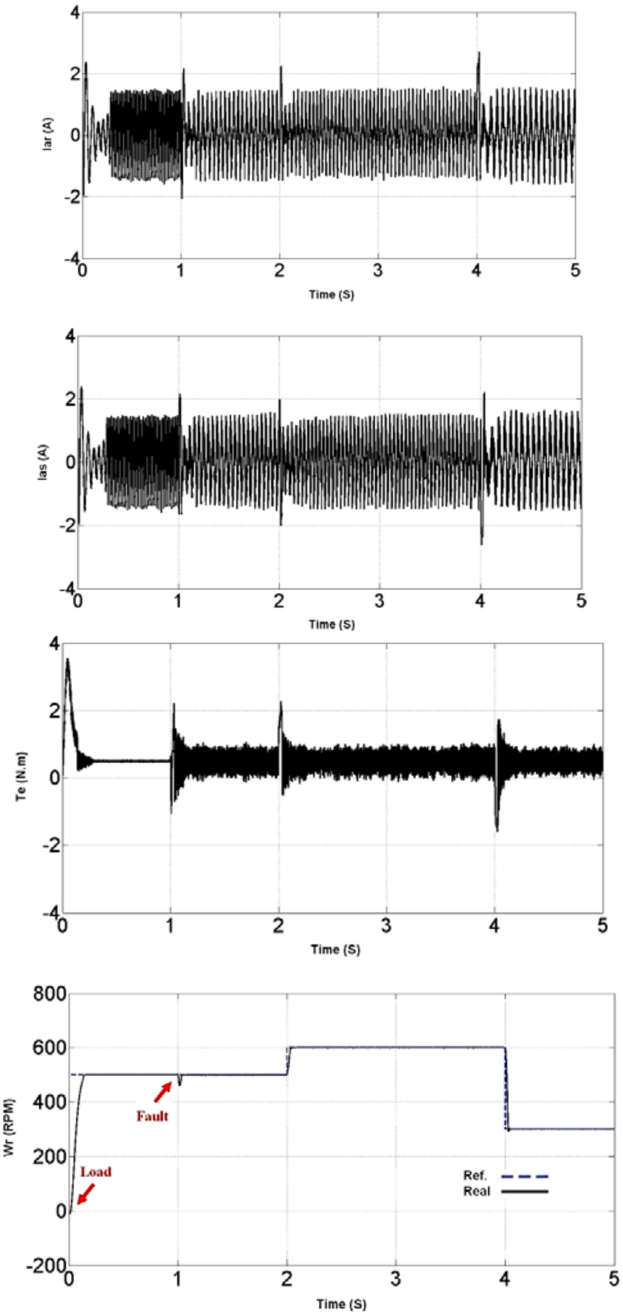

Figure 4. Simulation results of the proposed method in the different values of reference speed, from top to bottom: Rotor a-axis current, Stator a-axis current, Electromagnetic torque, Speed

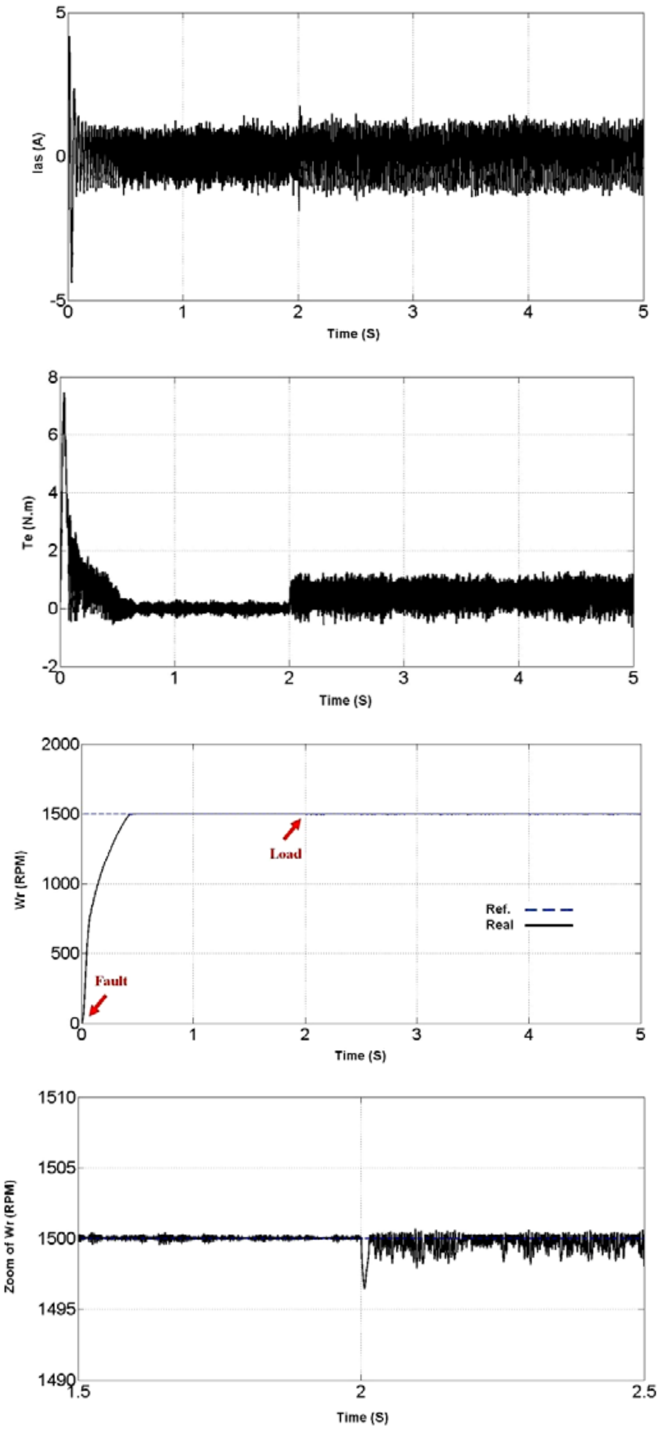

Figure 5. Simulation results of the proposed method in the high speed reference, from top to bottom: Stator a-axis current, Electromagnetic torque, Speed, Zoom of speed

5. CONCLUSION

This paper proposes a technique for rotor field-oriented control of three-phase IM drive which can be used for both healthy three-phase IM and three-phase IM under open-phase fault. The design of proposed fault-tolerant control system was discussed in detail. It was shown that with some changes on the conventional field-oriented control algorithm it is possible to control three-phase IM under open-phase fault. Simulation results indicate that the performance of the proposed fault-tolerant control system is satisfactory.

The application of the proposed method is its use for vector control of single-phase IM with main and auxiliary windings.

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