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Indirect Flux-Oriented Control of Faulty Single-Phase Induction Motors

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Abstract

Most types of electrical machines such as Induction Motors (IMs) can be modeled by an equivalent 2-phase machine (d-q model). For instance a single-phase IM with two main and auxiliary windings can be modeled as an equivalent 2-phase IM. Also a faulty single-phase IM (single-phase IM under open-phase fault) can be modeled as an unbalanced 2-phase IM. This study confirms this concept by modeling a single-phase IM with one of its stator phases, open. In addition the study shows that the vector control of this faulty IM can be performed by some modifications in the vector control of healthy IM (the proposed vector control in this paper is based on Indirect Flux-Oriented Control (IFOC)). MATLAB simulation results show the good performance of the proposed technique.

Keywords: *modeling, single-phase IM, open-phase fault, IFOC, simulation*

1. Introduction

One of the most known failures in stator windings of the Induction Motors (IMs) is open circuit. Some causes such as mechanical stirring machine, blown fuses, open coils and etc. make this failure. Recently, various techniques have been developed to indicate stator winding failures in IMs [1-3]. In [1] based on query tables and neural networks and in [2], a technique based on unfamiliar input observer and Extended Kalman Filter (EKF) have been proposed for detection of fault in IM stator windings. In [3], a balanced 3-phase small amplitude signal with high frequency was used to detect open-phase fault in stator windings. This method provides almost immediate open stator winding detection and is assumed in this paper.

One of the most general techniques for controlling the speed and torque in IMs is Flux-Oriented Control (FOC). In the last decades, various control methods were introduced for controlling single-phase IMs (or 2-phase IMs) which are listed as follows: In [4-6], Rotor Flux-Oriented Control (RFOC) of 2-phase IM with hysteresis current controller has been presented. In [7], Stator Flux-Oriented Control (SFOC) of single-phase IM with current double sequence controller was presented. A novel decoupling vector control of single-phase IM was suggested in [8]. Common problems encountered in the conventional vector control of single-phase IMs has been discussed in paper [9]. In this paper, a method based on FOC for a symmetrical 2-phase IM as replacement has been proposed. In [10-12], several exact models for vector control of 2-phase IMs based on FOC have been peoposed. High performance FOC of 2-phase IM with rotor speed estimation using Model Reference Adaptive System (MRAS) in [13], EKF in Ref, [14-16] and motor model in [6, 17] has been presented.

In spite of excellent performance of conventional vector control for IMs, its ability in controlling faulty motors is not good [19, 20]. This study concerns with the problem of modeling and vector control of faulty IMs. This paper explains a modeling method for a single-phase IM under open-phase fault. Based on this modeling, a new vector control method based on FOC is proposed. This control technique can be used to control a single-phase IM under healthy and faulty conditions (the fault condition in this paper is limited to open-phase fault). This study shows that the vector control of healthy and faulty single-phase IM can be performed by using transformation matrices and some modifications in the conventional FOC for 3-phase IM.

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2. Modeling of a Single-phase IM with One Opened Phase

Suppose that a phase cut off fault has been occurred in the auxiliary winding of a single-phase IM (b axis). Assuming sinusoidal waveform for the spatial distribution of the windings, stator and rotor flux axes can be shown as follows:

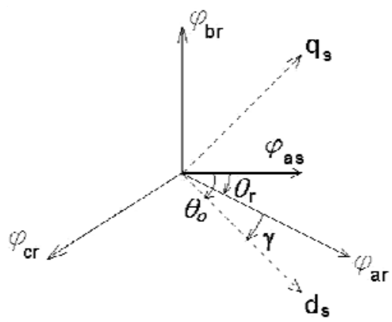


Figure 1. Stator and Rotor Winding's Flux Axes

d and *q* components of the stator fluxes can be written as following equations:

$$d_s = \varphi_{as} \cos\theta_o \quad , \quad q_s = \varphi_{as} \sin\theta_o \tag{1}$$

In (1), θ_o is the angle between a_s and d_s axes. The transformation vectors must be perpendicular to each other, therefore from Equation (1):

$$\sin\theta_o \cos\theta_o = 0 \Rightarrow \theta_o = 0 \text{ or } \frac{\pi}{2} \tag{2}$$

If we suppose that θ_o=0, the following normalized transformation matrix for the stator variables ($[T_s]$) is obtained.

$$[T_s] = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \tag{3}$$

Because the rotor variables are still in the balanced condition, the decomposition matrix for rotor variables ($[T_r]$) remains unchanged as follows [21]:

$$[T_r] = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin\gamma & \sin\left(\gamma - \frac{2\pi}{3}\right) & \sin\left(\gamma + \frac{2\pi}{3}\right) \\ \cos\gamma & \cos\left(\gamma - \frac{2\pi}{3}\right) & \cos\left(\gamma + \frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{4}$$

In (4), γ is the angle between a_r and d_s axes. By applying (3) and (4), the d-q model of single-phase IM under open-phase fault is obtained as following equations:

Stator and rotor voltage equations:

$$\begin{bmatrix} v_{ds}^{s} \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_{ds} + L_{ds}\frac{d}{dt} & 0 & M_{ds}\frac{d}{dt} & 0 \\ 0 & 0 & 0 & 0 \\ M_{ds}\frac{d}{dt} & 0 & R_r + L_r\frac{d}{dt} & \omega_r L_r \\ -\omega_r M_{ds} & 0 & -\omega_r L_r & R_r + L_r\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{ds}^{s} \\ 0 \\ i_{dr}^{s} \\ i_{qr}^{s} \end{bmatrix} \tag{5}$$

Stator and rotor flux equations:

$$\begin{bmatrix} \lambda_{ds}^{s} \\ 0 \\ \lambda_{dr}^{s} \\ \lambda_{qr}^{s} \end{bmatrix} = \begin{bmatrix} L_{ds} & 0 & M_{ds} & 0 \\ 0 & 0 & 0 & 0 \\ M_{ds} & 0 & L_r & 0 \\ 0 & 0 & 0 & L_r \end{bmatrix} \begin{bmatrix} i_{ds}^{s} \\ 0 \\ i_{dr}^{s} \\ i_{qr}^{s} \end{bmatrix} \tag{6}$$

Electromagnetic torque equations:

$$\tau_e = -\frac{Pole}{2} M_{ds} i_{ds}^{s} i_{qr}^{s} \tag{7}$$

As can be seen from Equqation (5)-(7), the single-phase IM equations under open-phase fault is the same as the healthy single-phase IM equations with two main and auxillary windings (the healthy single-phase IM equations with two main and auxillary windings are as Equation (8)-(10)). The only difference between equations of faulty and healthy IM is that, in the faulty mode: L_{qs}=M_{qs}=R_{qs}=0 but in the healthy mode we have different values of L_{ds}, L_{qs}, M_{ds}, M_{qs}, R_{ds} and R_{qs} (L_{ds}≠L_{qs}, M_{ds}≠M_{qs} and R_{ds}≠R_{qs}).

Stator and rotor voltage equations:

$$\begin{bmatrix} v_{ds}^{s} \\ v_{qs}^{s} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_{ds} + L_{ds}\frac{d}{dt} & 0 & M_{ds}\frac{d}{dt} & 0 \\ 0 & R_{qs} + L_{qs}\frac{d}{dt} & 0 & M_{qs}\frac{d}{dt} \\ M_{ds}\frac{d}{dt} & \omega_r M_{qs} & R_r + L_r\frac{d}{dt} & \omega_r L_r \\ -\omega_r M_{ds} & M_{qs}\frac{d}{dt} & -\omega_r L_r & R_r + L_r\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \\ i_{dr}^{s} \\ i_{qr}^{s} \end{bmatrix} \tag{8}$$

Stator and rotor flux equations:

$$\begin{bmatrix} \lambda_{ds}^{s} \\ \lambda_{qs}^{s} \\ \lambda_{dr}^{s} \\ \lambda_{qr}^{s} \end{bmatrix} = \begin{bmatrix} L_{ds} & 0 & M_{ds} & 0 \\ 0 & L_{qs} & 0 & M_{qs} \\ M_{ds} & 0 & L_r & 0 \\ 0 & M_{qs} & 0 & L_r \end{bmatrix} \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \\ i_{dr}^{s} \\ i_{qr}^{s} \end{bmatrix} \tag{9}$$

Electromagnetic torque equations:

$$\tau_e = \frac{Pole}{2}\left(M_{qs} i_{qs}^{s} i_{dr}^{s} - M_{ds} i_{ds}^{s} i_{qr}^{s}\right) \tag{10}$$

In (8)-(10), 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 stationary reference frame (superscript *s*). R_{ds}, R_{qs} and R_r denote the stator and rotor resistances. L_{ds}, L_{qs}, L_r, M_{ds} and M_{qs} denote the stator, and the rotor self and mutual inductances. ω_r and τ_e are machine speed and electromagnetic torque.

3. Vector Control of a Single-phase IM with One Opened Phase Based on IFOC

In the FOC technique for 3-phase IM and in the healthy mode, conventional or balanced rotational transformation ($[T_s^e]$) which is applied to the machine equations is as follows (conventional or balanced rotational transformation is a transformation matrix to transfer equations from stationary reference frame to rotating reference frame) [22]:

$$[T_s^e]=\begin{bmatrix}\cos\theta_e & \sin\theta_e\\ -\sin\theta_e & \cos\theta_e\end{bmatrix} \tag{11}$$

In this equation, θ_e is the angle between the stationary reference frame and rotating reference frame (in this paper, the superscript *e* indicates the variables are in the rotating reference frame). Because of unequal inductances and resistances in the single-phase IM model, this matrix can not be used for single-phase IMs vector control. In this study, the following unbalanced rotational transformation for both stator voltage and current variables is proposed (in this paper, a vector control technique for single-phase IM with different values of L_{ds}, L_{qs}, M_{ds}, M_{qs}, R_{ds} *and* R_{qs} is proposed. It is obvious by substations L_{qs}=M_{qs}=R_{qs}=0 in the equations, this method can be used for faulty single-phase IM).

Proposed unbalanced rotational transformation for stator voltage and current variables:

$$[T_{is}^e]=[T_{vs}^e]=\begin{bmatrix}\cos\theta_e & \dfrac{M_{qs}}{M_{ds}}\sin\theta_e\\ -\sin\theta_e & \dfrac{M_{qs}}{M_{ds}}\cos\theta_e\end{bmatrix} \tag{12}$$

Where,

$$\begin{bmatrix}i_{ds}^e\\ i_{qs}^e\end{bmatrix}=[T_{is}^e]\begin{bmatrix}i_{ds}^s\\ i_{qs}^s\end{bmatrix}$$
$$\begin{bmatrix}v_{ds}^e\\ v_{qs}^e\end{bmatrix}=[T_{vs}^e]\begin{bmatrix}v_{ds}^s\\ v_{qs}^s\end{bmatrix} \tag{13}$$

Using (11)-(13) and after simplifying, the equations of single-phase IM are obtained as following equations:

Rotor flux equations:

$$[T_s^e]\begin{bmatrix}\lambda_{dr}^e\\ \lambda_{qr}^e\end{bmatrix}=[T_s^e]\begin{bmatrix}M_{ds} & 0\\ 0 & M_{qs}\end{bmatrix}[T_{is}^e]^{-1}[T_{is}^e]\begin{bmatrix}i_{ds}^s\\ i_{qs}^s\end{bmatrix} + [T_s^e]\begin{bmatrix}L_r & 0\\ 0 & L_r\end{bmatrix}[T_s^e]^{-1}[T_s^e]\begin{bmatrix}i_{dr}^s\\ i_{qr}^s\end{bmatrix} \tag{14}$$

After simplifying, Equation (14) can be written as Equation (15).

$$\begin{bmatrix} \lambda_{dr}^{e} \\ \lambda_{qr}^{e} \end{bmatrix} = \begin{bmatrix} M_{ds} & 0 \\ 0 & M_{ds} \end{bmatrix} \begin{bmatrix} i_{ds}^{e} \\ i_{qs}^{e} \end{bmatrix} + \begin{bmatrix} L_r & 0 \\ 0 & L_r \end{bmatrix} \begin{bmatrix} i_{dr}^{e} \\ i_{qr}^{e} \end{bmatrix} \tag{15}$$

Rotor voltage equations:

$$\begin{aligned} \left[T_s^e\right]\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \left[T_s^e\right] \begin{bmatrix} M_{ds}\frac{d}{dt} & \omega_r M_{qs} \\ -\omega_r M_{ds} & M_{qs}\frac{d}{dt} \end{bmatrix} \left[T_{is}^e\right]^{-1}\left[T_{is}^e\right] \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} \\ + \left[T_s^e\right] \begin{bmatrix} R_r + L_r\frac{d}{dt} & \omega_r L_r \\ -\omega_r L_r & R_r + L_r\frac{d}{dt} \end{bmatrix} \left[T_s^e\right]^{-1}\left[T_s^e\right] \begin{bmatrix} i_{dr}^{s} \\ i_{qr}^{s} \end{bmatrix} \end{aligned} \tag{16}$$

After simplifying, Equation (16) can be written as:

$$\begin{aligned} \begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} M_{ds}\frac{d}{dt} & (\omega_r - \omega_e)M_{ds} \\ -(\omega_r - \omega_e)M_{ds} & M_{ds}\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{ds}^{e} \\ i_{qs}^{e} \end{bmatrix} \\ + \begin{bmatrix} R_r + L_r\frac{d}{dt} & (\omega_r - \omega_e)L_r \\ -(\omega_r - \omega_e)L_r & R_r + L_r\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{dr}^{e} \\ i_{qr}^{e} \end{bmatrix} \end{aligned} \tag{17}$$

Electromagnetic torque equation:

$$\begin{aligned} \tau_e = \frac{Pole}{2}\left(M_{qs} i_{qs}^{s} i_{dr}^{s} - M_{ds} i_{ds}^{s} i_{qr}^{s}\right) = \frac{Pole}{2}\begin{bmatrix} i_{dr}^{s} & i_{qr}^{s} \end{bmatrix} \begin{bmatrix} 0 & M_{qs} \\ -M_{ds} & 0 \end{bmatrix} \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} \\ = \left(\frac{Pole}{2}\begin{bmatrix} i_{dr}^{s} & i_{qr}^{s} \end{bmatrix} \left[T_s^e\right]^T \left(\left[T_s^e\right]^{-1}\right)^T \begin{bmatrix} 0 & M_{qs} \\ -M_{ds} & 0 \end{bmatrix} \left[T_{is}^e\right]^{-1}\left[T_{is}^e\right] \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} \right) \end{aligned} \tag{18}$$

After simplifying Equation (18) can be written as:

$$\tau_e = \frac{Pole}{2} M_{ds} \left(i_{qs}^{e} i_{dr}^{e} - i_{ds}^{e} i_{qr}^{e} \right) \tag{19}$$

Based on Equation (15), (17) and (19), RFOC equations of single-phase IM are obtained as following equations (in RFOC method, the rotor flux vector is aligned with d-axis; $\lambda_{dr}^{e} = |\lambda_r|$ and $\lambda_{qr}^{e} = 0$):

$$|\lambda_r| = \frac{M_{ds} i_{ds}^{e}}{1 + T_r \frac{d}{dt}} \tag{20}$$

$$\omega_e = \omega_r + \frac{M_{ds} i_{qs}^e}{T_r |\lambda_r|} \quad (21)$$

$$\tau_e = \frac{Pole}{2} |\lambda_r| \frac{M_{ds}}{L_r} i_{qs}^e \quad (22)$$

In Equation (20), T_r is rotor time constant (T_r=L_r/R_r). As shown by using the proposed rotational transformation, RFOC equations of single-phase IM change into balanced equations. Based on Equation (20)-(22), Figure 2 can be proposed for IRFOC of both healthy and faulty single-phase IM. In this block diagram, the arrows illustrate the parts that require to be modified for controlling faulty single-phase IM (as mentioned before by substations L_{qs}=M_{qs}=R_{qs}=0 in the equations, this method can be used for faulty single-phase IM). In summery, Table 1 shows the comparison between two vector control techniques.

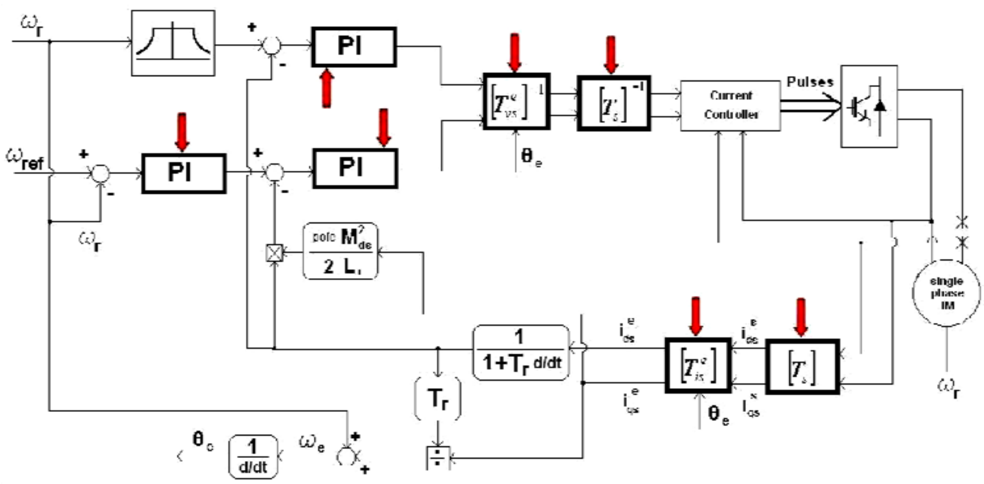


Figure 2. Block Diagram of the Proposed IFOC for Controlling Healthy and Faulty Single-phase IM

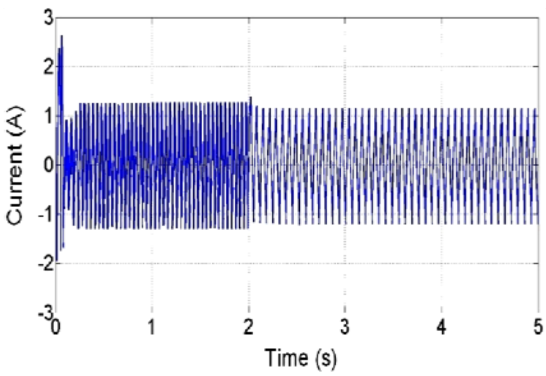
Table 1. Comparison between Two Vector Control Techniques

	Transformation matrix for stator variables	Proposed unbalanced rotational transformation for stator voltage and current variables based on equation (12):	PI Controllers
Healthy single-phase IM	$[T_s]=\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$	$[T_{is}^e]=[T_{vs}^e]=\begin{bmatrix}\cos\theta_e & \frac{M_{qs}}{M_{ds}}\sin\theta_e\\ -\sin\theta_e & \frac{M_{qs}}{M_{ds}}\cos\theta_e\end{bmatrix}$	-------------------
Faulty single-phase IM	$[T_s]=\begin{bmatrix}1\\ 0\end{bmatrix}$	$[T_{is}^e]=[T_{vs}^e]=\begin{bmatrix}\cos\theta_e & \frac{M_{qs}}{M_{ds}}\sin\theta_e\\ -\sin\theta_e & \frac{M_{qs}}{M_{ds}}\cos\theta_e\end{bmatrix}$ $M_{qs}=0$	Regulation of PI controller coefficients

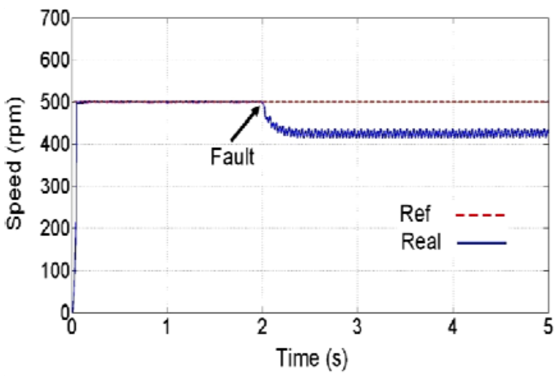
4. Simulation Results

To verify the effectiveness of the proposed drive system for both healthy and faulty single-phase IM, a vector control drive system is simulated using MATLAB software. The controller, which was used for the speed control of the balanced and unbalanced motor, is based on Figure 2. Runge–Kutta algorithm is used for solving the healthy and faulty single-phase dynamic equations. A single-phase IM is fed from a Sine Pulse Width Modulation (SPWM), 2-leg Voltage Source Inverter (VSI) as used in [4]. In simulations, the reference speed is 500rpm.

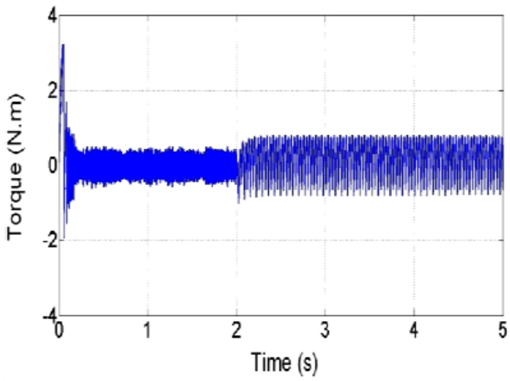
Figure 3 shows the simulation results of the conventional vector controller. At time t=2s, a phase cut out fault occurs and the single-phase IM becomes unbalanced. Simulation shows that the conventional vector controller can not properly control the unbalanced motor (see Figure 3(b)). A considerable oscillation is also seen in the electromagnetic torque after fault condition (about 0.8N.m around the average amount of 0N.m). In Figure 4, the same process is repeated but this time after the fault occurrence the proposed modifications in the vector controller are applied. Simulation results of the Figure 4 show that the proposed vector controller reduces the torque oscillation considerably (this time the torque oscillation is about 0.4N.m around the average amount of 0N.m).



(a) Stator current

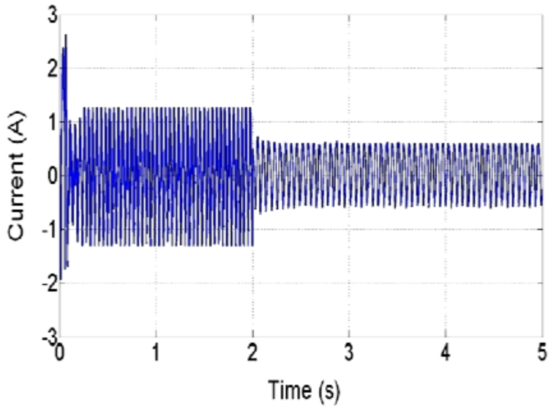


(b) Speed

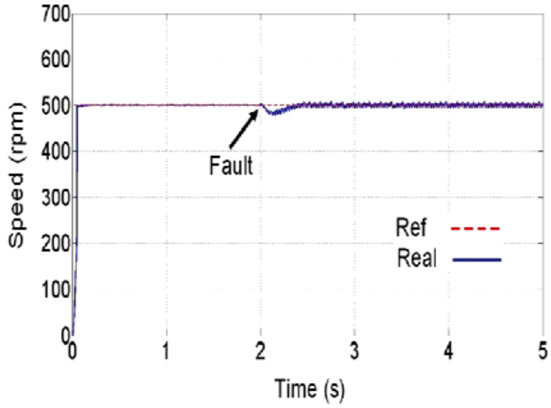


(c) Torque

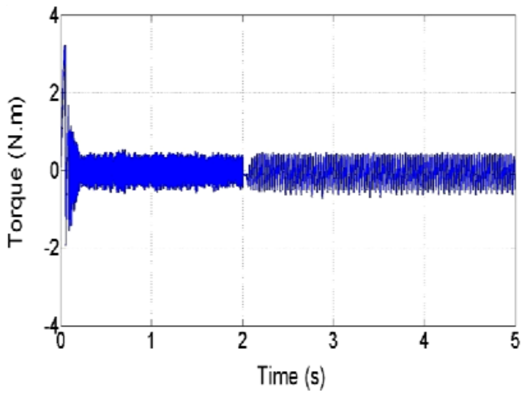
Figure 3. Simulation Results of the Conventional IFO Controller



(a) Stator current



(b) Speed



(c)Torque

Figure 4. Simulation Results of the Proposed IFO Controller

5. Conclusion

In this paper, a modeling method and a new scheme for vector control of both single-phase IM and single-phase IM under open phase fault (faulty single-phase IM) based on using transformation matrices has been presented. The performance of the presented IFOC scheme is highly satisfactory for controlling faulty single-phase IM especially in decreasing the speed and torque ripples. In this way, this technique seems to be suitable method for critical industrial applications where we need a fault-tolerant control system.

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