A Simple Method for Vector Control of 3-Phase Induction Motor under Open-Phase Fault for Electric Vehicle Applications

Rahemeh Tabasian[1], Mahmood Ghanbari[*2], Mohammad Jannati[1]

Abstract – In this paper, a simple method based on Field-Oriented Control (FOC) algorithm is proposed for Fault-Tolerant Control (FTC) of star-connected 3-phase Induction Motor (IM) drives for the Electric Vehicle (EV) applications. The proposed method is able to control 3-phase IM drive under both normal and stator winding open-phase fault conditions. The proposed FTC system is derived from a conventional FOC and requires only minor changes in parameters of the machine. The simulation results show that performance of the proposed control system is satisfactory in the case of 3-phase IM drive under open-phase fault.

Keywords: Star-Connected Induction Motor Drives, Electric Vehicle, Open-Phase Fault, Fault-Tolerant Control, Field-Oriented Control

1. Introduction

Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) are currently studied because they are the most practical solutions for load transportations in continuous effort to decrease global environmental as well as depleted fossil fuel energy resources problems. EVs or HEVs are characterized by electric motor drives, where electric power conversion is done by power electronic converters. Recently, considerable advanced controllers for EV or HEV IM drives have been presented. The aim of these researches is to expand new designs to improve performances of EV or HEV while respecting cost, reliability, efficiency, complexity and etc [1]-[7]. The configuration of a typical battery-powered EV utilizing Induction Motor (IM) is illustrated in Fig. 1. The system consists of an IM, an inverter, a DC-DC converter, a charger, wheels and a battery for energy storage.

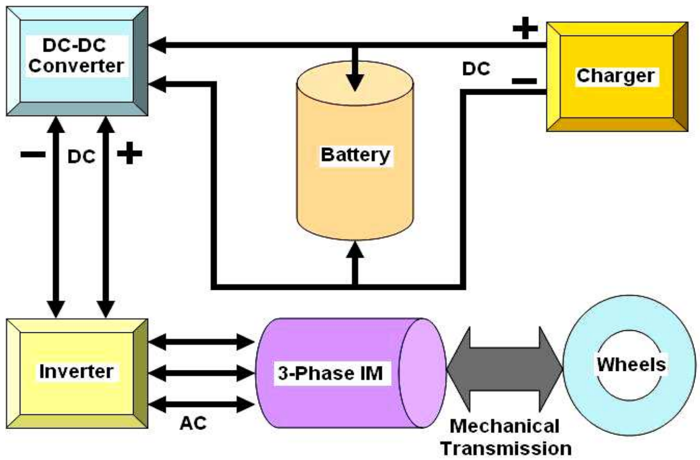

Fig. 1: General structure of EV

Undoubtedly, safety and reliability are among the most important issues normally associated with EV and HEV systems. Among the failures normally appeared in EVs or HEVs are: failures in the battery, failures in the inverter [8]-[9], and failures in the mechanical or electrical sensors [10], [11]. There are also well known failures related to the electrical machine, such as stator open-circuit fault [12]-[13], stator short-circuit fault [14], [15] and rotor faults [16], [17]. For safety reasons, vehicles must be capable of continuous operation over a certain period of time under these faulty conditions. A control system which is designed to perform such task is known as a Fault-Tolerant Control (FTC) system. In this regard, FTC techniques applications in motor drives have become one of the hot research topics in the past decades [18]-[31]. In general, based on the ability to maintain control performances in the faulty modes, there are two types of

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FTC systems: (1) Passive Fault-Tolerant Control (PFCT) [24]-[25] and, (2) Active Fault-Tolerant Control (AFTC) [18], [21], [23] and [28]. In PFTC, a robust controller is designed to cater for the internal or external disturbances, including faulty conditions. Despite the robustness of this method against internal and external disturbances and model uncertainties in faulty conditions, the controller and hence the system performance is not optimized for healthy condition. AFTC overcomes the drawbacks of PFTC by applying a new set of control algorithms, which are optimized under faulty conditions. AFTC is characterized by its ability to diagnose and identify faults so that the new control algorithm can be applied to the faulty system.

One of the most common faults in 3-phase IM drives is open-phase fault. The open-phase fault in the IM windings may result from extreme vibration, blown fuse, failure of the gate drive circuit of a switch, an accidental break in the cable connecting the drive to the IM and etc [19], [26]-[31]. This paper is focused on an open-phase fault of star-connected 3-phase IM drive with Rotor Field-Oriented Control (RFOC) technique. It is well known that a FOC designed for healthy 3-phase IM cannot be directly applied to a 3-phase IM with open-phase fault condition as the conventional vector controller has been designed based on the healthy machine equations. Using conventional controller for faulty IM drive will result in a significant torque oscillation which can cause serious mechanical failure and hence unsafe to adopt.

The results of some studies have been reported in the literature in the area of open-phase fault for 3-phase IM drive systems [19], [26]-[31]. In [19], the analysis of the star-connected 3-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 to the machine terminal. This method has been applied and implemented in a volts/hertz controlled IM. In [26], a scalar control method to control delta-connected 3-phase IM drive under stator winding open-phase fault has been proposed. In [27], [28], two methods for vector control of delta-connected 3-phase IM drive in case of open-phase fault have been proposed and implemented. In [27], it was shown that, during open-phase fault, the limitation due to the maximum permissible torque is about 30% of the nominal torque of the motor. In [29], using calculation of MMF, a method for FOC of star-connected 3-phase IM under open-phase fault has been suggested. ; this study shows that currents in the two remaining active stator phases are dependent on each other and cannot be controlled separately. To overcome this problem, the neutral point of 3-phase IM should be accessible and connected to the midpoint of the DC bus of drive system. The proposed methods in [27]-[29] are based on current controller that requires either current-control voltage source inverter (CC-VSI) or current source inverter (CSI), and hence is not suitable for high power industrial applications. In [30]-[31], based on voltage controller, different methods for FOC of star-connected 3-phase IM drives under open-phase fault using transformation matrices have been proposed; due to different transformation matrices for stator voltage and current variables, the suggested methods are more sensitive to parameter variations.

In this paper, a simple AFTC technique which is able to operate for star-connected 3-phase IM drive systems in two-phase operation mode is introduced. The proposed AFTC strategy can be activated either in the case of the normal condition or the open-phase fault conditions. Unlike most of the AFTC methods, the proposed technique does not need to switch to a new algorithm from balanced mode to faulty mode since it is based on a conventional FOC structure, with some minor changes in the machine's parameters. The results obtained from the simulations will be presented to confirm the effectiveness of the proposed control topology in decreasing the speed and torque pulsations under two-phase operation of star-connected 3-phase IM drive. The rest of the paper is organized as follows. Section II gives the mathematical model of IM under open-phase fault. Section III describes the development of the FOC algorithm for vector control of healthy and faulty 3-phase IMs. The performance of the proposed method is verified in section IV and finally, conclusions are listed in section V.

II. Mathematical Model of Faulty 3-Phase IM

Suppose that a phase cut off fault occurred in phase "C" of an IM. Assuming sinusoidal waveform for the spatial distribution of the windings, stator and rotor flux axes can be represented as shown in Fig. 2.

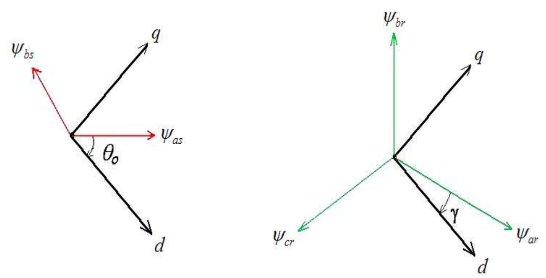


Fig. 2: Stator and rotor winding's flux axes

Based on fig.2, the following normalized transformation matrices are obtained for the stator and rotor variables [30]-

[31]:

$$\left[k_{stator}^{fault}\right]=\sqrt{2}\begin{bmatrix}0.5 & -0.5\\ 0.5 & 0.5\end{bmatrix} \tag{1}$$

$$\left[k_{roror}^{fault}\right]=\sqrt{2/3}\begin{bmatrix}\cos(\gamma) & \cos(\gamma+2\pi/3) & \cos(\gamma++4\pi/3)\\ \sin(\gamma) & \sin(\gamma+2\pi/3) & \sin(\gamma++4\pi/3)\end{bmatrix} \tag{2}$$

Using (1) and (2), the (d-q) model of IM under open-phase fault is obtained as [30]-[31]:

$$\begin{bmatrix}v_{ds}^s\\ v_{qs}^s\end{bmatrix}=\begin{bmatrix}r_s+L_{ds}p & 0\\ 0 & r_s+L_{qs}p\end{bmatrix}\begin{bmatrix}i_{ds}^s\\ i_{qs}^s\end{bmatrix}+\begin{bmatrix}L_{dm}p & 0\\ 0 & L_{qm}p\end{bmatrix}\begin{bmatrix}i_{dr}^s\\ i_{qr}^s\end{bmatrix} \tag{3}$$

$$\begin{bmatrix}v_{dr}^s\\ v_{qr}^s\end{bmatrix}=\begin{bmatrix}0\\ 0\end{bmatrix}=\begin{bmatrix}L_{dm}p & \Omega_r L_{qm}\\ -\Omega_r L_{dm} & L_{qm}p\end{bmatrix}\begin{bmatrix}i_{ds}^s\\ i_{qs}^s\end{bmatrix}+\begin{bmatrix}r_r+L_r p & \Omega_r L_r\\ -\Omega_r L_r & r_r+L_r p\end{bmatrix}\begin{bmatrix}i_{dr}^s\\ i_{qr}^s\end{bmatrix} \tag{4}$$

$$\begin{bmatrix}\psi_{ds}^s\\ \psi_{qs}^s\end{bmatrix}=\begin{bmatrix}L_{ds} & 0\\ 0 & L_{qs}\end{bmatrix}\begin{bmatrix}i_{ds}^s\\ i_{qs}^s\end{bmatrix}+\begin{bmatrix}L_{dm} & 0\\ 0 & L_{qm}\end{bmatrix}\begin{bmatrix}i_{dr}^s\\ i_{qr}^s\end{bmatrix} \tag{5}$$

$$\begin{bmatrix}\psi_{dr}^s\\ \psi_{qr}^s\end{bmatrix}=\begin{bmatrix}L_{dm} & 0\\ 0 & L_{qm}\end{bmatrix}\begin{bmatrix}i_{ds}^s\\ i_{qs}^s\end{bmatrix}+\begin{bmatrix}L_r & 0\\ 0 & L_r\end{bmatrix}\begin{bmatrix}i_{dr}^s\\ i_{qr}^s\end{bmatrix} \tag{6}$$

$$\tau_e=\frac{P}{2}\left(L_{qm}i_{qs}^s i_{dr}^s-L_{dm}i_{ds}^s i_{qr}^s\right) \tag{7}$$

$$\tau_e-\tau_l=\frac{2}{P}\left(Jp\Omega_r+F\Omega_r\right) \tag{8}$$

where, vsds, vsqs are the stator (d-q) axes voltages, isds, isqs are the stator (d-q) currents, isdr, isqr are the rotor (d-q) currents, λsds, λsqs are the stator (d-q) fluxes and λsdr and λsqr are the rotor (d-q) fluxes in the stationary reference frame (superscript “s”); rs and rr indicate the stator and rotor resistances. Lds, Lqs, Lr, Ldm and Lqm denote the stator, the rotor self and mutual inductances; Ωr is the motor speed; τe and τl are electromagnetic torque and load torque and P, J and F are the number of poles, moment of inertia and viscous friction coefficient, respectively. The self and mutual inductances are given by [30]-[31]:

$$L_{ds}=L_{ls}+1.5L_{ms}\; L_{qs}=L_{ls}+0.5L_{ms}\; L_{dm}=1.5L_{ms}\; L_{qm}=\sqrt{3}/2L_{ms} \tag{9}$$

It should be noted that (3)-(8) represent general equations of an unbalanced 2-phase IM. The same equations can be used to represent a 3-phase IM under open-phase fault by replacing the motor parameters (Ldm, Lqm, Lds and Lqs) as defined by (9). It is also interesting to note that the structure of the equations for a faulty IM is similar to the structure of healthy IM equations. In fact, by substituting Ldm=Lqm=Lm=3/2Lms and Lds=Lqs=Ls=Lls+3/2Lms, we obtain the familiar equations of healthy 3-phase IM.

III. Development of FOC Algorithm

In this section, a modified FOC algorithm based on the unbalanced IM model given in (3)-(8) is developed for vector control of faulty 3-phase IM. First, we introduce the following substitutions:

$$v_{ds}^s\rightarrow v_{x1s}^s+jv_{y1s}^s\ ,\ i_{ds}^s\rightarrow i_{x1s}^s+ji_{y1s}^s\ ,\ v_{dr}^s\rightarrow v_{x1r}^s+jv_{y1r}^s\ ,\ i_{dr}^s\rightarrow i_{x1r}^s+ji_{y1r}^s\ ,\ \psi_{qr}^s=\psi_{x2r}^s+j\psi_{y2r}^s \tag{10}$$

$$v_{qs}^s\rightarrow v_{x2s}^s+jv_{y2s}^s\ ,\ i_{qs}^s\rightarrow i_{x2s}^s+ji_{y2s}^s\ ,\ v_{qr}^s\rightarrow v_{x2r}^s+jv_{y2r}^s\ ,\ i_{qr}^s\rightarrow i_{x2r}^s+ji_{y2r}^s\ ,\ \psi_{dr}^s=\psi_{x1r}^s+j\psi_{y1r}^s \tag{11}$$

Using (10), the d-axis equivalent circuit of IM under open-phase fault (Fig. 3(a)) is transformed into two balanced circuits as shown in Fig. 3(b). Similarly, using (11), the q-axis equivalent circuit of IM under open-phase fault (Fig. 3(c)) is transformed into two balanced circuits as shown in Fig. 3(d).

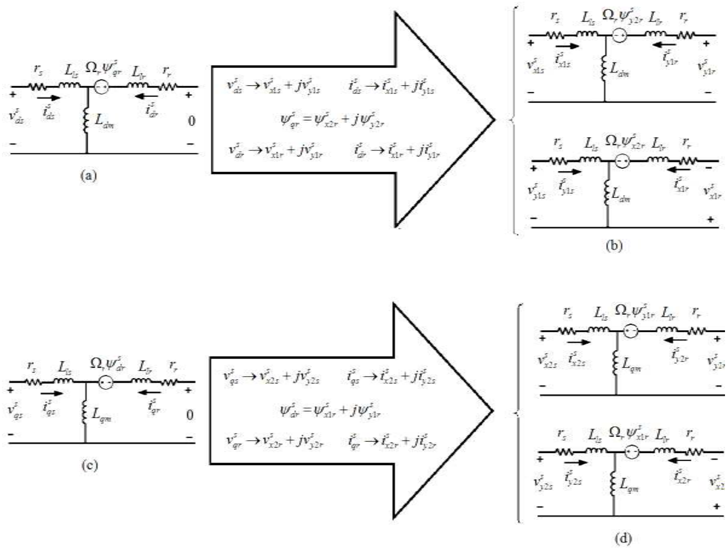


Fig. 3: Equivalent circuit of the 3-phase IM under open-phase fault

As can be seen from fig. 3(b) and fig.3(d), using the proposed substitutions (equations (10) and (11)), the equivalent circuit of the 3-phase IM under open-phase fault splits into two balanced circuits which represent two balanced 3-phase IM equivalent circuits. From (10) and (11), the following matrices are obtained:

$$v_{ds}^{s}=\begin{bmatrix}1 & j\end{bmatrix}\begin{bmatrix}v_{x1s}^{s}\\ v_{y1s}^{s}\end{bmatrix}\quad,\quad i_{ds}^{s}=\begin{bmatrix}1 & j\end{bmatrix}\begin{bmatrix}i_{x1s}^{s}\\ i_{y1s}^{s}\end{bmatrix}$$

$$v_{dr}^{s}=\begin{bmatrix}1 & j\end{bmatrix}\begin{bmatrix}v_{x1r}^{s}\\ v_{y1r}^{s}\end{bmatrix}\quad,\quad i_{dr}^{s}=\begin{bmatrix}1 & j\end{bmatrix}\begin{bmatrix}i_{x1r}^{s}\\ i_{y1r}^{s}\end{bmatrix}$$

(12)

which gives,

$$\begin{bmatrix}A_{d(s/r)}^{s}\\ A_{q(s/r)}^{s}\end{bmatrix}=\begin{bmatrix}1 & j\\ j & -1\end{bmatrix}\begin{bmatrix}A_{x1(s/r)}^{s}\\ A_{y1(s/r)}^{s}\end{bmatrix}\Rightarrow$$

$$\begin{bmatrix}-A_{d(s/r)}^{s}\\ jA_{d(s/r)}^{s}\end{bmatrix}=\begin{bmatrix}-1 & -j\\ j & -1\end{bmatrix}\begin{bmatrix}A_{x1(s/r)}^{s}\\ A_{y1(s/r)}^{s}\end{bmatrix}$$

(13)

In (13), "A" can be voltage or current vector.

Applying the variable substitutions as given by (14), a transformation matrix that transforms an unbalanced set of variables (e.g, fig. 3(a) and fig. 3(c)) into a balanced set of variables (e.g, fig. 3(b) and fig. 3(d)) can be derived as given by (15):

$$-1\rightarrow\cos\theta_e\quad,\quad -j\rightarrow\sin\theta_e\quad,\quad A_{x1(s/r)}^{s}\rightarrow A_{ds}^{s}$$

$$A_{y1(s/r)}^{s}\rightarrow A_{qs}^{s}\quad,\quad -A_{d(s/r)}^{s}\rightarrow A_{ds}^{e}\quad,\quad jA_{d(s/r)}^{s}\rightarrow A_{qs}^{e}$$

(14)

$$\begin{bmatrix}A_{ds}^{e}\\ A_{qs}^{e}\end{bmatrix}=\begin{bmatrix}k_s^e\end{bmatrix}\begin{bmatrix}A_{ds}^{s}\\ A_{qs}^{s}\end{bmatrix}=\begin{bmatrix}\cos\theta_e & \sin\theta_e\\ -\sin\theta_e & \cos\theta_e\end{bmatrix}\begin{bmatrix}A_{ds}^{s}\\ A_{qs}^{s}\end{bmatrix}$$

(15)

where, θe is the angle between the stationary and rotating reference frames. In the RFOC technique, IM equations are transformed to a rotating reference frame fixed to the rotor flux; for this purpose, the transformation matrix is applied [32]. It can be seen that (15) is in fact the same as the transformation matrix. Therefore, it is expected that using (15), the unbalanced equations of the faulty machine split into two balanced equations. By applying (15) to the equations of the faulty motor, (16) and (17) are obtained:

$$\begin{bmatrix}\cos\theta_e & \sin\theta_e\\ -\sin\theta_e & \cos\theta_e\end{bmatrix}\begin{bmatrix}v_{ds}^{s}\\ v_{qs}^{s}\end{bmatrix}=\begin{bmatrix}\cos\theta_e & \sin\theta_e\\ -\sin\theta_e & \cos\theta_e\end{bmatrix}\begin{bmatrix}r_s+L_{ds}p & 0\\ 0 & r_s+L_{qs}p\end{bmatrix}$$

$$\left(\begin{bmatrix}\cos\theta_e & \sin\theta_e\\ -\sin\theta_e & \cos\theta_e\end{bmatrix}^{-1}\begin{bmatrix}i_{ds}^{e}\\ i_{qs}^{e}\end{bmatrix}\right)+\begin{bmatrix}\cos\theta_e & \sin\theta_e\\ -\sin\theta_e & \cos\theta_e\end{bmatrix}\begin{bmatrix}L_{dm}p & 0\\ 0 & L_{qm}p\end{bmatrix}$$

$$\left(\begin{bmatrix}\cos\theta_e & \sin\theta_e\\ -\sin\theta_e & \cos\theta_e\end{bmatrix}^{-1}\begin{bmatrix}i_{dr}^{e}\\ i_{qr}^{e}\end{bmatrix}\right)$$

(16)

for the stator voltage and

$$\begin{bmatrix}\cos\theta_e & \sin\theta_e\\ -\sin\theta_e & \cos\theta_e\end{bmatrix}\begin{bmatrix}0\\ 0\end{bmatrix}=\begin{bmatrix}\cos\theta_e & \sin\theta_e\\ -\sin\theta_e & \cos\theta_e\end{bmatrix}\begin{bmatrix}L_{dm}p & \Omega_r L_{qm}\\ -\Omega_r L_{dm} & L_{qm}p\end{bmatrix}$$

$$\left(\begin{bmatrix}\cos\theta_e & \sin\theta_e\\ -\sin\theta_e & \cos\theta_e\end{bmatrix}^{-1}\begin{bmatrix}i_{ds}^{e}\\ i_{qs}^{e}\end{bmatrix}\right)+\begin{bmatrix}\cos\theta_e & \sin\theta_e\\ -\sin\theta_e & \cos\theta_e\end{bmatrix}\begin{bmatrix}r_r+L_rp & \Omega_r L_r\\ -\Omega_r L_r & r_r+L_rp\end{bmatrix}$$

$$\left(\begin{bmatrix}\cos\theta_e & \sin\theta_e\\ -\sin\theta_e & \cos\theta_e\end{bmatrix}^{-1}\begin{bmatrix}i_{dr}^{e}\\ i_{qr}^{e}\end{bmatrix}\right)$$

(17)

for the rotor voltage equations. Then, (16) and (17) can be written as (18)-(20):

$$\begin{bmatrix}v_{ds}^{e}\\ v_{qs}^{e}\end{bmatrix}=\begin{bmatrix}r_s+\left(\dfrac{L_{ds}+L_{qs}}{2}\right)p & -\Omega_e\left(\dfrac{L_{ds}+L_{qs}}{2}\right)\\ \Omega_e\left(\dfrac{L_{ds}+L_{qs}}{2}\right) & r_s+\left(\dfrac{L_{ds}+L_{qs}}{2}\right)p\end{bmatrix}\begin{bmatrix}i_{ds}^{f}\\ i_{qs}^{f}\end{bmatrix}$$

$$+\begin{bmatrix}\left(\dfrac{L_{dm}+L_{qm}}{2}\right)p & -\Omega_e\left(\dfrac{L_{dm}+L_{qm}}{2}\right)\\ \Omega_e\left(\dfrac{L_{dm}+L_{qm}}{2}\right) & \left(\dfrac{L_{dm}+L_{qm}}{2}\right)p\end{bmatrix}\begin{bmatrix}i_{dr}^{f}\\ i_{qr}^{f}\end{bmatrix}$$

$$+\begin{bmatrix}\left(\dfrac{L_{ds}-L_{qs}}{2}\right)p & \Omega_e\left(\dfrac{L_{ds}-L_{qs}}{2}\right)\\ \Omega_e\left(\dfrac{L_{ds}-L_{qs}}{2}\right) & -\left(\dfrac{L_{ds}-L_{qs}}{2}\right)p\end{bmatrix}\begin{bmatrix}i_{ds}^{b}\\ i_{qs}^{b}\end{bmatrix}$$

$$+\begin{bmatrix}\left(\dfrac{L_{dm}-L_{qm}}{2}\right)p & (\Omega_e-\Omega_r)\left(\dfrac{L_{dm}-L_{qm}}{2}\right)\\ (\Omega_e-\Omega_r)\left(\dfrac{L_{dm}-L_{qm}}{2}\right) & -\left(\dfrac{L_{dm}-L_{qm}}{2}\right)p\end{bmatrix}\begin{bmatrix}i_{dr}^{b}\\ i_{qr}^{b}\end{bmatrix}$$

(18)

for the stator voltage equations and

$$\begin{bmatrix}0\\ 0\end{bmatrix}=\begin{bmatrix}\left(\dfrac{L_{dm}+L_{qm}}{2}\right)p & -(\Omega_e-\Omega_r)\left(\dfrac{L_{dm}+L_{qm}}{2}\right)\\ (\Omega_e-\Omega_r)\left(\dfrac{L_{dm}+L_{qm}}{2}\right) & \left(\dfrac{L_{dm}+L_{qm}}{2}\right)p\end{bmatrix}\begin{bmatrix}i_{ds}^{f}\\ i_{qs}^{f}\end{bmatrix}$$

$$+\begin{bmatrix}r_r+L_rp & -(\Omega_e-\Omega_r)L_r\\ (\Omega_e-\Omega_r)L_r & r_r+L_rp\end{bmatrix}\begin{bmatrix}i_{dr}^{f}\\ i_{qr}^{f}\end{bmatrix}$$

$$+\begin{bmatrix}\left(\dfrac{L_{dm}-L_{qm}}{2}\right)p & (\Omega_e-\Omega_r)\left(\dfrac{L_{dm}-L_{qm}}{2}\right)\\ (\Omega_e-\Omega_r)\left(\dfrac{L_{dm}-L_{qm}}{2}\right) & -\left(\dfrac{L_{dm}-L_{qm}}{2}\right)p\end{bmatrix}\begin{bmatrix}i_{ds}^{b}\\ i_{qs}^{b}\end{bmatrix}$$

(19)

for Rotor voltage equations, where,

$$\begin{bmatrix} i_{ds}^{f} \\ i_{qs}^{f} \end{bmatrix} = \left[k_s^e\right] \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} \quad , \quad \begin{bmatrix} i_{dr}^{f} \\ i_{qr}^{f} \end{bmatrix} = \left[k_s^e\right] \begin{bmatrix} i_{dr}^{s} \\ i_{qr}^{s} \end{bmatrix}$$

$$\begin{bmatrix} i_{ds}^{b} \\ i_{qs}^{b} \end{bmatrix} = \left[k_s^e\right]^{1} \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} \quad , \quad \begin{bmatrix} i_{dr}^{b} \\ i_{qr}^{b} \end{bmatrix} = \left[k_s^e\right]^{1} \begin{bmatrix} i_{dr}^{s} \\ i_{qr}^{s} \end{bmatrix} \qquad (20)$$

As it can be seen, (18) and (19) include two terms which rotates in the forward or backward direction (forward term: superscript "f" and backward term: superscript "b"). As expected, each term represents a healthy 3-phase IM. In the fault condition, the backward terms are obtained because of the unequal inductances in the faulty 3-phase IM model (Ldm≠Lqm and Lds≠Lqs).

As mentioned above, the structure of the forward and backward equations is similar to the healthy 3-phase IM equations. The difference between forward and backward equations and healthy 3-phase IM equations is listed in Table I and Table II, respectively.

Table I: The Difference between the Forward Terms of Equation (18) and (19) and Healthy IM Equation

Forward terms of (18) and (19)	**Healthy IM equation**
(Ldm+Lqm)/2=Lms(3+√3)/4	Lm=3/2Lms
(Lds+Lqs)/2=Lls+Lms	Ls=Lls+3/2Lms

Table II: The Difference between the Backward Terms of Equation (18) and (19) and Healthy IM Equation

Backward terms of (18) and (19)	**Healthy IM equation**
(Ldm-Lqm)/2=Lms(3-√3)/4 (Lds-Lqs)/2=1/2Lms rr=0, Lr=0	Lm =3/2Lms Ls=Lls+3/2Lms rr≠0, Lr=Llr+3/2Lmr≠0
-iqse and -iqre	iqse and iqre

From (18) and (19), the forward terms are proportional to the sum of the inductances ((Lds+Lqs)/2 and (Ldm+Lqm)/2) while the backward terms are proportional to the difference of the inductances ((Lds-Lqs)/2 and (Ldm-Lqm)/2). To simplify the equations of vector control, it is therefore possible to neglect backward terms since the values are typically small as compared to the forward terms. Consequently, for rotor flux FOC of a 3-phase IM under open-phase fault, only the forward equations are used. Note that, the structure of the proposed method is the same as the conventional FOC; in the proposed method, we apply Lm→(Ldm+Lqm)/2 and Ls→(Lds+Lqs)/2. So, with minimum changes in the RFO vector control, it should be possible to control the faulty motor. We observe that without neglecting the backward components, two FOC algorithms for vector control of 3-phase IM under open-phase fault are needed. However, adoption of two FOC algorithms will significantly increase the complexity of the drive system and sampling time.

Fig. 4 shows the block diagram of the conventional Indirect RFOC (IRFOC) for 3-phase IM drive systems [32].

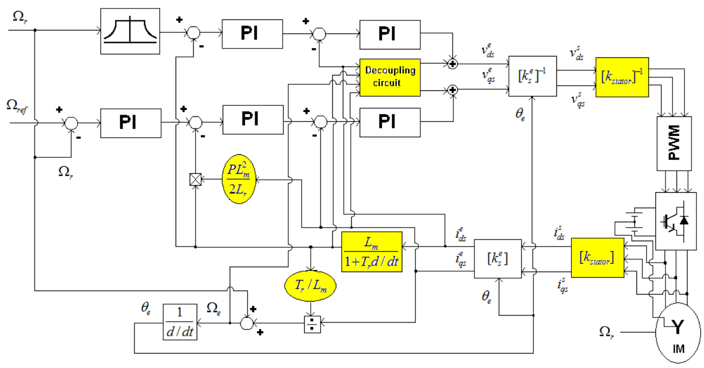


Fig. 4: Block diagram of IRFOC for 3-phase IM drive systems

The parameters of the conventional method, which are used in Fig. 4 during normal and faulty conditions, are given in Table III.

Table III: The Parameters of 3-Phase IM during Normal and Faulty Conditions (Conventional Method)

Normal condition	**Faulty condition**
Lm=3/2Lms Ls=Lls+3/2Lms	Lm=3/2Lms Ls=Lls+3/2Lms
$\left[k_{stator}\right] = \sqrt{2/3}\begin{bmatrix} 1 & -0.5 \\ 0 & \sqrt{3}/2 \end{bmatrix}$	$\left[k_{stator}\right] = \sqrt{2/3}\begin{bmatrix} 1 & -0.5 \\ 0 & \sqrt{3}/2 \end{bmatrix}$

The parameters for the proposed method (again, referring to fig.4) during normal and faulty conditions, are given in Table IV.

Table IV: The Parameters of 3-Phase IM during Normal and Faulty Conditions (Proposed Method)

Normal condition	**Faulty condition**
Lm=3/2Lms	L-m=(Ldm+Lqm)/2= Lms(3+√3)/4
Ls=Lls+3/2Lms	Ls=(Lds+Lqs)/2= Lls+Lms
$[k_{stator}] = \sqrt{2/3}\begin{bmatrix} 1 & -0.5 & -0. \\ 0 & \sqrt{3}/2 & -\sqrt{3} \end{bmatrix}$	$[k_{stator}] = \sqrt{2}\begin{bmatrix} 0.5 & -0. \\ 0.5 & 0.5 \end{bmatrix}$

In summary, the colored blocks in fig. 4 indicate the necessary modifications needed to change from healthy to faulty conditions. Notice that, in the proposed method, for the change from normal condition to faulty condition, the PI controller coefficients should be readjusted.

IV. Simulation Results

In order to study the theoretical analysis and to verify the performance of the presented method discussed earlier, the IM drive system was simulated at different operating conditions. The simulations are carried out by MATLAB/M-File. The ratings and parameters of the 3-phase IM are as given in Appendix. In simulations, we assumed that an open-phase fault is happening in phase "C" of the stator windings. The 1.5kW 3-phase IM is star-connected and fed by a 3-leg inverter. The used inverter is shown in fig. 5. As shown in the figure, the neutral point of 3-phase IM is connected to the midpoint of the DC bus of drive system. In order to create a midpoint DC bus voltage, two large capacitors are connected in series between the positive and negative rail of the DC link voltage. Therefore, when an open-phase fault is just happened in one of the stator phases, the active phases can be controlled individually. During normal mode operation, the current flowing in the neutral wire is small only due to the PWM operation of the inverter [29].

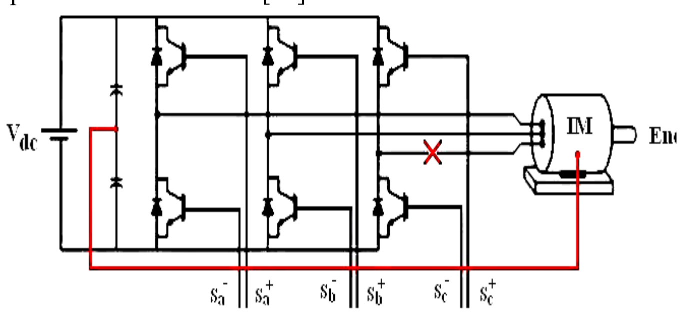


Fig. 5: Scheme of the inverter for faulty machine

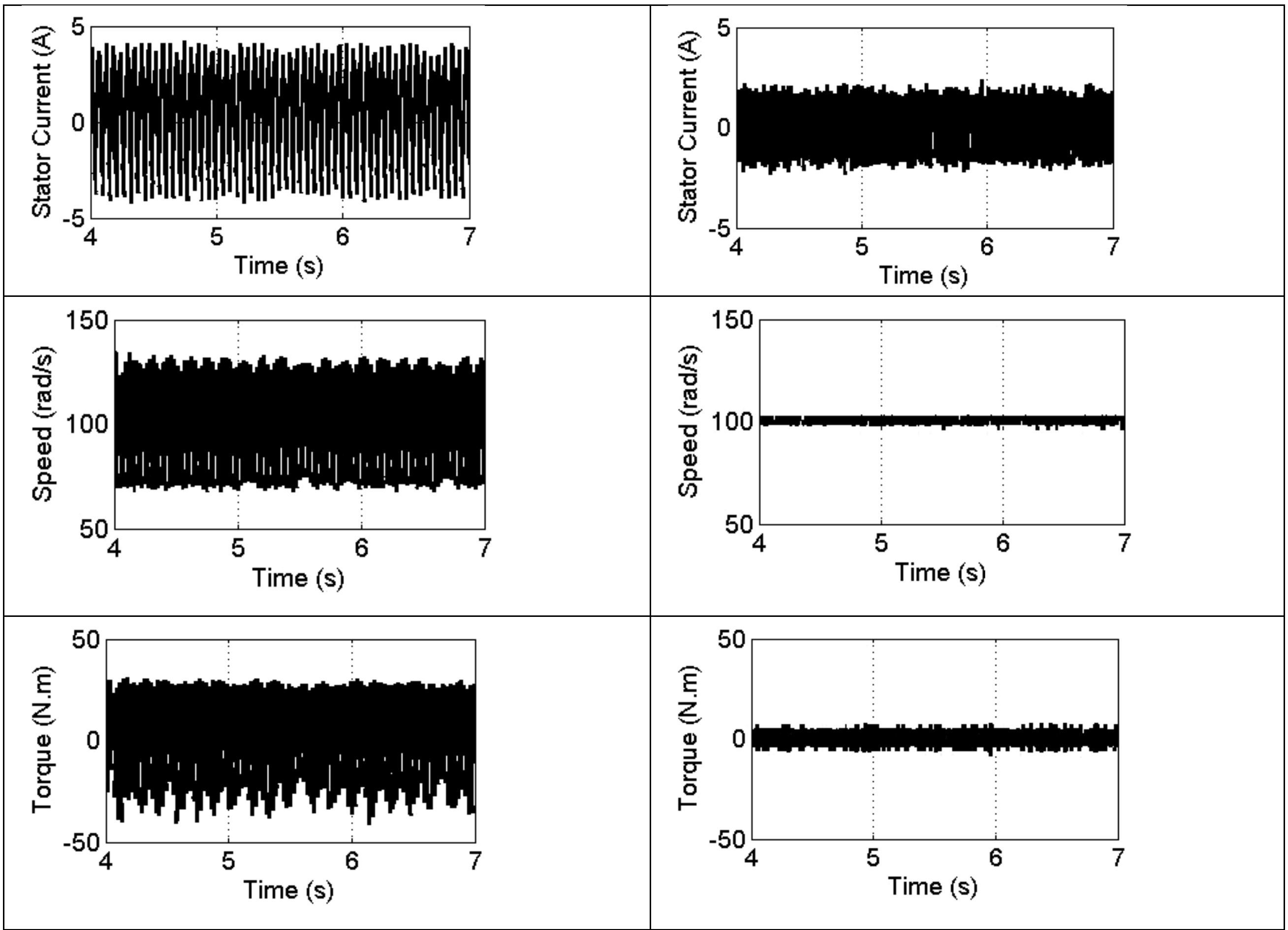
The results presented in fig. 6 show the performance of the IM drive system for, respectively, when the introduced controller was deactivated, and when this controller was activated for the 2-phase open-phase mode and the motor speed is equal to 100rad/s. Fig. 6 shows the simulation results of the of stator phase-A current, speed and torque waveforms for the faulty 3-phase machine.

As shown in fig. 6, the sinusoidal form of the line current for healthy phase of stator windings is maintained during 2-phase open-phase mode. From the estimated torque response and speed response of Fig. 6, it can be seen that the steady state of torque and speed ripples in the conventional method is higher than those obtained from the proposed method. It can be seen that the introduced scheme delivers a much smoother steady state performance in terms of torque and speed ripples during 2-phase open-phase mode. It can be concluded then, that in comparison to conventional method, the proposed method can provide better steady and dynamic properties.

It should be noted that at low speed, the FOC of faulty 3-phase IM drive is sensitive to accurate values of motor parameters such as resistances and inductances of the stator and rotor circuits. The sensitivity of the proposed control technique on the motor parameters affects the decoupling between the torque and the flux of the stator current, and hence the dynamic and steady state torque responses. To improve the performance of the proposed controller under open-phase fault, further research on the controller should be considered.

V. Conclusion

In this paper, a simple FTC for star-connected 3-phase IM drive systems for EV applications has been proposed. The proposed system is based on a well-known FOC for a 3-phase IM and applicable to the healthy and open-phase fault, without requiring changes in the control structure. The proposed FTC strategy is verified through simulation on a 1.5kW, star-connected 3-phase IM. Simulation results show that the proposed FOC has managed to reduce the torque and speed oscillations under open-phase fault. At zero or low speed operation, the proposed FOC of 3-phase IM drive under open-phase fault is sensitive to the accurate values of machine parameters. To further improve the performance at low speed, parameter compensation technique can be incorporated to the proposed controller.



(a) (b)

Fig. 6: Simulation results of the conventional and proposed method for vector control of the faulty machine; (a): Conventional method, (b) Proposed method

Appendix

Ratings and parameters of 3-phase IM:
V=400V, f=50Hz, P=4, rs=5.5Ω, rr=4.51Ω, Lm=0.299H, Ls=Lr=0.3065H, J=0.0086kg.m2, Rated current=3.39A, Rated torque=9N.m

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