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Vector Control of Three-Phase Induction Motor Under Open-Phase Fault

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***Abstract*—This paper is an effort to introduce two new and simple transformations for three-phase Induction Motor (IM) under open-phase fault (faulty IM) along with a correspondent Rotor Field-Oriented Control (RFOC) method. Fundamental knowledge in regard with new transformations based on faulty IM model is presented. The presented transformations are a new approach to tackle control design difficulties cause by asymmetrical structure of faulty IM. Ultimately, MATLAB/SIMULINK is used to verify performance of the proposed method for faulty IM. Simulation results reveal the great potential of the proposed method to reduce torque and speed pulsation.**

Keywords—faulty induction motor; rotor field-oriented control; transformation matrixes; reduce torque and speed pulsation

I. INTRODUCTION

Using the vector space decomposition theory, the electromechanical energy conversion property of the unbalanced three-phase Induction Motor (IM) investigated in this note has been previously represented in [1]. This model is an equivalent two-phase IM with unequal stator q-axis self and mutual inductance [1]. Recently, the issues which include the modeling and vector control of unbalanced or single-phase IMs methods have becoming one of the significant study issues among researchers [2-12].

Because of the asymmetrical structure of the unbalanced IM, Field-Oriented Control (FOC) technique developed from machine with balanced stator winding structure cannot be used directly [1] and [2]. To obtain FOC method for vector of faulty three-phase IM two unbalanced stationary to synchronous reference frame transformations for current and voltage variables based on d-q model of unbalanced IM was introduced and applied. With proposed transformations, a symmetrical IM model was obtained, thus by some modifications in the conventional FOC for symmetric machine, vector control of faulty IM become possible. The new FOC technique is appropriate for unbalanced and single-phase IM drives. To verify the proposed control method, a three-phase IM drive system with an open phase has been simulated using MATLAB software. The results have shown very good agreement with the theoretical analysis. This paper is organized as follows:

In section II, the d-q model of faulty IM is presented. Proposed technique to control faulty IM is discussed in section III. The simulation results are presented in section IV. Finally, conclusion is presented in section V.

II. THE FAULTY THREE-PHASE IM MODEL

The main objective of this section is to develop a model of a faulty 3-phase IM that has similar structure of equation to a balanced 3-phase IM. By doing so, a conventional RFOC that is used to a balanced 3-phase IM can be readily applied to the faulty motor, with minimum modifications. The minor modifications that are needed to the conventional RFOC of 3-phase IM are presented in the next section. The scenario of this model is as:

Step 1: obtaining normalized transformation matrices for stator and rotor variables:

Stator and rotor flux axes can be presented as Fig. 1 (in this paper, we assumed a phase cut-off is occurred in phase "c" of stator windings). Based on Fig. 1, the transformation vectors d and q can be defined as follows:

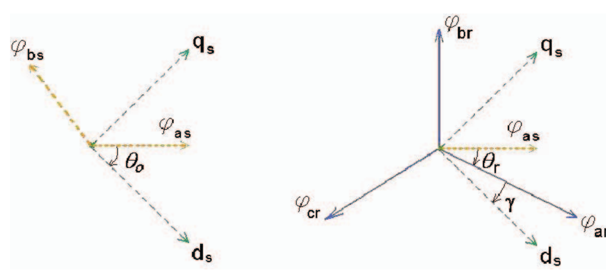


Fig. 1. Stator and rotor winding's flux axes

$$\begin{aligned}
\bar{d}_s &= [\cos(\theta_o) \quad \cos(\theta_o + 2\pi/3)] \\
\bar{q}_s &= [\sin(\theta_o) \quad \sin(\theta_o + 2\pi/3)] \\
\bar{d}_r &= [\cos(\gamma) \quad \cos(\gamma + 2\pi/3) \quad \cos(\gamma + 4\pi/3)] \\
\bar{q}_r &= [\sin(\gamma) \quad \sin(\gamma + 2\pi/3) \quad \sin(\gamma + 4\pi/3)]
\end{aligned} \quad (1)$$

The transformation vectors must be perpendicular to each other, therefore from (1), this leads to,

$$\bar{d}_s.\bar{q}_s^T = \bar{q}_s.\bar{d}_s^T = 0 \quad \Rightarrow \quad \theta_o = \frac{\pi}{6} \tag{2}$$

Therefore, by using (1) and (3), the following normalized transformation matrixes can be obtained for the stator and rotor variables:

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

Step 2: obtaining equation of faulty motor in the "abc" frame

Stator and rotor voltage and flux equations for faulty three-phase IM in the "abc" frame can be expressed as follows:

$$\begin{bmatrix} v_{abS}^{2\times1} \\ v_{abcR}^{3\times1} \end{bmatrix} = \begin{bmatrix} R_S^{2\times2} & 0^{2\times3} \\ 0^{3\times2} & R_R^{3\times3} \end{bmatrix}\begin{bmatrix} i_{abS}^{2\times1} \\ i_{abcR}^{3\times1} \end{bmatrix} + \frac{d}{dt}\begin{bmatrix} \lambda_{abS}^{2\times1} \\ \lambda_{abcR}^{3\times1} \end{bmatrix}$$
$$\begin{bmatrix} \lambda_{abS}^{2\times1} \\ \lambda_{abcR}^{3\times1} \end{bmatrix} = \begin{bmatrix} L_{SS}^{2\times1} & L_{SR}^{2\times3} \\ L_{SR}^{2\times3\,T} & L_{RR}^{3\times3} \end{bmatrix}\begin{bmatrix} i_{abS}^{2\times1} \\ i_{abcR}^{3\times1} \end{bmatrix} \tag{4}$$

Where $[v_{abcR}]$, $[i_{abcR}]$, $[\lambda_{abcR}]$, $[R_R]$ and $[L_{RR}]$, are identical to the balanced three-phase IM. It is because the structure of rotor has not changed. The $[v_{abS}]$, $[i_{abS}]$, $[\lambda_{abS}]$, $[R_S]$, $[L_{SS}]$, $[L_{SR}]$ and $[L_{RS}]$ have the similar formation to the balanced IM. The only different in these matrixes are the row and column for the phase "c" is removed.

Step 3: obtaining equation of faulty motor in the d-q frame

Applying the transformation vectors ($[T_S]$ and $[T_r]$), stator and rotor voltages can be written as following equations:

$$[v^s{}_{dqs}] = [T_S][R_S][T_S]^{-1}[i^s{}_{dqs}] + [T_S]\frac{d}{dt}\left([T_S]^{-1}[\lambda^s{}_{dqs}]\right)$$
$$[\lambda^s{}_{dqs}] = [T_S][L_{SS}][T_S]^{-1}[i^s{}_{dqs}] + [T_S][L_{SR}][T_r]^{-1}[i^s{}_{dqr}]$$
$$[v^s{}_{dqr}] = [T_r][R_R][T_r]^{-1}[i^s{}_{dqr}] + [T_r]\frac{d}{dt}\left([T_r]^{-1}[\lambda^s{}_{dqr}]\right)$$
$$[\lambda^s{}_{dqr}] = [T_r][L_{RR}][T_r]^{-1}[i^s{}_{dqr}] + [T_r][L_{RS}][T_S]^{-1}[i^s{}_{dqs}] \tag{5}$$

By simplifying (5), the equations of faulty three-phase IM with unequal stator windings in a stationary reference frame (superscript "s") can be expressed as following equations:

$$\lambda_{dr}^s = M_d i_{ds}^s + L_r i_{dr}^s \quad , \quad \lambda_{qr}^s = M_q i_{qs}^s + L_r i_{qr}^s$$
$$\tau_e = \frac{Pole}{2}(M_q i_{qs}^s i_{dr}^s - M_d i_{ds}^s i_{qr}^s)$$
$$\frac{Pole}{2}(\tau_e - \tau_l) = J\frac{d\omega_r}{dt} + F\omega_r$$
$$v_{ds}^s = r_{ds} i_{ds}^s + \frac{d\lambda_{ds}^s}{dt} \quad , \quad v_{qs}^s = r_{qs} i_{qs}^s + \frac{d\lambda_{qs}^s}{dt}$$
$$0 = r_r i_{dr}^s + \frac{d\lambda_{dr}^s}{dt} + \omega_r \lambda_{qr}^s, 0 = r_r i_{qr}^s + \frac{d\lambda_{qr}^s}{dt} - \omega_r \lambda_{dr}^s$$
$$\lambda_{ds}^s = L_{ds} i_{ds}^s + M_d i_{dr}^s \quad , \quad \lambda_{qs}^s = L_{qs} i_{qs}^s + M_q i_{qr}^s \tag{6}$$

Where, $v^s{}_{ds}$, $v^s{}_{qs}$, $i^s{}_{ds}$, $i^s{}_{qs}$, $i^s{}_{dr}$, $i^s{}_{qr}$, $\lambda^s{}_{ds}$, $\lambda^s{}_{qs}$, $\lambda^s{}_{dr}$ and $\lambda^s{}_{qr}$ are d-q axes voltages, currents, and fluxes of the stator and rotor. r_{ds}, $r_{qs}$and $r_r$denote the stator and rotor resistances. L_{ds}, L_{qs}, L_r, $M_d$and M_q denote the stator, and the rotor self 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. For three-phase IM with same stator windings, we have:

$$r_{ds} = r_{qs} = r_s, L_{ds} = L_{ls} + L_{md}, L_{qs} = L_{ls} + L_{mq}, L_r = L_{lr} + \frac{3}{2}L_{ms}$$
$$L_{md} = \frac{3}{2}L_{ms}, L_{mq} = \frac{1}{2}L_{ms}, M_d = \frac{3}{2}L_{ms}, M_q = \frac{\sqrt{3}}{2}L_{ms} \tag{7}$$

In summary, the difference between model of balanced and unbalanced IM equations are summarized in following TABLE I.

TABLE I. COMPARISON BETWEEN MODEL OF BALANCED AND UNBALANCED IM EQUATIONS

Balanced Motor	Unbalanced Motor
q-axis mutual inductance as follows: $M = \frac{3}{2}L_{ms}$	**q-axis mutual inductance as follows:** $M_q = \frac{\sqrt{3}}{2}L_{ms}$
d-axis mutual inductance as follows: $M = \frac{3}{2}L_{ms}$	**d-axis mutual inductance as follows:** $M_d = \frac{3}{2}L_{ms}$
stator q-axis self-inductance as follows: $L_s = L_{ls} + \frac{3}{2}L_{ms}$	**stator q-axis self-inductance as follows:** $L_{qs} = L_{ls} + \frac{1}{2}L_{ms}$
stator d-axis self-inductance as follows: $L_s = L_{ls} + \frac{3}{2}L_{ms}$	**stator d-axis self-inductance as follows:** $L_{ds} = L_{ls} + \frac{3}{2}L_{ms}$

In the RFOC method, we need to transfer equations of machine to the RFO reference frame. The conventional rotational transformation that should be applied to the equations of IM is as follows (this matrix transfer equations of IM from stationary reference frame to rotating reference frame) [13]:

$$T_s^e = \begin{bmatrix} \cos\theta_e & \sin\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix} \tag{8}$$

In this equation, θ_e is the angle between the stationary reference frame and rotating reference frame. It can be shown, the equations of faulty three-phase IM (equations (6)), by applying conventional rotational transformation (equations (8)), are divided into forward terms and backward terms (it is because of unequal inductances in the equations of faulty three-phase IM: $M_d \neq M_q$and $L_{ds} \neq L_{qs}$). Each term has the same structure with equations of balanced motor. One of them is rotated in the forward direction and one of them is rotated in the backward direction. By controlling of forward and backward components, controlling of faulty IM can be done but the controlling structure for faulty IM will be complex.

III. Proposed Method for Vector Control of Faulty Three-Phase IM

As mentioned before by using of conventional rotational transformation, the backward terms are generated in the RFOC equations of faulty three-phase IM. In this paper, new rotational transformations are introduced and applied to the faulty three-phase IM equations. By using of proposed matrices, the unbalanced equations of faulty motor change into balanced equations. New rotational transformation for stator current variables is considered as:

$$\begin{bmatrix} i_{ds}^e \\ i_{qs}^e \end{bmatrix} = \begin{bmatrix} T_{is}^e \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} = \begin{bmatrix} a_i & b_i \\ c_i & d_i \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} \quad (9)$$

By applying of this matrix to the electromagnetic torque equation of faulty three-phase IM we have:

$$\begin{aligned} \tau_e &= \frac{Pole}{2}(M_q i_{qs}^s i_{dr}^s - M_d i_{ds}^s i_{qr}^s) \\ &= \frac{Pole}{2}\begin{bmatrix} i_{dr}^s & i_{qr}^s \end{bmatrix} \begin{bmatrix} 0 & M_q \\ -M_d & 0 \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} \qquad (10) \\ &= \left(\frac{Pole}{2}\begin{bmatrix} i_{dr}^s & i_{qr}^s \end{bmatrix} \begin{bmatrix} T_s^e \end{bmatrix}^T \left(\begin{bmatrix} T_s^e \end{bmatrix}^{-1} \right)^T \right. \\ &\left. \begin{bmatrix} 0 & M_q \\ -M_d & 0 \end{bmatrix} \begin{bmatrix} T_{is}^e \end{bmatrix}^{-1} \begin{bmatrix} T_{is}^e \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} \right) \end{aligned}$$

With following equations:

$$\begin{aligned} a_i M_q \cos\theta_e + b_i M_d \sin\theta_e &= M_d \\ c_i M_q \cos\theta_e + d_i M_d \sin\theta_e &= 0 \end{aligned} \quad (11)$$

The electromagnetic torque equation of faulty IM (equation (10)) is obtained like electromagnetic torque equation of symmetric IM. Therefore, a_i, b_i, c_i, d_i and proposed rotational transformation for stator current variables are obtained as (12) and (13) respectively.

$$a_i = \frac{M_d}{M_q}\cos\theta_e, b_i = \sin\theta_e, c_i = -\frac{M_d}{M_q}\sin\theta_e, d_i = \cos\theta_e \quad (12)$$

$$\begin{bmatrix} i_{ds}^e \\ i_{qs}^e \end{bmatrix} = \begin{bmatrix} T_{is}^e \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} = \begin{bmatrix} \frac{M_d}{M_q}\cos\theta_e & \sin\theta_e \\ -\frac{M_d}{M_q}\sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} \quad (13)$$

Based on (8), (13) and after simplifying the electromagnetic torque equation (equation (10)) can be expressed as follows:

$$\tau_e = \frac{Pole}{2} M_q (i_{qs}^e i_{dr}^e - i_{ds}^e i_{qr}^e) \quad (14)$$

As it can be seen by using of this rotational transformation for current variables, equations of electromagnetic torque became like symmetric IM. The only difference between this equation and symmetric IM torque equation is that, in the balanced mode we have M=3/2L_{ms}instead of M_q. By applying (8), (13) to the rotor voltage equation of faulty IM we have:

$$\begin{aligned} \begin{bmatrix} T_s^e \end{bmatrix} \begin{bmatrix} 0 \\ 0 \end{bmatrix} &= \begin{bmatrix} T_s^e \end{bmatrix} \begin{bmatrix} M_d \frac{d}{dt} & \omega_r M_q \\ -\omega_r M_d & M_q \frac{d}{dt} \end{bmatrix} \begin{bmatrix} T_{is}^e \end{bmatrix}^{-1} \begin{bmatrix} T_{is}^e \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} \qquad (15) \\ &+ \begin{bmatrix} T_s^e \end{bmatrix} \begin{bmatrix} r_r + L_r \frac{d}{dt} & \omega_r L_r \\ -\omega_r L_r & r_r + L_r \frac{d}{dt} \end{bmatrix} \begin{bmatrix} T_s^e \end{bmatrix}^{-1} \begin{bmatrix} T_s^e \end{bmatrix} \begin{bmatrix} i_{dr}^s \\ i_{qr}^s \end{bmatrix} \end{aligned}$$

After simplifying:

$$\begin{aligned} \begin{bmatrix} 0 \\ 0 \end{bmatrix} &= \begin{bmatrix} M_q \frac{d}{dt} & (\omega_r - \omega_e) M_q \\ -(\omega_r - \omega_e) M_q & M_q \frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{ds}^e \\ i_{qs}^e \end{bmatrix} \qquad (16) \\ &+ \begin{bmatrix} r_r + L_r \frac{d}{dt} & (\omega_r - \omega_e) L_r \\ -(\omega_r - \omega_e) L_r & r_r + L_r \frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{dr}^e \\ i_{qr}^e \end{bmatrix} \end{aligned}$$

Like equation (14), equation (16) has been also obtained as symmetric IM equation. The only difference between this equation and symmetric IM rotor voltage equation is that, in the balanced mode we have M=3/2L_{ms} instead of M_q. In summary, the comparison between RFOC equations in balanced and unbalanced IM (flux, speed and torque) is presented in TABLE II (in RFOC technique, the rotor flux vector is aligned with d-axis: $\lambda_{dr}^e = |\lambda_r|$ and $\lambda_{qr}^e = 0$).

TABLE II. Comparison Between RFOC Equations in Balanced and Unbalanced IM (Flux, Speed, Torque)

Balanced Motor	Unbalanced Motor
$\lvert\lambda_r\rvert = \frac{M i_{ds}^e}{1 + T_r \frac{d}{dt}}$	$\lvert\lambda_r\rvert = \frac{M_q i_{ds}^e}{1 + T_r \frac{d}{dt}}$
$\omega_e = \omega_r + \frac{M i_{qs}^e}{T_r \lvert\lambda_r\rvert}$	$\omega_e = \omega_r + \frac{M_q i_{qs}^e}{T_r \lvert\lambda_r\rvert}$
$\tau_e = (\frac{Pole}{2})(\frac{M}{L_r})(\lvert\lambda_r\rvert i_{qs}^e)$	$\tau_e = (\frac{Pole}{2})(\frac{M_q}{L_r})(\lvert\lambda_r\rvert i_{qs}^e)$

A rotational transformation for stator voltage variables is considered as follows:

$$\begin{bmatrix} v_{ds}^e \\ v_{qs}^e \end{bmatrix} = \begin{bmatrix} T_{vs}^e \end{bmatrix} \begin{bmatrix} v_{ds}^s \\ v_{qs}^s \end{bmatrix} = \begin{bmatrix} a_v & b_v \\ c_v & d_v \end{bmatrix} \begin{bmatrix} v_{ds}^s \\ v_{qs}^s \end{bmatrix} \quad (17)$$

By employing equation (17) to the stator voltage equations of faulty IM and after simplifying, we have:

$$\left[T_{vs}^{e}\right]\begin{bmatrix} v_{ds}^{s} \\ v_{qs}^{s} \end{bmatrix} = \left[T_{vs}^{e}\right]\begin{bmatrix} r_{ds} + L_{ds}\dfrac{d}{dt} & 0 \\ 0 & r_{qs} + L_{qs}\dfrac{d}{dt} \end{bmatrix}\left[T_{is}^{e}\right]^{-1}\left[T_{is}^{e}\right]\begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} \quad (18)$$

$$+\left[T_{vs}^{e}\right]\begin{bmatrix} M_d\dfrac{d}{dt} & 0 \\ 0 & M_q\dfrac{d}{dt} \end{bmatrix}\left[T_{s}^{e}\right]^{-1}\left[T_{s}^{e}\right]\begin{bmatrix} i_{dr}^{s} \\ i_{qr}^{s} \end{bmatrix}$$

So,

$$\begin{bmatrix} v_{ds}^{e} \\ v_{qs}^{e} \end{bmatrix} = \begin{bmatrix} a_v & b_v \\ c_v & d_v \end{bmatrix}\begin{bmatrix} \dfrac{M_q}{M_d} r_{ds}\cos\theta_e & \dfrac{-M_q}{M_d} r_{ds}\sin\theta_e \\ r_{qs}\sin\theta_e & r_{qs}\cos\theta_e \end{bmatrix}\begin{bmatrix} i_{ds}^{e} \\ i_{qs}^{e} \end{bmatrix}$$

$$+\begin{bmatrix} a_v & b_v \\ c_v & d_v \end{bmatrix}\begin{bmatrix} \dfrac{M_q}{M_d} L_{ds}\cos\theta_e & \dfrac{-M_q}{M_d} L_{ds}\sin\theta_e \\ L_{qs}\sin\theta_e & L_{qs}\cos\theta_e \end{bmatrix}\begin{bmatrix} \dfrac{di_{ds}^{e}}{dt} \\ \dfrac{di_{qs}^{e}}{dt} \end{bmatrix}$$

$$+\omega_e\begin{bmatrix} a_v & b_v \\ c_v & d_v \end{bmatrix}\begin{bmatrix} \dfrac{-M_q}{M_d} L_{ds}\sin\theta_e & \dfrac{-M_q}{M_d} L_{ds}\cos\theta_e \\ L_{qs}\cos\theta_e & -L_{qs}\sin\theta_e \end{bmatrix}\begin{bmatrix} i_{ds}^{e} \\ i_{qs}^{e} \end{bmatrix} \quad (19)$$

$$+\omega_e\begin{bmatrix} a_v & b_v \\ c_v & d_v \end{bmatrix}\begin{bmatrix} -M_d\sin\theta_e & -M_d\cos\theta_e \\ M_q\cos\theta_e & -M_q\sin\theta_e \end{bmatrix}\begin{bmatrix} i_{dr}^{e} \\ i_{qr}^{e} \end{bmatrix}$$

$$+\begin{bmatrix} a_v & b_v \\ c_v & d_v \end{bmatrix}\begin{bmatrix} M_d\cos\theta_e & -M_d\sin\theta_e \\ M_q\sin\theta_e & M_q\cos\theta_e \end{bmatrix}\begin{bmatrix} \dfrac{di_{dr}^{e}}{dt} \\ \dfrac{di_{qr}^{e}}{dt} \end{bmatrix}$$

With following equations:

$$a_v = -b_v.Z_5.\cot\theta_e \quad (20)$$
$$c_v = d_v.Z_5.\tan\theta_e$$

Where,

$$Z_5 = \left(\frac{L_{qs} - \dfrac{M_q^2}{L_r}}{-\dfrac{L_{ds}M_q}{M_d} + \dfrac{M_d M_q}{L_r}}\right) \quad (21)$$

Equation of stator voltage is gained like equation of stator voltage for balanced IM. Therefore, a_v, b_v, c_v and d_v can be considered as:

$$a_v = -\cos\theta_e \quad , \quad b_v = \left(\frac{-L_{ds}L_r M_q + M_d^2 M_q}{L_{qs}L_r M_d - M_d M_q^2}\right)\sin\theta_e \quad (22)$$
$$c_v = \sin\theta_e \quad , \quad d_v = \left(\frac{-L_{ds}L_r M_q + M_d^2 M_q}{L_{qs}L_r M_d - M_d M_q^2}\right)\cos\theta_e$$

Consequently, the rotational transformation for stator voltage variables is obtained as:

$$\left[T_{vs}^{e}\right] = \begin{bmatrix} -\cos\theta_e & \left(\dfrac{-L_{ds}L_r M_q + M_d^2 M_q}{L_{qs}L_r M_d - M_d M_q^2}\right)\sin\theta_e \\ \sin\theta_e & \left(\dfrac{-L_{ds}L_r M_q + M_d^2 M_q}{L_{qs}L_r M_d - M_d M_q^2}\right)\cos\theta_e \end{bmatrix} \quad (23)$$

By considering of $(M_d/ M_q)^2 = L_{ds}/ L_{qs}$ equation (23) can be simplified as equation (24).

$$\begin{bmatrix} v_{ds}^{e} \\ v_{qs}^{e} \end{bmatrix} = \left[T_{vs}^{e}\right]\begin{bmatrix} v_{ds}^{s} \\ v_{qs}^{s} \end{bmatrix} = \begin{bmatrix} -\cos\theta_e & -\dfrac{M_d}{M_q}\sin\theta_e \\ \sin\theta_e & -\dfrac{M_d}{M_q}\cos\theta_e \end{bmatrix}\begin{bmatrix} v_{ds}^{s} \\ v_{qs}^{s} \end{bmatrix} \quad (24)$$

As expected, by using (8), (13) and (24), equation (18) is obtained as balanced IM equations (see TABLE III). In summary, the comparison between RFOC equations in balanced and unbalanced IM (stator voltage) is presented in TABLE III. Based on TABLE II and III, Fig. 2 and TABLE IV are proposed for vector control of three-phase IM under open-phase fault. In this figure, the blue blocks show the essential modifications to the conventional vector control, so that it can be applied to the faulty motor.

TABLE III. COMPARISON BETWEEN RFOC EQUATIONS IN BALANCED AND UNBALANCED IM (STATOR VOLTAGE)

Balanced Motor	**Unbalanced Motor**
$v_{ds}^{e} = r_s i_{ds}^{e} + (L_s - \frac{M^2}{L_r})\frac{di_{ds}^{e}}{dt} - \omega_e(L_s - \frac{M^2}{L_r})i_{qs}^{e} + (\frac{M}{L_r})(\frac{M i_{ds}^{e} - \lvert\lambda_r\rvert}{T_r})$	$v_{ds}^{e} = (\frac{r_s M_q^2 + r_s M_d^2}{2M_d^2})i_{ds}^{e} + (L_{qs} - \frac{M_q^2}{L_r})\frac{di_{ds}^{e}}{dt} - \omega_e(L_{qs} - \frac{M_q^2}{L_r})i_{qs}^{e} + (\frac{M_q}{L_r})(\frac{M_q i_{ds}^{e} - \lvert\lambda_r\rvert}{T_r}) + (\frac{r_s M_q^2 - r_s M_d^2}{2M_d^2}) \times (\cos 2\theta_e i_{ds}^{e} - \sin 2\theta_e i_{qs}^{e})$
$v_{qs}^{e} = r_s i_{qs}^{e} + (L_s - \frac{M^2}{L_r})\frac{di_{qs}^{e}}{dt} + \omega_e(L_s - \frac{M^2}{L_r})i_{ds}^{e} + \omega_e M\frac{\lvert\lambda_r\rvert}{L_r}$	$v_{qs}^{e} = (\frac{r_s M_q^2 + r_s M_d^2}{2M_d^2})i_{qs}^{e} + (L_{qs} - \frac{M_q^2}{L_r})\frac{di_{qs}^{e}}{dt} + \omega_e(L_{qs} - \frac{M_q^2}{L_r})i_{ds}^{e} + \omega_e M_q\frac{\lvert\lambda_r\rvert}{L_r} + (\frac{r_s M_q^2 - r_s M_d^2}{2M_d^2}) \times (-\sin 2\theta_e i_{ds}^{e} - \cos 2\theta_e i_{qs}^{e})$

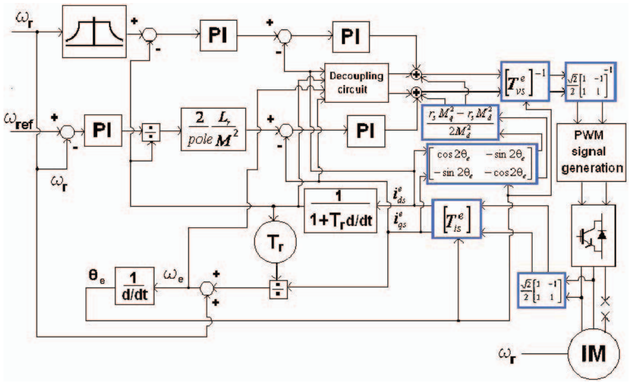


Fig. 2. Proposed block diagram for vector control of faulty IM

TABLE IV. COMPARISON BETWEEN TWO VECTOR CONTROL METHODS

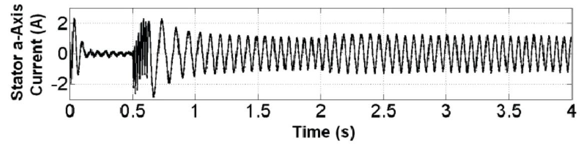
Conventional Vector Control for Balanced IM	Proposed Vector Control for Unbalanced IM
Stator self-inductance: $L_s = L_{ls} + \frac{3}{2} L_{ms}$	**Stator self-inductance:** $L_s = L_{qs} = L_{ls} + \frac{1}{2} L_{ms}$
Stator and rotor mutual inductance: $M = \frac{3}{2} L_{ms}$	**Stator and rotor mutual inductance:** $M = M_q = \frac{\sqrt{3}}{2} L_{ms}$
Stator resistance: r_s	**Stator resistance:** $\frac{r_s M_q^2 + r_s M_d^2}{2M_d^2} = \frac{2}{3} r_s$

IV. PERFORMANCE EVALUATION

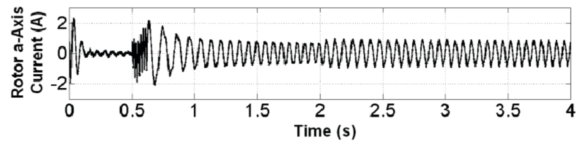
A three-phase IM which is fed from PWM-VSI was studied by simulation. The parameters of the IM used this work are as follows:

Voltage:125V, Power=475W, f =50Hz, No. of poles=4, r_s=20.6 Ω, r_r=19.15Ω, L_{lr}=L_{ls}=0.0814H, L_{ms}=0.851H, J=0.0038 kg.m^2.

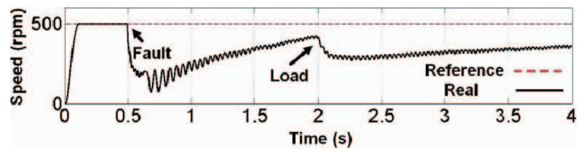
Fig. 3 shows the simulation of the conventional vector controller and Fig. 4 shows the simulation of the modified vector controller based on Fig. 2 and Table 4. In the simulations it is assumed that the fault is immediately detected. During starting the simulated motor is healthy. A fault cut-off (phase "c" cut-off) and load torque is introduced at t=0.5 and t=2 respectively (T_l=1.2N.m). Moreover, the reference rotor speed is set to 500rpm. As it is shown, the simulation results of the conventional controller show that the conventional controller cannot control the faulty IM appropriately. Especially a significant oscillation in the electromagnetic torque can been seen (see Fig. 3). We can observe from simulation results that the modified controller decreases the electromagnetic torque oscillation notably with a considerable improved in the rotor speed response (see Fig. 4).



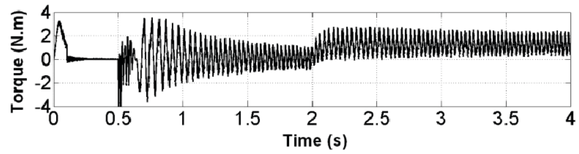
(a)



(b)

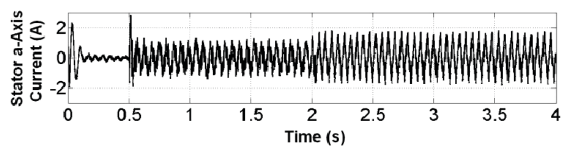


(c)

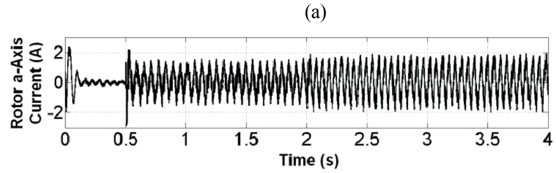


(d)

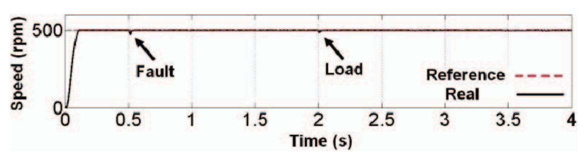
Fig. 3. Simulation results of the modified vector control; (a) Stator a-Axis Current, (b) Rotor a-Axis Current, (c) Speed, (d) Torque



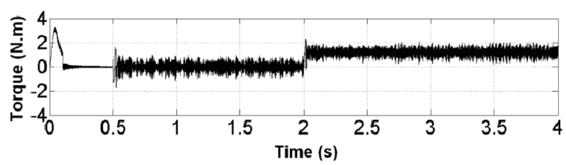
(a)



(b)



(c)



(d)

Fig. 4. Simulation results of the conventional vector control; (a) Stator a-Axis Current, (b) Rotor a-Axis Current, (c) Speed, (d) Torque

V. Conclusion

An accurate and simple technique for vector control of three-phase IM when one of the stator phases is opened has been presented. Stator q-axis self and mutual inductances asymmetry in the model of faulty IM cause torque and speed pulsations under a vector control system. The problem can be overcome by the proposed modified vector control as explained. The proposed scheme can be used in critical industrial applications and vector control of single-phase IMs with main and auxiliary windings. The simulation results have demonstrated the accuracy and feasibility of the presented technique.

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