Modeling and Simulation of Dual Three Phase Induction Machine in Fault condition (Two Phase cut off) and Propose A New Vector Control Approach for Torque Oscillation Reduction

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ABSTRACT:
From the energy conversion point of view, structure of all electrical machines can be simplified to an equivalent two-phase machine. At normal operation this equivalent machine has a balanced structure which is the basis for vector control equations at this mode. Similarly at phase - cut off condition this equivalent model has an unbalanced structure, which can be used to obtain vector control equations under fault conditions. In this paper, first a dual three-phase induction machine has been modeled with two phases of stator cut off, then vector control equations have been obtained from d-q model of machine. On the basis of these equations a new "Rotor Field Oriented (R.F.O) control" approach is presented which indicates how the conventional R.F.O control can be adapted for fault conditions. Finally, a computer simulation has been presented to compare the operation of conventional R.F.O control with improved R.F.O control, while two phase of machine is cut off. Results show considerable improvement in drive performance especially in reduction of torque oscillations reduction.

Keywords: Fault–Vector control–Dual three phase- Induction machine.

I) INTRODUCTION:

High-power electric machine drive systems have found many applications such as pumps, fans, compressors, rolling mills, cement mills, mine hoists, just to name a few. At present, the most successful type of the high power drive systems is cycloconverter-electric machine drives and synchronous machines fed by current source thyristor inverters. Voltage source inverters, despite their advantage in line power factor over a cycloconverter as well as their advantage of being able to use low cost induction machines, are still limited to the lower end of the high power range due to limitations on the gate - turn - off type semiconductor power device ratings. As an approach in achieving high power ratings with voltage source inverters, multi - phase machine drive systems have emerged [1]. In the most common such structure two sets of three- phase windings are spatially phase shifted by 30 electrical degrees and each set of the three - phase stator windings is excited by a three-phase inverter, therefore the total power rating of the system is doubled .In addition to enhancing power rating, it is also believed that drive systems with such multi - phase structure will improve the reliability at the system level [2-5]. In particular with loss of one or more of stator winding excitation sets, a multi - phase induction machine can continue to be operated with an asymmetrical winding structure and unbalanced excitation [6], [7].

The most commonly used analytical tool for the analysis of unbalanced operation of electric machines has been the well-known symmetrical component method. Although this method has been used successfully in the steady state analysis on sinusoidal excitation, however, as far as the dynamics of machine is concerned the method loses its utility. As the dynamic behavior of an electric machine is critical in a modern drive system it is necessary to develop analytical tools which can handle the dynamics of electric machines under structurally unbalanced operation condition. R.zhao and T.Lipo developed a modeling and control approach for a dual three-phase induction machine with one stator winding open. Their proposed method was directly based on the asymmetrical winding structure [6]. Decoupling of energy-conversion-related components from non- energy-conversion-related components, is the important advantage of this model, which is used in control applications.

From the past decades "Vector control" method is known as one of the best methods in controlling the torque and speed of ac machines. Between the various types of " Vector control" approaches, "Rotor field oriented control" is more suitable for induction machines [7]. However, in the phase cut off condition, conventional R.F.O control-which is designed for normal operation of machine-can not be used to control the machine. The problem is specially observed in oscillations in electromagnetic torque. Lipo and Zhao presented a control approach for controlling the inverter, which fed a dual three-phase induction machine with one phase open [8].

In this paper, a dual three-phase induction machine has been modeled at the stator fault condition of two-phase cut off. Matrix transformation method is used to obtain a decoupled model for machine. Energy-conversion-related components of machine variables, in this decoupling approach, are mapped to a so-called d-q subspace, and the non-related energy conversion components are mapped to a so-called Z_1-Z_2 subspace of model. On the basis of this model, "stator voltage equations" for R.F.O vector control is obtained and a method has been proposed to adapt the conventional blocks of vector control, for operating under fault conditions. To show the capabilities of this proposed method, a computer simulation has been presented. It includes dqz_1z_2 model of motor under fault conditions, fed from a SPWM voltage source inverter. The operation of the proposed R.F.O control in reducing machine torque oscillation has been compared with the operation of conventional method. Simulation results show suitable performance for the proposed control method under fault condition.

II) MODEL OF DUAL THREE-PHASE INDUCTION MACHINE WHILE TWO PHASES OF STATOR ARE CUT OFF:

Suppose that a phase cut off fault is occurred in phases “e” and “f”’ of a multi - phase drive system including a dual three phase induction machine, as shown in fig 1:

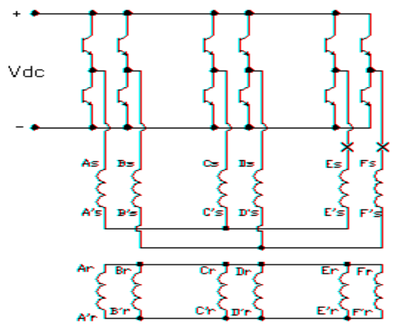


Fig.1: Dual three phase induction machine drive With two phases open.

Since, four independent currents can flow in the general case, it is expected that machine model to be four-dimensional. The four dimensional space spanned by vectors of real machine variables can be expressed as the direct sum of two orthogonal subspace with one of two-dimensional subspace representing the energy conversion property of the machine (d - q subspace) and the other the non - electromechanical energy conversion portion (Z_1 -Z_2 subspace). Assuming sinusoidal waveform for winding spatial distribution, Stator and rotor winding flux, axes can be shown as follows:

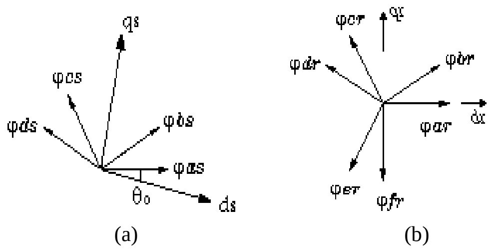


Fig.2: a) Stator winding flux axes
b) Rotor winding flux axes.

If the angle between d - axis of air gap flux plane and “ as “ winding flux axis is θ_o , ds-axis and qs-axis flux can be written as follows:

$$\phi_{ds} = \begin{bmatrix} \cos(\theta_o) & \cos(\theta_o + \frac{\pi}{6}) & \cos(\theta_o + \frac{2\pi}{3}) & \cos(\theta_o + \frac{5\pi}{6}) \end{bmatrix} \begin{bmatrix} \phi_{as} \\ \phi_{bs} \\ \phi_{cs} \\ \phi_{ds} \end{bmatrix} \quad (1)$$

$$\phi_{qs} = \begin{bmatrix} \sin(\theta_o) & \sin(\theta_o + \frac{\pi}{6}) & \sin(\theta_o + \frac{2\pi}{3}) & \sin(\theta_o + \frac{5\pi}{6}) \end{bmatrix} \begin{bmatrix} \phi_{as} \\ \phi_{bs} \\ \phi_{cs} \\ \phi_{ds} \end{bmatrix} \quad (2)$$

Equations (1) and (2) state that the ds - axis and qs - axis fluxes are projections of the stator flux vector in a four dimensional space, on another set of vectors in that space. The vectors named “d” and “q” are the basis vectors of the new four-dimensional space:

$$d = \begin{bmatrix} \cos(\theta_o) & \cos(\theta_o + \frac{\pi}{6}) & \cos(\theta_o + \frac{2\pi}{3}) & \cos(\theta_o + \frac{5\pi}{6}) \end{bmatrix}$$

$$q = \begin{bmatrix} \sin(\theta_o) & \sin(\theta_o + \frac{\pi}{6}) & \sin(\theta_o + \frac{2\pi}{3}) & \sin(\theta_o + \frac{5\pi}{6}) \end{bmatrix}$$

From the orthogonality of basis vectors, “ θ_o ’’ is obtained:

$$d^T . q = q^T . d = 0 \quad \Rightarrow \quad \theta_o = \frac{\pi}{12}$$

The subspace spanned by vector d and q represents the energy conversion property of the machine. The vectors, which span the two-dimensional non- electromechanical energy conversion subspace, can be determined mathematically. Defining two vectors as Z_1 and Z_2 , from the orthogonality of basis vectors, these two vectors can be obtained. Using four basis vectors to form the new basis for the four dimensional space, the following normalized decomposition transformation results:

$$[T_s] = \begin{bmatrix} .5706 & .4177 & -.4177 & -.5706 \\ .2430 & .6640 & .6640 & .2430 \\ -.4177 & .5706 & -.5706 & .4177 \\ .6640 & -.2430 & -.2430 & .6640 \end{bmatrix} \quad (3)$$

The decomposition matrix for rotor variables of the machine “ [Tr]” remains the same as the transformation for balanced operation, because the rotor still maintains a balanced winding structure [6]. Applying the transformation “ [Ts]” and “[Tr]” to the voltage equations of stator and rotor fields, yield:

Machine model in d - q subspace:

$$\begin{bmatrix} v^s_{ds} \\ v^s_{qs} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_s + L_{ds}\frac{d}{dt} & 0 & M_d \frac{d}{dt} & 0 \\ 0 & r_s + L_{qs}\frac{d}{dt} & 0 & M_q \frac{d}{dt} \\ M_d \frac{d}{dt} & \omega_r M_q & r_r + L_r \frac{d}{dt} & \omega_r L_r \\ -\omega_r M_d & M_q \frac{d}{dt} & -\omega_r L_r & r_r + L_r \frac{d}{dt} \end{bmatrix} \begin{bmatrix} i^s_{ds} \\ i^s_{qs} \\ i^r_{dr} \\ i^r_{qr} \end{bmatrix} \quad (4)$$

Where:

$$L_{ds} = L_{ls} + 2.866\, L_{ms} \;,\; L_{qs} = L_{ls} + 1.134\, L_{ms} \;,\; L_r = L_{lr} + 3\, L_{ms} \;,$$
$$M_d = 2.9324\, L_{ms} \;,\; M_q = 1.8443\, L_{ms}$$

Machine model in Z_1 -Z_2 subspace:

Stator voltage equation:

$$\begin{bmatrix} v^s_{Z1s} \\ v^s_{Z2s} \end{bmatrix} = \begin{bmatrix} r_s + L_{ls}\frac{d}{dt} & 0 \\ 0 & r_s + L_{ls}\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i^s_{Z1s} \\ i^s_{Z2s} \end{bmatrix} \quad (5)$$

Rotor voltage equation:

$$\begin{bmatrix}0\\0\\0\\0\end{bmatrix} = \begin{bmatrix} r_r + L_{lr}\frac{d}{dt} & 0 & 0 & 0 \\ 0 & r_r + L_{lr}\frac{d}{dt} & 0 & 0 \\ 0 & 0 & r_r + L_{lr}\frac{d}{dt} & 0 \\ 0 & 0 & 0 & r_r + L_{lr}\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i^r_{z1r} \\ i^r_{z2r} \\ i^r_{o1r} \\ i^r_{o2r} \end{bmatrix} \qquad (6)$$

Electromagnetic torque:

$$T_e = \frac{Pole}{2}\left(M_q i^s_{qs} i^s_{dr} - M_d i^s_{ds} i^s_{qr} \right) \qquad (7)$$

Equation (4) to (7) completely represent dqz1z2 model of dual three-phase induction machine with two phase's open. Writing these equations in the form of state equations, the computer simulation of model can be performed.

III) EQUATIONS OF R.F.O VECTOR CONTROL IN PHASE CUT OFF MODE:

For obtaining vector control equations it is necessary to indicate machine equations in rotor field oriented reference frame. For the unbalanced operating situation investigated in this paper, the transformation of stator variables using the balanced rotation transformation would result in ac components in the R.F.O reference frame [7]. Therefore the following unbalanced transformation is proposed for stator variable [7]:

$$\left[T^e_s\right] = \begin{bmatrix} \sqrt{\frac{M_d}{M_q}}\cos\theta_e & \sqrt{\frac{M_q}{M_d}}\sin\theta_e \\ -\sqrt{\frac{M_d}{M_q}}\sin\theta_e & \sqrt{\frac{M_q}{M_d}}\cos\theta_e \end{bmatrix}$$

Where θ_e is the angle between stationary reference frame and an arbitrary rotating reference frame. Applying the appropriate transformation on rotor and stator voltage equations and electromagnetic torque the following equations result, which express machine equations in the arbitrary rotating reference frame.

Stator voltage equations:

$$\begin{bmatrix} v^e_{ds} \\ v^e_{qs} \end{bmatrix} = \begin{bmatrix} r_s + (\frac{L_{ds}+L_{qs}}{2})\frac{d}{dt} & -(\frac{L_{ds}+L_{qs}}{2})\omega_e \\ (\frac{L_{ds}+L_{qs}}{2})\omega_e & r_s + (\frac{L_{ds}+L_{qs}}{2})\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i^e_{ds} \\ i^e_{qs} \end{bmatrix} + \begin{bmatrix} (\frac{L_{ds}-L_{qs}}{2})\frac{d}{dt} & (\frac{L_{ds}-L_{qs}}{2})\omega_e \\ (\frac{L_{ds}-L_{qs}}{2})\omega_e & -(\frac{L_{ds}-L_{qs}}{2})\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i^{-e}_{ds} \\ i^{-e}_{qs} \end{bmatrix} +$$

$$\begin{bmatrix} (\frac{M_d^2+M_q^2}{2\sqrt{M_d M_q}})\frac{d}{dt} & -(\frac{M_d^2+M_q^2}{2\sqrt{M_d M_q}})\omega_e \\ (\frac{M_d^2+M_q^2}{2\sqrt{M_d M_q}})\omega_e & (\frac{M_d^2+M_q^2}{2\sqrt{M_d M_q}})\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i^e_{dr} \\ i^e_{qr} \end{bmatrix} + \begin{bmatrix} (\frac{M_d^2-M_q^2}{2\sqrt{M_d M_q}})\frac{d}{dt} & (\frac{M_d^2-M_q^2}{2\sqrt{M_d M_q}})\omega_e \\ (\frac{M_d^2-M_q^2}{2\sqrt{M_d M_q}})\omega_e & -(\frac{M_d^2-M_q^2}{2\sqrt{M_d M_q}})\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i^{-e}_{dr} \\ i^{-e}_{qr} \end{bmatrix} \qquad (9)$$

Rotor voltage equations:

$$\begin{bmatrix}0\\0\end{bmatrix} = \begin{bmatrix} \sqrt{M_d M_q}\frac{d}{dt} & -(\omega_e-\omega_r)\sqrt{M_d M_q} \\ (\omega_e-\omega_r)\sqrt{M_d M_q} & \sqrt{M_d M_q}\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i^e_{ds} \\ i^e_{qs} \end{bmatrix} + \begin{bmatrix} r_r + L_r\frac{d}{dt} & -(\omega_e-\omega_r) L_r \\ (\omega_e-\omega_r) L_r & r_r + L_r\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i^e_{dr} \\ i^e_{qr} \end{bmatrix} \qquad (10)$$

Electromagnetic torque:

$$T_e = \frac{Pole}{2}\sqrt{M_d M_q}\left(i^e_{qs} i^e_{dr} - i^e_{ds} i^e_{qr} \right) \qquad (11)$$

Where subtitle " - " indicates backward rotating variables. On the basis of equations (9) to (11) R.F.O vector control equations can be obtained. These equations are similar to the R.F.O vector control equations in the balance mode. These equations are compared in table (1).

Table 1. Comparing R.F.O vector control equations in fault mode and balance mode

Description	Balance mode eq.'s	Fault mode eq.'s
Torque Equation.	$T_e = \frac{Pole}{2}\frac{M}{L_r}\lvert\lambda_r\rvert i^{mr}_{qs}$	$T_e = \frac{Pole}{2}\frac{\sqrt{M_d M_q}}{L_r}\lvert\lambda_r\rvert i^{mr}_{qs}$
Rotor flux Equation.	$T_r\frac{d}{dt}\lvert\lambda_r\rvert + \lvert\lambda_r\rvert = M i^{mr}_{ds}$	$T_r\frac{d}{dt}\lvert\lambda_r\rvert + \lvert\lambda_r\rvert = \sqrt{M_d M_q}\, i^{mr}_{ds}$
Angular Velocity of Rotor flux	$\omega_{mr} = \omega_r + \frac{M\, i^{mr}_{qs}}{T_r\lvert\lambda_r\rvert}$	$\omega_{mr} = \omega_r + \frac{\sqrt{M_d M_q}\, i^{mr}_{qs}}{T_r\lvert\lambda_r\rvert}$
D-axis Component Of stator Voltage Equation.	$v^{mr}_{ds} = U^d_{ds} + U^{ref}_{ds}$	$v^{mr}_{ds} = U^{+d}_{ds} + U^{-d}_{ds} + U^{+ref}_{ds} + U^{-ref}_{ds}$
	$U^d_{ds} = -\omega_{mr} L'_s i^{mr}_{qs}$	$U^{+d}_{ds} = -\omega_{mr}(\frac{L'_{ds}+L'_{qs}}{2}) i^{mr}_{qs}$ $U^{-d}_{ds} = -\omega_{mr}(\frac{L'_{ds}-L'_{qs}}{2}) i^{-mr}_{qs} +$ $\omega_{mr}(\frac{L_{ds}-L_{qs}-L'_{ds}+L'_{qs}}{2})\lambda^{-mr}_{qr}$
	$U^{ref}_{ds} = r_s i^{mr}_{ds} + L'_s\frac{d}{dt} i^{mr}_{ds} +$ $(\frac{L_s-L'_s}{M})\frac{d}{dt}\lvert\lambda_r\rvert$	$U^{+ref}_{ds} = r_s i^{mr}_{ds} + (\frac{L'_{ds}+L'_{qs}}{2})\frac{d}{dt} i^{mr}_{ds} +$ $(\frac{L_{ds}+L_{qs}-L'_{ds}-L'_{qs}}{2\sqrt{M_d M_q}})\frac{d}{dt}\lvert\lambda_r\rvert$ $U^{-ref}_{ds} = (\frac{L'_{ds}-L'_{qs}}{2})\frac{d}{dt} i^{-mr}_{ds} +$ $(\frac{L_{ds}-L_{qs}-L'_{ds}+L'_{qs}}{2\sqrt{M_d M_q}})\frac{d}{dt}\lambda^{-mr}_{dr}$
D-axis Component Of stator Voltage Equation.	$v^{mr}_{qs} = U^d_{qs} + U^{ref}_{qs}$	$v^{mr}_{qs} = U^{+d}_{qs} + U^{-d}_{qs} + U^{+ref}_{qs} + U^{-ref}_{qs}$
	$U^d_{qs} = -\omega_{mr} L'_s i^{mr}_{ds} +$ $\omega_{mr}(\frac{L_s-L'_s}{M})\lvert\lambda_r\rvert$	$U^{+d}_{qs} = -\omega_{mr}(\frac{L'_{ds}+L'_{qs}}{2}) i^{mr}_{ds} +$ $\omega_{mr}(\frac{L_{ds}+L_{qs}-L'_{ds}-L'_{qs}}{2})\lvert\lambda_r\rvert$ $U^{-d}_{qs} = \omega_{mr}(\frac{L'_{ds}-L'_{qs}}{2}) i^{-mr}_{ds} +$ $\omega_{mr}(\frac{L_{ds}-L_{qs}-L'_{ds}+L'_{qs}}{2})\lambda^{-mr}_{dr}$
	$U^{ref}_{qs} = r_s i^{mr}_{qs} + L'_s\frac{d}{dt} i^{mr}_{qs}$	$U^{+ref}_{qs} = r_s i^{mr}_{qs} + (\frac{L'_{ds}+L'_{qs}}{2})\frac{d}{dt} i^{mr}_{qs}$ $U^{-ref}_{qs} = -(\frac{L'_{ds}-L'_{qs}}{2})\frac{d}{dt} i^{-mr}_{qs} -$ $(\frac{L_{ds}-L_{qs}-L'_{ds}+L'_{qs}}{2\sqrt{M_d M_q}})\frac{d}{dt}\lambda^{-mr}_{qr}$

It is observed that in the fault mode rotor and electromagnetic torque equations are similar to those in balance mode, and only "M" is substituted by "$\sqrt{M_d M_q}$". In stator voltage equations in addition to forward rotating components - which are similar to balance mode equations - backward rotating component have appeared as well. In fact, the part of equations due to forward rotating components are the same as balance mode equations except that machine inductances are substituted by the mean value of d-axis and q-axis inductances in the fault mode. The parts due to the backward rotating components are almost similar to the forward rotating components but sum of the inductances is substituted by the difference.

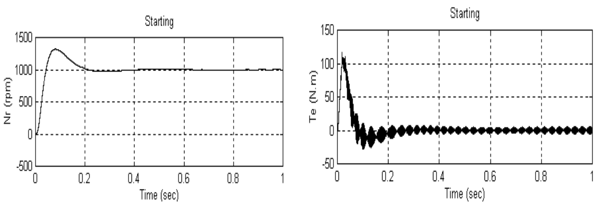
Considering the amount of inductances on d and q - axis directions, it is possible to neglect the difference of the inductances in comparison to the sum of the inductances and propose a control approach, which results in the following changes in the vector control blocks.

Table 2. Necessary changes in conventional R.F.O control blocks for operating at fault condition.

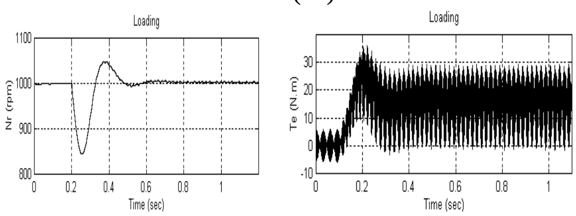
In balance mode	In fault mode
M	$\sqrt{M_d\ M_q}$
L_S	$\dfrac{L_{ds}+L_{qs}}{2}$
L'_S	$\dfrac{L'_{ds}+L'_{qs}}{2}$
Matrix transformation 6 to 2 according to reference [1].	Matrix transformation 4 to 2 according to eq. (6)
Balance mode rotational transformation according to [1].	Fault mode rotational transformation according to eq. (13)

IV) SIMULATION RESULTS:

In this section computer simulation results are presented. Simulations include a dual three-phase induction machine with two phases open, and is fed from a SPWM voltage source inverter. Two controllers are used for machine speed control. The first is the conventional R.F.O vector controller and the second is the same controller with proposed changes according to table 2. Simulation results of the conventional controller is shown in fig.3:



(a)



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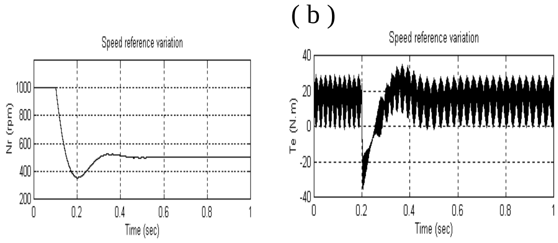
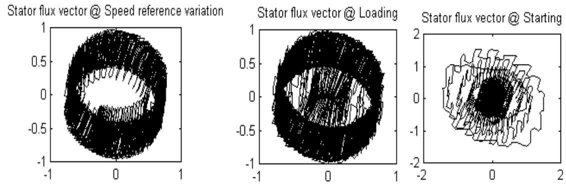


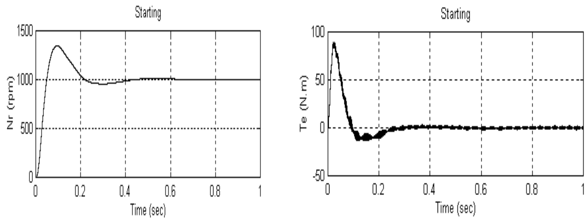
(c)



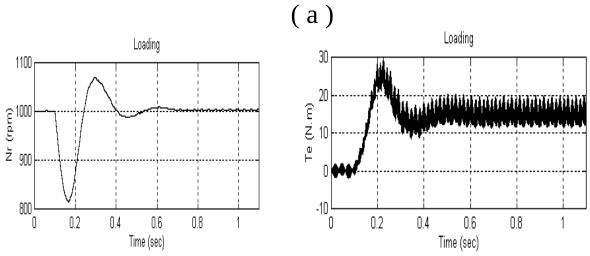
(d)

Fig. 3: Simulation results of conventional R.F.O vector controller
(a) No load starting: Nref= 1000 rpm, Tload = 0N.m
(b) Loading: Nref= 1000rpm, Tload = 15N.m
(c) Speed reference variation: Nref=500rpm, Tload = 15N.m
(d) Stator flux vector characteristic

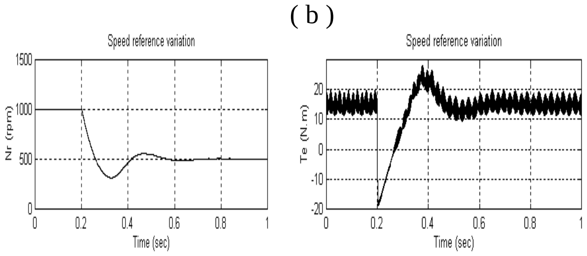
Results show considerable oscillations in electromagnetic torque, with amplitude of about 14N.m for a load torque of 15 N.m. Stator flux vector characteristic is not suitable either. Simulation results for modified R.F.O vector controller is shown in fig.4:



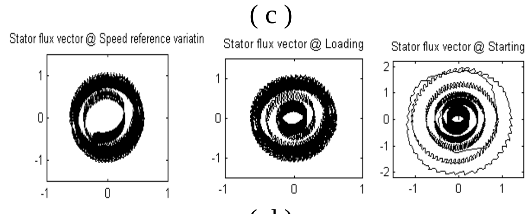
(a)



(b)



(c)



(d)

Fig.4) Simulation results of modified R.F.O vector controller.
(a) No load starting: Nref = 1000rpm, Tload = 0N.m
(b) Loading: Nref = 1000rpm, Tload = 15N.m
(c) Speed reference variation: Nref = 500rpm, Tload = 15N.m
(d) Stator flux vector characteristic

It is observed that with the proposed modifications, torque oscillation is reduced considerably and the oscillation amplitude decreased to about 4 N.m for the same fault conditions. Also the stator flux vector characteristic is improved. Existence of small torque oscillations in this case is due to the fact that the effect of backward rotating component is neglected, since proposed modifications in table-2 implicitly have such an assumption.

V) CONCLUSION:

The method, proposed in this paper for modeling of a dual three-phase induction machine with two phases open shows the capabilities of matrix transformation method in modeling various type of phase-cut-off faults in the stator of induction machines. The importance of this modeling method is in decoupling energy-conversion-related components from non-energy-conversion related components of machine variables such that suitable control relations can be obtained for control of the machine. It is shown that under fault conditions using an unbalanced rotational transformation, vector control equations can be obtained which are similar to these equations in the balanced mode. On the basis of these similarities a method is proposed where applying a few changes in the conventional R.F.O vector controller blocks, it can be capable of controlling the machine under fault conditions. Simulation results show suitable performance of proposed control method. Especially, with this method, torque oscillations are considerably reduced. However torque oscillations are not completely eliminated since the effect of backward rotating components are neglected. Given that the structure of two phase open-dual three phase induction machine is similar to the structure of one phase open conventional three phase induction machine the proposed method of modeling and control can be used for one phase open-conventional three phase induction machine as well.

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