Scientia Iranica, Vol. 9, No. 4, pp 321–327
© Sharif University of Technology, October 2002

SCIENTIA
IRANICA

Modeling and Simulation of Dual Three-Phase Induction Machine Under Fault Conditions and Proposal of a New Vector Control Approach for Torque Oscillation Reduction

K. Abbaszadeh[1], E. Fallah[1] and J. Milli Monfared*

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 in this mode. Similarly, at a 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 the d–q model of the 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 a conventional R.F.O. control with an improved R.F.O. control, while the two phases of the machine are cut off. Results show considerable improvement in drive performance, especially in reduction of torque oscillation.

INTRODUCTION

High-power electric machine drive systems have many applications such as those found in pumps, fans, compressors, rolling mills, cement mills and mine hoists, just to name a few. At present, the most successful types of high power drive systems are cycloconverter-electric machine drives and synchronous machines fed by current source thyristor inverters. Voltage source inverters, despite their advantage in the amount of line power over a cycloconverter, as well as 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 to achieving high power ratings with voltage source inverters, multi-phase machine drive systems have emerged [1]. In the most common of such structures, 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 structures will improve reliability at the system level [2-5]. In particular, with the loss of one or more 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 the unbalanced operation of electric machines has been the well-known symmetrical component method. Although this method has been used successfully in steady-state analysis of sinusoidal excitation, as far as the dynamics of the 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 operating conditions. Zhao and Lipo [6] developed a modeling and control approach for a dual three-phase induction machine with one open stator winding. Their proposed method was directly based on the asymmetrical winding structure

1. *Department of Electrical Engineering, Amir Kabir University of Technology, Tehran, I.R. Iran.*
*. *Corresponding Author, Department of Electrical Engineering, Amir Kabir University of Technology, Tehran, I.R. Iran.*

Decoupling of energy-conversion-related components from non- energy-conversion-related components, is an important advantage of this model, which is used in control applications.

Until now, the "vector control" method was known as one of the best in controlling the torque and speed of ac machines. Among the various types of "vector control" approach, "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 the normal operation of a machine, cannot be used to control the machine. This problem is specially observed in oscillations in electromagnetic torque. Lipo and Zhao [8] presented a control approach for controlling the inverter, which fed a dual three-phase induction machine with one open phase.

In this paper, a dual three-phase induction machine has been modeled at the stator fault condition of a two-phase cut off. The matrix transformation method is used to obtain a decoupled model for the 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 the model. On the basis of this model, "stator voltage equations" for R.F.O. vector control are obtained and a method is proposed to adapt the conventional blocks of vector control for operating under fault conditions. To show the capabilities of the proposed method, a computer simulation has been presented. It includes a dqz_1z_2 model of the motor under fault conditions, fed from a SPWM voltage source inverter. The proposed R.F.O. control has been compared with conventional methods in the reduction of machine torque oscillation. Simulation results show suitable performance for the proposed control method under fault conditions.

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

Suppose that a phase cut off fault has occurred in phases "e" and "f" of a multi-phase drive system, including a dual three-phase induction machine, as shown in Figure 1.

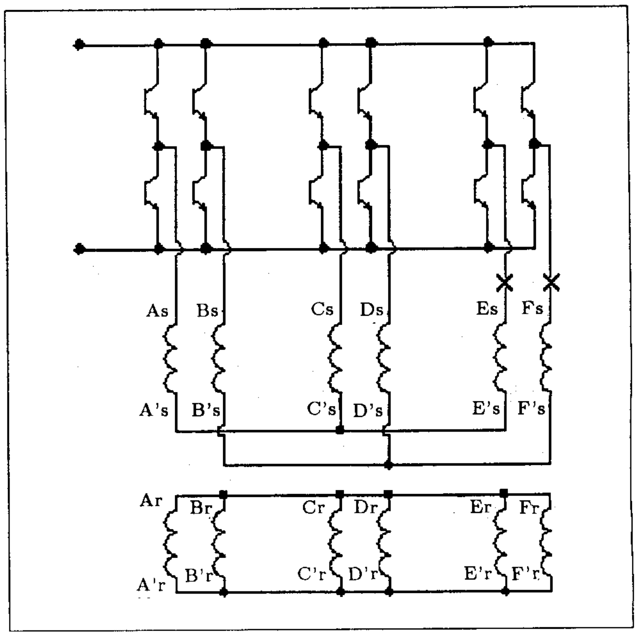


Figure 1. Dual three-phase induction machine drive with two-phase open.

Since four independent currents can flow in the general case, the machine model is expected 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 subspaces with one of the two-dimensional subspaces 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, the axes can be shown as follows.

Figure 2 shows the stator and rotor winding flux axis. If the angle between d-axis of air gap flux and "as" winding flux axis is θ_0, ds-axis and qs-axis flux can be written as follows:

$$\phi_{ds} = \Big[\cos(\theta_0)\cos\Big(\theta_0 + \frac{\pi}{6}\Big)\cos\Big(\theta_0 + \frac{2\pi}{3}\Big)\cos\Big(\theta_0 + \frac{5\pi}{6}\Big)\Big]\begin{bmatrix}\phi_{as}\\ \phi_{bs}\\ \phi_{cs}\\ \phi_{ds}\end{bmatrix}, \quad (1)$$

$$\phi_{qs} = \Big[\sin(\theta_0)\sin\Big(\theta_0 + \frac{\pi}{6}\Big)\sin\Big(\theta_0 + \frac{2\pi}{3}\Big)\sin\Big(\theta_0 + \frac{5\pi}{6}\Big)\Big]\begin{bmatrix}\phi_{as}\\ \phi_{bs}\\ \phi_{cs}\\ \phi_{ds}\end{bmatrix}. \quad (2)$$

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:

$$d=\Big[\cos(\theta_0)\cos\Big(\theta_0+\frac{\pi}{6}\Big)\cos\Big(\theta_0+\frac{2\pi}{3}\Big)\cos\Big(\theta_0+\frac{5\pi}{6}\Big)\Big],$$

$$q=\Big[\sin(\theta_0)\sin\Big(\theta_0+\frac{\pi}{6}\Big)\sin\Big(\theta_0+\frac{2\pi}{3}\Big)\sin\Big(\theta_0+\frac{5\pi}{6}\Big)\Big].$$

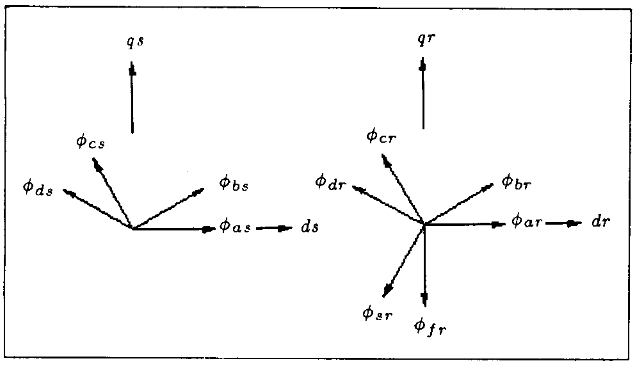


Figure 2. a) Stator winding flux axes; b) Rotor winding flux axes.

From the orthogonality of basis vectors, "θ_0" is obtained:

$$d^T.q = q^T.d = 0 \quad \Rightarrow \quad \theta_0 = \frac{\pi}{12}.$$

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:

$$[T_s] = \begin{bmatrix} 0.5706 & 0.4177 & -0.4177 & -0.5706 \\ 0.2430 & 0.6640 & 0.6640 & 0.2430 \\ -0.4177 & 0.5706 & -0.5706 & 0.4177 \\ 0.6640 & -0.2430 & -0.2430 & 0.6640 \end{bmatrix}. \quad (3)$$

The decomposition matrix for rotor variables of the machine "$[T_r]$" remains the same as the transformation for balanced operation, because the rotor still maintains a balanced winding structure [6]. Applying the transformation "$[T_s]$" and "$[T_r]$" to the voltage equations of stator and rotor fields, yields:

1. Machine model in $d-q$ subspace:

$$\begin{bmatrix} v_{ds}^s \\ v_{qs}^s \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_s + L_{ds}\frac{d}{dt} & 0 & M_d\frac{d}{dt} & 0 \\ 0 & r_s + L_{qs}\frac{d}{dt} & 0 & M_q\frac{d}{dt} \\ M_d\frac{d}{dt} & \omega_r M_q & r_r + L_r\frac{d}{dt} & \omega_r L_r \\ -\omega_r M_d & M_q\frac{d}{dt} & -\omega_r L_r & r_r + L_r\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \\ i_{dr}^r \\ i_{qr}^r \end{bmatrix}, \quad (4)$$

where:

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

2. Machine model in $Z_1 - Z_2$ subspace:
   - Stator voltage equation:

$$\begin{bmatrix} v_{z_1s}^s \\ v_{z_2s}^s \end{bmatrix} = \begin{bmatrix} r_s + L_{ls}\frac{d}{dt} & 0 \\ 0 & r_s + L_{ls}\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{z_1s}^s \\ i_{z_2s}^s \end{bmatrix} \quad (5)$$

   - Rotor voltage equation:

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_r + L_{lr}\frac{d}{dt} & 0 & 0 & 0 \\ 0 & r_r + L_{lr}\frac{d}{dt} & 0 & 0 \\ 0 & 0 & r_r + L_{lr}\frac{d}{dt} & 0 \\ 0 & 0 & 0 & r_r + L_{lr}\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{z_1r}^r \\ i_{z_2r}^r \\ i_{o_1r}^r \\ i_{o_2r}^r \end{bmatrix}. \quad (6)$$

   - Electromagnetic torque:

$$T_e = \frac{\text{Pole}}{2}(M_q i_{qs}^s i_{dr}^s - M_d i_{ds}^s i_{qr}^s). \quad (7)$$

Equations 4 to 7 completely represent the dqz_1z_2 model of a dual, three-phase induction machine with two-phase open. Writing these in the form of state equations, the computer simulation of the model can be performed.

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

For obtaining vector control equations, it is necessary to indicate the machine equations in a 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 the stator variable [7]:

$$[T_s^e] = \begin{bmatrix} \sqrt{\frac{M_d}{M_q}}\cos\theta_e & \sqrt{\frac{M_q}{M_d}}\sin\theta_e \\ -\sqrt{\frac{M_d}{M_q}}\sin\theta_e & \sqrt{\frac{M_q}{M_d}}\cos\theta_e \end{bmatrix}, \quad (8)$$

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

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

Description	Balance Mode Equations	Fault Mode Equations
Torque Equation	$T_e = \frac{\text{Pole}}{2}\frac{M}{L_r}\lvert\lambda_r\rvert i_{qs}^{mr}$	$T_e = \frac{\text{Pole}}{2}\frac{\sqrt{M_dM_q}}{L_r}\lvert\lambda_r\rvert i_{qs}^{mr}$
Rotor Flux Equation	$T_r\frac{d}{dt}\lvert\lambda_r\rvert + \lvert\lambda_r\rvert = Mi_{ds}^{mr}$	$T_r\frac{d}{dt}\lvert\lambda_r\rvert + \lvert\lambda_r\rvert = \sqrt{M_dM_q}i_{ds}^{mr}$
Angular Velocity of Rotor Flux	$\omega_{mr} = \omega_r + \frac{Mi_{qs}^{mr}}{T_r\lvert\lambda_r\rvert}$	$\omega_{mr} = \omega_r + \frac{\sqrt{M_dM_q}i_{qs}^{mr}}{T_r\lvert\lambda_r\rvert}$
D-axis Component of Stator Voltage Equation	$v_{ds}^{mr} = U_{ds}^d + U_{ds}^{ref}$	$v_{ds}^{mr} = U_{ds}^{+d} + U_{ds}^{-d} + U_{ds}^{+ref} + U_{ds}^{-ref}$
	$U_{ds}^d = -\omega_{mr}L'_s i_{qs}^{mr}$	$U_{ds}^{+d} = -\omega_{mr}\left(\frac{L'_{ds}+L'_{qs}}{2}\right)i_{qs}^{mr}$ $U_{ds}^{-d} = -\omega_{mr}\left(\frac{L'_{ds}L'_{qs}}{2}\right)i_{qs}^{-mr} + \omega_{mr}\left(\frac{L_{ds}-L_{qs}-L'_{ds}+L'_{qs}}{2}\right)\lambda_{qr}^{-m}$
	$U_{ds}^{ref} = r_s i_{ds}^{mr} + L'_s\frac{d}{dt}i_{ds}^{mr} + \left(\frac{L_s-L'_s}{M}\right)\frac{d}{dt}\lvert\lambda_r\rvert$	$U_{ds}^{+ref} = r_s i_{ds}^{mr} + \left(\frac{L'_{ds}+L'_{qs}}{2}\right)\frac{d}{dt}i_{ds}^{mr} + \left(\frac{L_{ds}+L_{qs}-L'_{ds}-L'_{qs}}{2\sqrt{M_dM_q}}\right)\frac{d}{dt}\lvert\lambda_r\rvert$ $U_{ds}^{-ref} = \left(\frac{L'_{ds}-L'+qs}{2}\right)\frac{d}{dt}i_{ds}^{mr} + \left(\frac{L_{ds}-L_{qs}-L'_{ds}+L'_{qs}}{2\sqrt{M_dM_q}}\right)\frac{d}{dt}\lambda_{dr}^{-m}$
D-axis Component of Stator Voltage Equation	$v_{qs}^{mr} = U_{qs}^d + U_{qs}^{ref}$	$v_{qs}^{mr} = U_{qs}^{+d} + U_{qs}^{-d} + U_{qs}^{+ref} + U_{qs}^{-ref}$
	$U_{qs}^d = -\omega_{mr}L'_s i_{ds}^{mr} + \omega_{mr}\left(\frac{L_s-L'_s}{M}\right)\lvert\lambda_r\rvert$	$U_{qs}^{+d} = -\omega_{mr}\left(\frac{L'_{ds}+L'_{qs}}{2}\right)i_{ds}^{mr} + \omega_{mr}\left(\frac{L_{ds}+L_{qs}-L'_{ds}-L'_{qs}}{2}\right)\lvert\lambda_r\rvert$ $U_{qs}^{-d} = \omega_{mr}\left(\frac{L'_{ds}-L'_{qs}}{2}\right)i_{ds}^{-mr} + \omega_{mr}\left(\frac{L_{ds}-L_{qs}-L'_{ds}+L'_{qs}}{2}\right)\lambda_{dr}^{-m}$
	$U_{qs}^{ref} = r_s i_{qs}^{mr} + L'_s\frac{d}{dt}i_{qs}^{mr}$	$U_{qs}^{+ref} = r_s i_{qs}^{mr} + \left(\frac{L'_{ds}+L'_{qs}}{2}\right)\frac{d}{dt}i_{qs}^{mr}$ $U_{qs}^{-ref} = -\left(\frac{L'_{ds}-L'_{qs}}{2}\right)\frac{d}{dt}i_{qs}^{-mr} - \left(\frac{L_{ds}-L_{qs}-L'_{ds}+L'_{qs}}{2\sqrt{M_dM_q}}\right)\frac{d}{dt}\lambda_{qr}^{-mr}$

- Stator voltage equations:

$$\begin{bmatrix} v_{ds}^e \\ v_{qs}^e \end{bmatrix} = \begin{bmatrix} r_s + \left(\frac{L_{ds}+L_{qs}}{2}\right)\frac{d}{dt} & -\left(\frac{L_{ds}+L_{qs}}{2}\right)\omega_e \\ \left(\frac{L_{ds}+L_{qs}}{2}\right)\omega_e & r_s + \left(\frac{L_{ds}+L_{qs}}{2}\right)\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{ds}^e \\ i_{qs}^e \end{bmatrix} + \begin{bmatrix} \left(\frac{L_{ds}-L_{qs}}{2}\right)\frac{d}{dt} & \left(\frac{L_{ds}-L_{qs}}{2}\right)\omega_e \\ \left(\frac{L_{ds}-L_{qs}}{2}\right)\omega_e & -\left(\frac{L_{ds}-L_{qs}}{2}\right)\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{ds}^{-e} \\ i_{qs}^{-e} \end{bmatrix} + \begin{bmatrix} \left(\frac{M_d^2+M_q^2}{2\sqrt{M_dM_q}}\right)\frac{d}{dt} & -\left(\frac{M_d^2+M_q^2}{2\sqrt{M_dM_q}}\right)\omega_e \\ \left(\frac{M_d^2+M_q^2}{2\sqrt{M_dM_q}}\right)\omega_e & \left(\frac{M_d^2+M_q^2}{2\sqrt{M_dM_q}}\right)\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{dr}^e \\ i_{qr}^e \end{bmatrix} + \begin{bmatrix} \left(\frac{M_d^2-M_q^2}{2\sqrt{M_dM_q}}\right)\frac{d}{dt} & \left(\frac{M_d^2-M_q^2}{2\sqrt{M_dM_q}}\right)\omega_e \\ \left(\frac{M_d^2-M_q^2}{2\sqrt{M_dM_q}}\right)\omega_e & -\left(\frac{M_d^2-M_q^2}{2\sqrt{M_dM_q}}\right)\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{dr}^{-e} \\ i_{qr}^{-e} \end{bmatrix}. \tag{9}$$

- Rotor voltage equations:

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} \sqrt{M_dM_q}\frac{d}{dt} & -(\omega_e-\omega_r)\sqrt{M_dM_q} \\ (\omega_e-\omega_r)\sqrt{M_dM_q} & \sqrt{M_dM_q}\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{ds}^e \\ i_{qs}^e \end{bmatrix} + \begin{bmatrix} r_r + L_r\frac{d}{dt} & -(\omega_e-\omega_r)L_r \\ (\omega_e-\omega_r)L_r & r_r + L_r\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{dr}^e \\ i_{qr}^e \end{bmatrix} \tag{10}$$

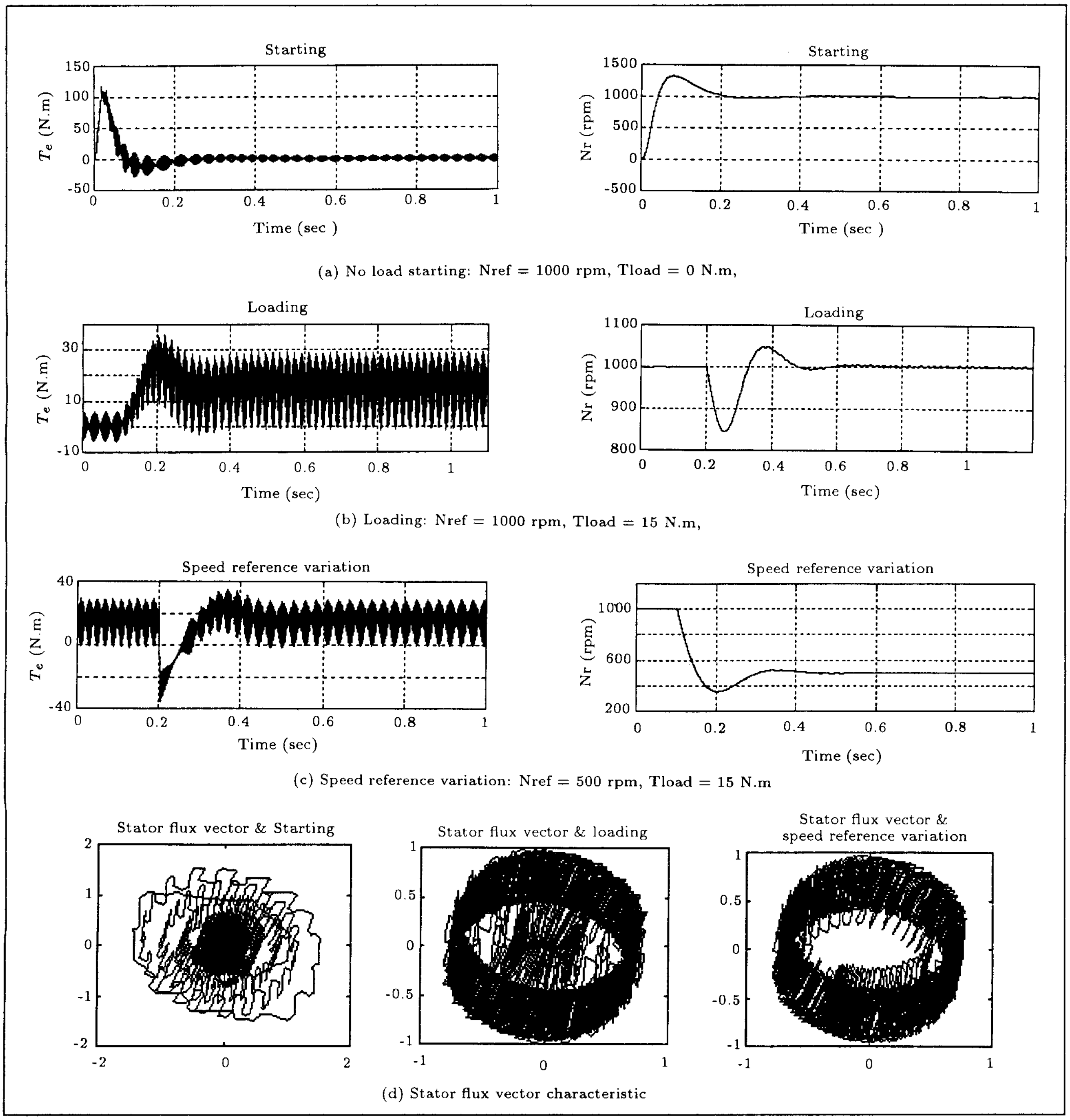
- Electromagnetic torque:

$$T_e = \frac{\text{Pole}}{2}\sqrt{M_dM_q}\left(i_{qs}^e i_{dr}^e - i_{ds}^e i_{qr}^e\right), \tag{11}$$

where subtitle "$-$" indicates backward rotating variables. On the basis of Equations 9 to 11 the R.F.O. vector control equations can be obtained. These are similar to the R.F.O. vector control equations in the balance mode and are compared in Table 1.

It is observed that in the fault mode, the rotor and the electromagnetic torque equations are similar to those in the balance mode and only "M" is substituted by "$\sqrt{M_dM_q}$". In addition to forward rotating components, which are similar to balanced mode equations, backward rotating component have also appeared in stator voltage equations. In fact, the parts of the equations, which are due to forward rotating components, are the same as the balanced 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 of the equation, due to the backward rotating components, are almost similar to the forward-rotating components, but the sum of the inductances is substituted by the difference.

Considering the amount of inductance at d and q-axis directions, it is possible to neglect the difference of the inductances in comparison to their sum and propose a control approach, which results in the following changes in the vector control blocks as shown in Table 2.



(a) No load starting: Nref = 1000 rpm, Tload = 0 N.m,

(b) Loading: Nref = 1000 rpm, Tload = 15 N.m,

(c) Speed reference variation: Nref = 500 rpm, Tload = 15 N.m

(d) Stator flux vector characteristic

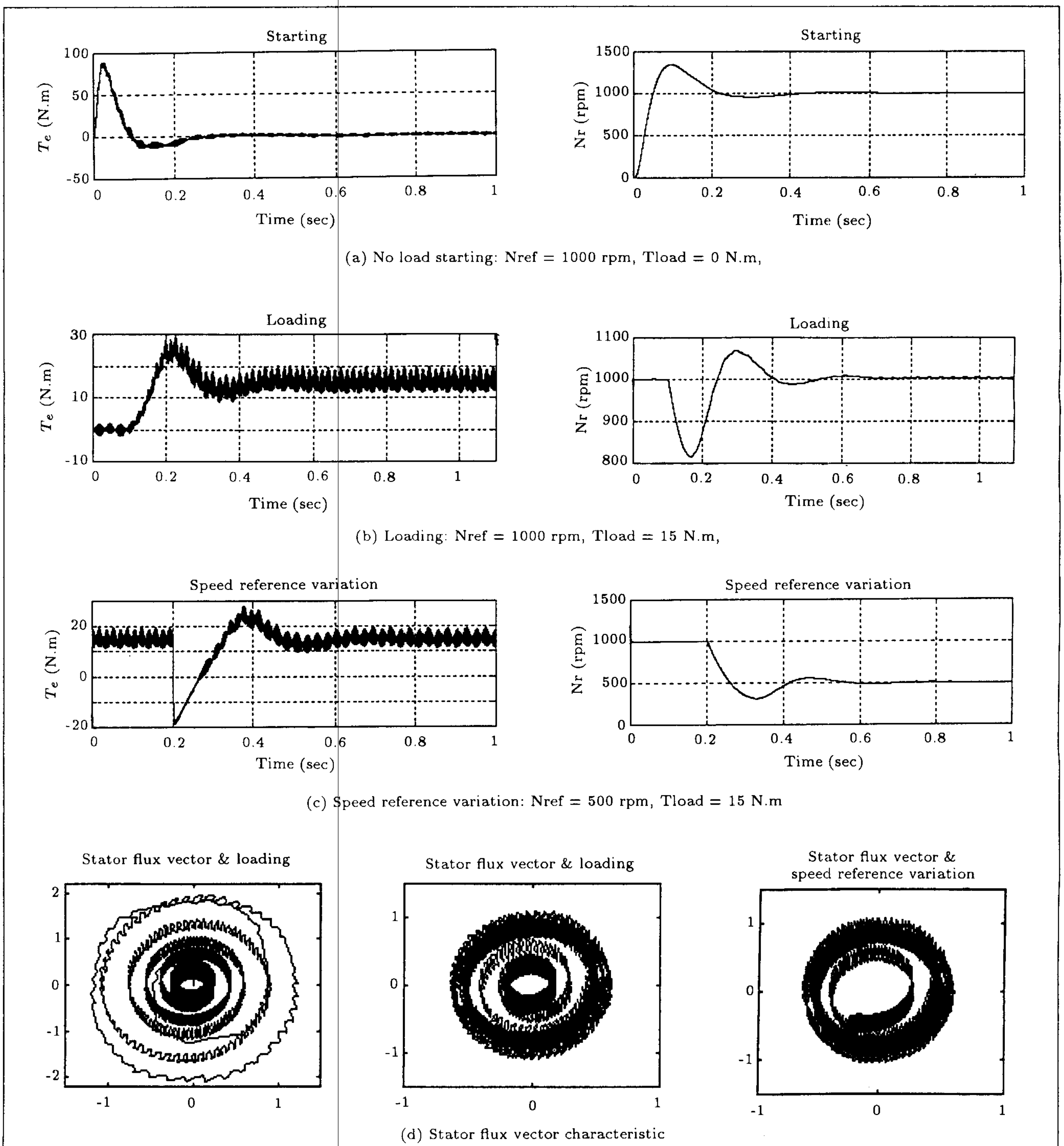
Figure 3. Simulation results of conventional R.F.O. vector controller.

SIMULATION RESULTS

In this section, computer simulation results are presented. Simulations include a dual three-phase induction machine with two-phase open and fed from an 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 the proposed changes, according to Table 2. The simulation results of the conventional controller is shown in Figure 3.

The results show considerable oscillations in the electromagnetic torque, with an amplitude of about 14 N.m for a load torque of 15 N.m. The stator flux vector characteristic is not suitable either. Simulation results for a modified R.F.O. vector controller are shown in Figure 4.

It is observed that with the proposed modifica-



(a) No load starting: Nref = 1000 rpm, Tload = 0 N.m,

(b) Loading: Nref = 1000 rpm, Tload = 15 N.m,

(c) Speed reference variation: Nref = 500 rpm, Tload = 15 N.m

(d) Stator flux vector characteristic

Figure 4. Simulation results of modified R.F.O. vector controller.

tions, torque oscillation is reduced considerably and oscillation amplitude is 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 the backward rotating component is neglected, since proposed modifications in Table 2 implicitly have such an assumption.

CONCLUSION

The proposed method in this paper, for modeling of a dual three-phase induction machine with two-phase open, shows the capabilities of the matrix transformation method in modeling various types of phase cut off faults in the stator of induction machines. The importance of this modeling method is in the

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	$\frac{L_{ds}+L_{qs}}{2}$
L'_s	$\frac{L'_{ds}+L'_{qs}}{2}$
Matrix transformation 6 to 2 according to [1].	Matrix transformation 4 to 2 according to Equation 6
Balance mode rotational transformation according to [1].	Fault mode rotational transformation according to Equation 13

decoupling of energy conversion related components from the non energy conversion related components of machine variables, such that suitable control relations can be obtained for the machine. It is shown that under fault conditions, using an unbalanced rotational transformation, vector control equations can be obtained which are similar to equations in the balanced mode. On the basis of these similarities, a method is proposed by which a few changes in the conventional R.F.O. vector controller blocks, can make the machine capable of being controlled under fault conditions. Simulation results show a suitable performance of the proposed control method. With this method, torque oscillations are considerably reduced. However, torque oscillations are not completely eliminated, since the effects of backward rotating components are neglected. Given that the structure of a two-phase open-dual, three-phase induction machine is similar to the structure of a one-phase open conventional three-phase induction machine, the proposed method of modeling and control can also be used for a one-phase open conventional three-phase induction machine.

REFERENCES

1. Zhao, Y. and Lipo, T.A. "Space vector PWM control of dual three-phase induction machine using vector space decomposition", *IEEE Trans. Ind. Appl.*, **31**(5), pp 1100-1109 (Sept./Oct. 1995).

2. Jahns, T.M. "Improved reliability in solid-state ac drives by means of multiple independent phase-drive units", *IEEE Trans. Ind. Appl.*, **IA-16**(3), pp 321-331, (May/June 1980).

3. Klingshirn, E.A. "High phase order induction motors, part I-description and theoretical consideration", *IEEE Trans. on Power Apparatus and Systems*, **Pas-102**(1), pp 47-53 (January 1983).

4. Klingshirn, E.A. "High phase order induction motors, part II-experimental results", *IEEE Trans. on Power Apparatus and Systems*, **Pas-102**(1), pp 54-59 (Jan. 1983).

5. Fu, J.R. and Lipo, T.A. "Disturbance free operation of a multiphase current regulated motor drive with an opened phase", *IEEE Trans. Ind. Appl.*, **30**(5), pp 1267-1274 (Sept./Oct., 1994).

6. Zhao, Y. and Lipo, T.A. "Modeling and control of a multiphase induction machine with structural unbalance, part I-machine modeling and multi-dimensional current regulation", *IEEE Trans. Energy Conv.*, (3), pp 570-577 (Sept. 1996).

7. *Vector Control of AC Machines, Peter Vas*, Oxford Science Publication (1990).

8. Zhao, Y. and Lipo, T.A. "Modeling and control of a multiphase induction machine with structural unbalance, part II-field-oriented control and experimental verification", *IEEE Trans. Energy Conv.*, (3), pp 578-584 (Sept. 1996).