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Vector Control of Five-Phase Induction Motor under Asymmetrical Connection

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Abstract: This study deals with the reliability of the five-phase induction motor drive in vector control. Regarding the three-phase induction motor if one phase of the motor or inverter were opened, a divided DC bus and neutral connections would be required so that the currents in the other 2 phases are controlled independently. By the above a zero sequence component is necessary in a three-phase induction motor to provide an undisturbed rotation after one phase is opened. But in the 5-phase drive the event of losing 1 or 2 legs of the inverter or motor phases, the 5-phase induction motor an operate continuously and steadily with the remaining four phase or three phase connections. Simulation is done in MATLAB and results are attached.

Key words: Vector control, asymmetrical connection, mathematical modeling MATLAB

INTRODUCTION

The conventional three-phase induction motor having the sinusoidal winding structure, generates sinusoidal magnetic flux in the air gap. By this flux distribution the flux can obtain a maximum value only in a small region. So the most of the iron core in the unsaturated state and the power density and torque density are comparatively lower. But here a five-phase induction motor based on field-oriented controls that overcome the above drawbacks (Depenbrook, 1988). Compared with the conventional three-phase induction motors the five-phase induction motor has two important differences in the view of its structure and input current profiles. In the structure concern, concentrated windings are used instead of sinusoidal windings and in the current profile concern the third harmonic current is introduced into the motor, by this a nearly rectangular wave form flux is obtained (Toliyat and Lipo, 1991). By this rectangular current most of the iron core is in the saturated state so the flux density and the torque density are higher (Toliyat *et al.*, 1994).

Vector control: With the increasing demand for the variable speed AC drives in modern industry the need for a simple Approach to Control AC motor is obvious necessity. The speed and torque control of AC motors is not as easy as that in the case of DC motor. This is due to the non-linear interaction of the torque and flux in AC motors. This led to the new advanced methods of independent control of torque and flux in the AC motors. Taking into electrical point of view current components responsible to produce torque and flux are entirely dependant on stator current (Toliyat, 1998). Due to this, there is inherent coupling between the above two and this prevents the motor from achieving the fast dynamic response. It is here this field-oriented control comes into picture.

Scalar control involves only magnitude of the control variables with no concern for the coupling effects between these variables. Conversely vector or field oriented control involves adjusting the magnitude and phase alignment of the vector qualities of the motor (Pavithran *et al.*, 1988). Scalar control such as the constant Volts/Hertz method when applied to an AC induction motor is relatively simple to implement but gives a sluggish response because of the inherent coupling effect due to torque and flux being functions of current and frequency. Vector control de-couples the vectors of field current and armature flux so that they may be controlled independently to provide fast transient response.

The accuracy of the field-oriented control is largely governed by the accuracy with which the flux angle is calculated and rotating frame variables transferred in to

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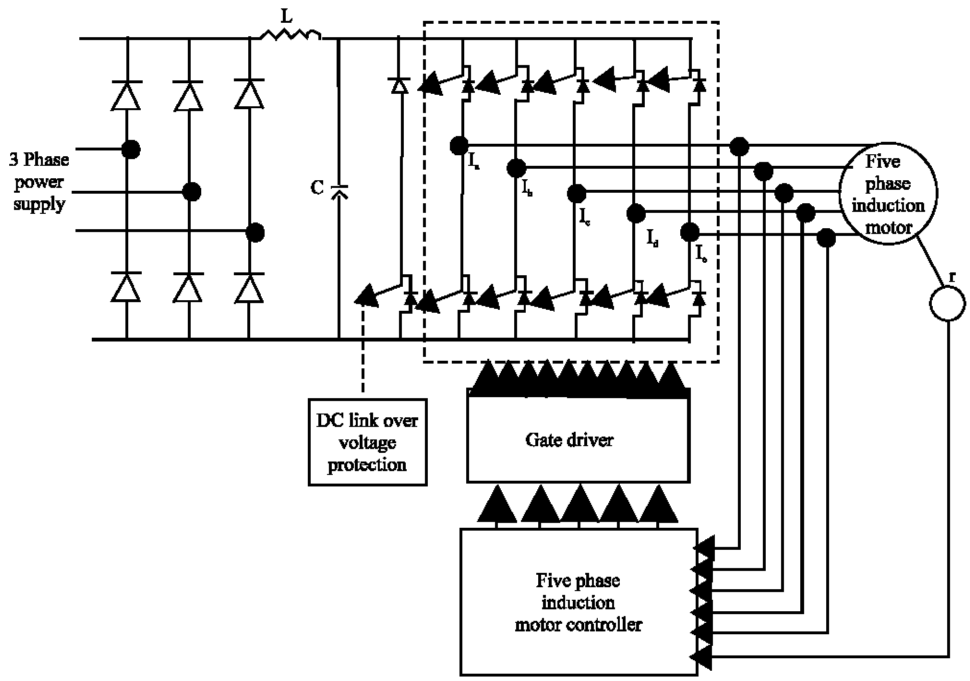

Fig. 1: Five-phase Inverter motor

the stator variables. A significant feature of AC induction motor control is the emergence of field-oriented control as a commercial reality in high performance drives. It is used to producehigh-performance servomechanisms by predicting the location of the internal and then injecting current to interact optimally with that flux. Standard field oriented control is a power fed control system. This control improves the dynamic performance of the drive at all speed. The steady state accuracy that can be achieved using inverter fed AC motors is as good as what is possible using the separately excited DC motor. Figure 1 show the Five-phase inverter motor set up.

Equations of five-phase induction motor: The winding axes of the five stator windings are displaced by 70 degree. Iron saturation is neglected in the analysis. The basic equations of five-phase induction motor are expressed in instantaneous vectors forms. The voltages V_s and currents I_s for the five-phase induction motor are represented as follows, respectively, that is:

$$V_s = \frac{2}{5}\left[v_a + v_b e^{j\frac{2\pi}{5}} + v_c e^{j\frac{4\pi}{5}} + v_d e^{-j\frac{4\pi}{5}} + v_e e^{-j\frac{2\pi}{5}}\right] \quad (1)$$

$$I_S = \frac{2}{5}\left[i_a + i_b e^{j\frac{2\pi}{5}} + i_c e^{j\frac{4\pi}{5}} + i_d e^{-j\frac{4\pi}{5}} + i_e e^{-j\frac{2\pi}{5}}\right] \quad (2)$$

Where, v_a, v_b, v_c, v_d, v_e are the instantaneous values of phase voltages and i_a, i_b, i_c, i_d, i_e, are instantaneous values of phase currents (Huangsheng and Toliyat, 1998).

The stationary transformation matrix T is given by:

$$T = \frac{2}{5}\begin{bmatrix} 1 & \cos\left(\frac{2\pi}{5}\right) & \cos\left(\frac{4\pi}{5}\right) & \cos\left(\frac{4\pi}{5}\right) & \cos\left(\frac{2\pi}{5}\right) \\ 0 & -\sin\left(\frac{2\pi}{5}\right) & -\sin\left(\frac{4\pi}{5}\right) & \sin\left(\frac{4\pi}{5}\right) & \sin\left(\frac{2\pi}{5}\right) \end{bmatrix} \quad (3)$$

The dynamic behavior of five-phase induction motor is described by the following equations written in terms of space vectors in the stationary reference frame:
Stator voltage and rotor voltage equations:

$$\lambda_s = R_s I_s + \frac{d\lambda_s}{dt} \quad (4)$$

$$0 = R_r I_r + \frac{d\lambda_r}{dt} - \omega_r J \lambda_r \quad (5)$$

where, λ_r λ_s, are stator and rotor flux linkages, respectively, R_s, R_r, are stator and rotor resistances, respectively, ω_r is the rotor angular speed expressed in electrical radians, Stator and rotor flux linkage equations:

$$\lambda_s = L_s I_s + L_m I_r \tag{6}$$

$$\lambda_r = L_m I_s + L_r I_r \tag{7}$$

where, L_s, L_r, L_m are stator, rotor and magnetizing inductance, respectively,

$$L_s = \frac{5}{2} L_{ms} + L_{\sigma s} \tag{8}$$

$$L_r = \frac{5}{2} L_{mr} + L_{\sigma r} \tag{9}$$

$$L_m = \frac{5}{2} L_{ms} \tag{10}$$

where, I_s, I_r are stator and rotor currents, respectively, Electromagnetic torque and mechanical motion equations are given by:

$$T_e = \frac{5}{2}\frac{P}{2}(\lambda_s \times I_s) = \frac{5}{2}\frac{P}{2}(\lambda_r \times I_r) \tag{11}$$

$$T_e - T_L = J_m \frac{d\omega_r}{dt} \tag{12}$$

Where, P is the pole number, J_m is the mechanical motion inertia.

Axes Transformation: Consider a symmetrical five-phase induction machine with stationary as-bs-cs-ds-es axes at 72° angle apart (Huangsheng and Toliyat, 1998). To transform the five-phase stationary reference frame (as-bs-cs-ds-es) variables into two-phase stationary reference frame (d^s-q^s)variables and the transform these to synchronously rotating reference frame (d^e-q^e) and vice versa. Assume that the d^s-q^s axes are oriented at θ angle. The voltages V_{ds} and V_{qs} can be resolved into as-bs-cs-ds-es components and can be represented in the matrix form as:

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \\ V_{ds} \\ V_{es} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & \cos 3\theta & \sin 3\theta & 1 \\ \cos(\theta - \frac{2\pi}{5}) & \sin(\theta - \frac{2\pi}{5}) & \cos 3(\theta - \frac{2\pi}{5}) & \sin 3(\theta - \frac{2\pi}{5}) & 1 \\ \cos(\theta - \frac{4\pi}{5}) & \sin(\theta - \frac{4\pi}{5}) & \cos 3(\theta - \frac{4\pi}{5}) & \sin 3(\theta - \frac{4\pi}{5}) & 1 \\ \cos(\theta + \frac{4\pi}{5}) & \sin(\theta + \frac{4\pi}{5}) & \cos 3(\theta + \frac{4\pi}{5}) & \sin 3(\theta + \frac{4\pi}{5}) & 1 \\ \cos(\theta + \frac{2\pi}{5}) & \sin(\theta + \frac{2\pi}{5}) & \cos 3(\theta + \frac{2\pi}{5}) & \sin 3(\theta + \frac{2\pi}{5}) & 1 \end{bmatrix} \begin{bmatrix} V_{qs1} \\ V_{ds1} \\ V_{qs3} \\ V_{ds3} \\ V_{0s} \end{bmatrix} \tag{13}$$

The corresponding inverse relation is

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \\ V_{ds} \\ V_{es} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & \cos 3\theta & \sin 3\theta & 1 \\ \cos(\theta - \frac{2\pi}{5}) & \sin(\theta - \frac{2\pi}{5}) & \cos 3(\theta - \frac{2\pi}{5}) & \sin 3(\theta - \frac{2\pi}{5}) & 1 \\ \cos(\theta - \frac{4\pi}{5}) & \sin(\theta - \frac{4\pi}{5}) & \cos 3(\theta - \frac{4\pi}{5}) & \sin 3(\theta - \frac{4\pi}{5}) & 1 \\ \cos(\theta + \frac{4\pi}{5}) & \sin(\theta + \frac{4\pi}{5}) & \cos 3(\theta + \frac{4\pi}{5}) & \sin 3(\theta + \frac{4\pi}{5}) & 1 \\ \cos(\theta + \frac{2\pi}{5}) & \sin(\theta + \frac{2\pi}{5}) & \cos 3(\theta + \frac{2\pi}{5}) & \sin 3(\theta + \frac{2\pi}{5}) & 1 \end{bmatrix} \begin{bmatrix} V_{qs1} \\ V_{ds1} \\ V_{qs3} \\ V_{ds3} \\ V_{0s} \end{bmatrix} \tag{14}$$

V_{0s} is added as the zero sequence components. Here, consider voltage as the variable. The current and flux linkages can be transformed by similar equations.

Resilient current control algorthm: With the proposed resilient current control strategy in this study, the zero-sequence Current is no longer a necessary component in the five-phase induction motor drive. From a reliability standpoint, the zero sequence currents have been to have detrimental effects on motor bearing failure, reducing the reliability and increasing the cost of maintenance of the motor (Toliyat, 1998). The proposed current control strategy eliminates the use of a neutral line and provides the same rotating MMF to ensure that the motor is running smoothly as it was during the normal operations. The third harmonic current is still superimposed on the fundamental current of the 5-phase induction motor with remaining phases. This is to ensure a nearly rectangular air-gap flux is generated as with the symmetrical connections. Therefore the 5-phase induction motor can still maintain its advantages such as high power density and torque even under faulty conditions. The third harmonic current is assumed to be about 15% of the fundamental current. The interaction between any 2 components of different frequencies is decoupled, the 5-phase induction motor under the fundamental plus third harmonic of currents can be considered as 2 independent 5 phase induction motors, which are fed by the fundamental current and the third harmonic flux. The total flux distribution, a nearly rectangular flux distribution, can be obtained by combining the flux vectors generated by these 2 different components of currents.

Five phase induction motor under symmetrical connections: The current commands under normal condition:

$$\begin{aligned} i_a &= i_{a1} + i_{a3} \\ &= I_1 \cos\omega t + I_3 \cos 3\omega t \end{aligned} \tag{15}$$

$$i_b = i_{b1} + i_{b3}$$

$$= I_1 \cos(\omega t - \frac{2\pi}{5}) + I_3 \cos 3(\omega t - \frac{2\pi}{5}) \tag{16}$$

$$i_c = i_{c1} + i_{c3}$$

$$= I_1 \cos(\omega t - \frac{4\pi}{5}) + I_3 \cos 3(\omega t - \frac{4\pi}{5}) \tag{17}$$

$$i_d = i_{d1} + i_{d3}$$

$$= I_1 \cos(\omega t + \frac{4\pi}{5}) + I_3 \cos 3(\omega t + \frac{4\pi}{5}) \tag{18}$$

$$i_e = i_{e1} + i_{e3}$$

$$= I_1 \cos(\omega t + \frac{2\pi}{5}) + I_3 \cos 3(\omega t + \frac{2\pi}{5}) \tag{19}$$

Five-phase induction motor under asymmetrical connections: When phase a is open, the current commands

$$\begin{aligned} i'b_1 = -i'd_1 &= \frac{5I1}{4\left(\sin\frac{2\pi}{5}\right)^2} \cos\left(\omega t - \frac{\pi}{5}\right) \\ &= 1.382\, i_1 \cos\left(\omega t - \frac{\pi}{5}\right) \end{aligned} \tag{20}$$

$$\begin{aligned} i'e_1 = -i'e_1 &= \frac{5I1}{4\left(\sin\frac{2\pi}{5}\right)^2} \cos\left(\omega t - \frac{4\pi}{5}\right) \\ &= 1.382\, I_1 \cos\left(\omega t - \frac{4\pi}{5}\right) \end{aligned} \tag{21}$$

$$\begin{aligned} i'b_3 = -i'd_3 &= \frac{5I_3}{4\left(\sin\frac{2\pi}{5}\right)^2} \cos\left(3\omega t - \frac{3\pi}{5}\right) \\ &= 3.618\, i_3 \cos\left(3\omega t - \frac{3\pi}{5}\right) \end{aligned} \tag{22}$$

$$\begin{aligned} i'e_1 = -i'e_1 &= \frac{5I_3}{4\left(\sin\frac{2\pi}{5}\right)^2} \cos\left(3\omega t - \frac{12\pi}{5}\right) \\ &= 3.618\, i_3 \cos\left(3\omega t - \frac{12\pi}{5}\right) \end{aligned} \tag{23}$$

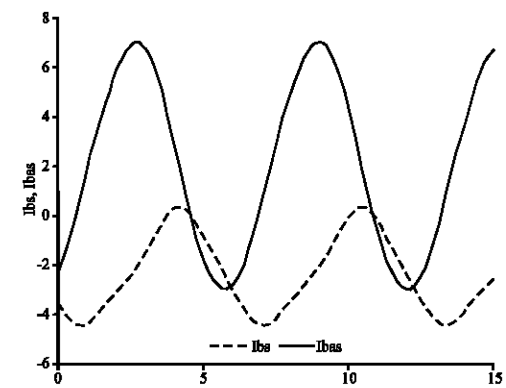

Fig. 2: Simulation results of five-phase induction motor under symmetrical (thin) and asymmetrical (thick) conditions, (B phase current Vs time)

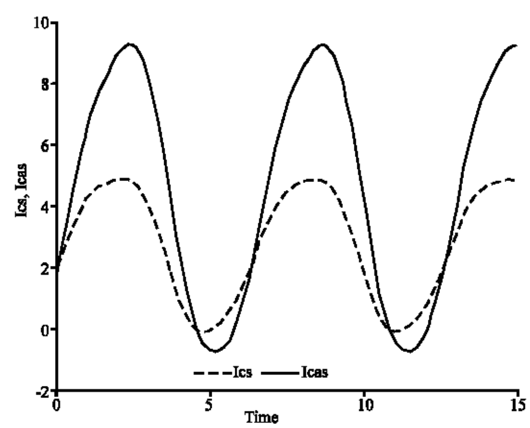

Fig. 3: Simulation results of five-phase induction motor under symmetrical (thin) and asymmetrical (thick) conditions, (C phase current Vs time)

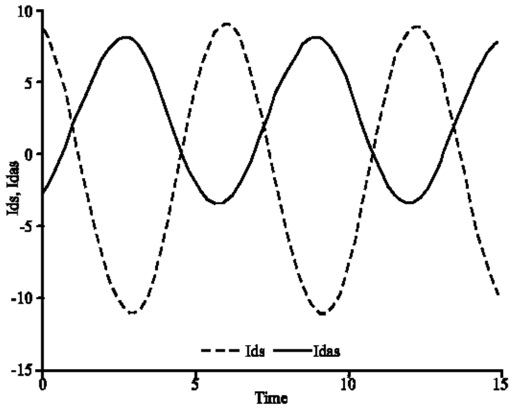

Fig. 4: Simulation results of five-phase induction motor under symmetrical (thin) and asymmetrical (thick) conditions, (D phase current Vs time)

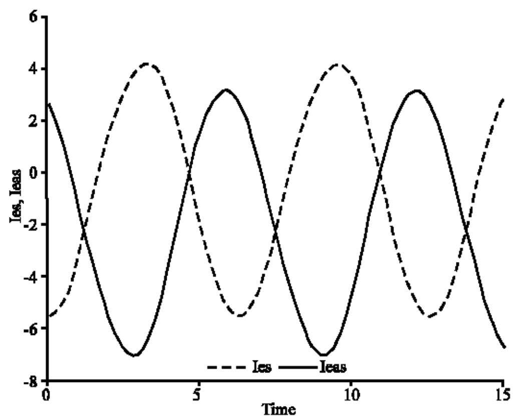

Fig. 5: Simulation results of five-phase induction motor under symmetrical (thin) and asymmetrical (thick) conditions, (E phase current Vs time)

As mentioned above, this flux distribution in iron to assume a more rectangular shape, resulting in a more efficient and effective use of the iron. Simulation results as shown in Fig. 2-5 shows that If phase A opened in the five-phase induction motor, the fundamental and third harmonic of currents in the remaining four phases can maintain an un disturbed rotating MMF and can be used to control the torque of the motor without the presence of a negative sequence and zero-sequence current. In this case, the fundamental current and third harmonic current amplitudes of the healthy phases need to be increased up to 1.382 and 3.618, respectively of the initial values when all 5-phases were functional so the 5-phase induction motor operates without any disturbance under any loss of 1 or 2 phase voltage conditions also.

Appendix

Specification	Values
Number of phases	5 phases
Power	1 hp
Poles	4
Slots	20
stamping thickness	0.5 mm
Speed	1440 rpm
Phase voltage	220 v
Frequency	50 Hz

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