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Direct Torque Control of Induction Motor using Space Vector Modulation

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Abstract

A novel technique of controlling induction motor, called direct torque control, which controls both torque and flux directly and independently, is the topic of this work. In this work a control scheme for speed regulation based on the stator flux control in the stator reference frame using direct control of inverter switching has been adapted. The speed of induction motor is controlled by varying the stator flux through a PI flux controller. The validation of the MATLAB code is carried out using a typical induction motor drive details available from reference [1]. In the present investigations, the desired speed is set at 0.9 per unit. The initial value of the stator flux is set at 0.8 per unit. By varying the proportional gain, integral gain and integral time constant attempt is made to obtain the best response for speed, stator flux, torque, and d-q axis stator flux of the motor.

Keywords: *Induction Motor, Vector Control, DTC.*

Introduction

Direct torque control (DTC) is one of the most excellent control strategies of torque control in induction machine. It is considered as an alternative to the field oriented control (FOC) or vector control technique. These two control strategies are different on the operation principle but their objectives are the same. They aim to control effectively the torque and flux. Torque control of an induction machine based on DTC strategy has been developed and a comprehensive study is present in this research. Iduction machine have provided the most common form of electromechanical drive for industrial, commercial and domestic applications that can operate at essentially constant speed. Induction machines have simpler and more rugged structure, higher maintainability and economy than DC motors. They are also robust and immune to heavy loading. Basically, there are two types of instantaneous electromagnetic torque-controlled AC drive used for high performance applications which are:

- **Vector Control (VC):** Based on stator current control in the field rotating reference frame.
- **Direct Torque control (DTC):** based on stator flux control in the stator fixed reference frame using direct control of the inverter switching.

Principle of Vector Control

To explain the principle of vector control, an assumption is made that the position of the rotor flux linkages phasor, λ_r, is known. λ_r is at θ_f from a stationary reference, θ_f is referred to as field angle hereafter, and the three stator currents can be transformed into q and d axes currents in the synchronous reference frames by using the transformation

$$\begin{bmatrix} i_{qs}^{e} \\ i_{ds}^{e} \end{bmatrix} = 2/3 \begin{bmatrix} \sin\theta_f & \sin\left(\theta_f - \frac{2\pi}{3}\right) & \sin\left(\theta_f + \frac{2\pi}{3}\right) \\ \cos\theta_f & \cos\left(\theta_f - \frac{2\pi}{3}\right) & \cos\left(\theta_f + \frac{2\pi}{3}\right) \end{bmatrix} \quad (1)$$

From which the stator current phasor, i_s, is derived as

$$I_s = \sqrt{\left(\left(i_{qs}^{e}\right)^2 + \left(i_{ds}^{e}\right)^2\right)} \quad (2)$$

$$\Theta_s = \tan^{-1}\left\{\frac{i_{qs}^{e}}{i_{ds}^{e}}\right\} \quad (3)$$

The current phasor i_s procedure the rotor flux λ_r and the torque T_e. The component of current producing the rotor flux phasor has to be in phase with λ_r. Therefore, resolving the stator current phasor along λ_r reveals that the component i_f is the field-producing component, shown in Fig. 1.

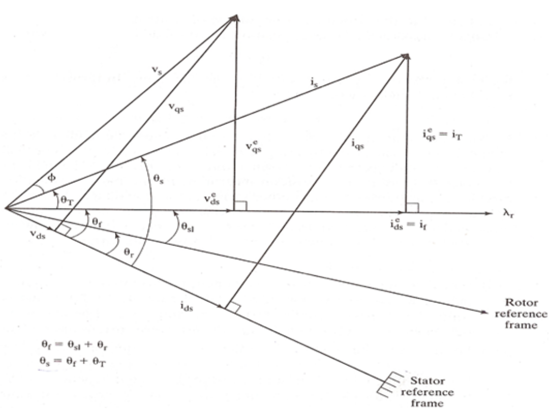

Figure 1: Phasor Diagram of the Vector Controller

Direct Vector Control in Stator Reference Frames with Space-Vector Modulation

The direct torque control method uses feedback control of torque and stator flux, which are computed from the measured stator voltage and currents. As the method does not use a position or speed sensor to control the machine and uses its own electrical output currents and resulting terminal voltages, this is also referred as a direct self-control scheme. The method uses a stator reference model of the induction motor for its implementation, thereby avoiding the trigonometric operations in the coordinate transformation of the synchronous reference frames. This is one of the key advantages of the control scheme.

The stator q and d axes flux linkages are

$$\lambda_{qs} = \int (V_{qs} - R_s i_{qs}) dt \quad (4)$$

$$\lambda_{ds} = \int (V_{ds} - R_s i_{ds}) dt \quad (5)$$

Where the direct and quadrature axis components are obtain from the abc variables by using the transformation,

$$i_{qs} = i_{as} \quad (6)$$

$$i_{ds} = \frac{i_{cs} - i_{bs}}{\sqrt{3}} \quad (7)$$

Voltage Source Inverter Fed Induction Motor Drives

The two basic voltage inverter fed induction motor systems are the pulse width modulated (PWM) inverter and the six step voltage source inverter (VSI) fed drives. The input converter is usually a diode bridge rectifier, which provides a constant dc voltage. After that a regenerative circuit is used which performs motor drive control and regenerative control. The dc voltage is filtered by a capacitor, which also provides a portion of the reactive current required by the inductive characteristics of an induction motor load. The filtered dc voltage is inverted by the PWM to provide the variable voltage and variable frequency ac output. Variable output voltage is achieved by pulse width modulation of the constant filtered dc bus voltage, which is the basic for the drive name.

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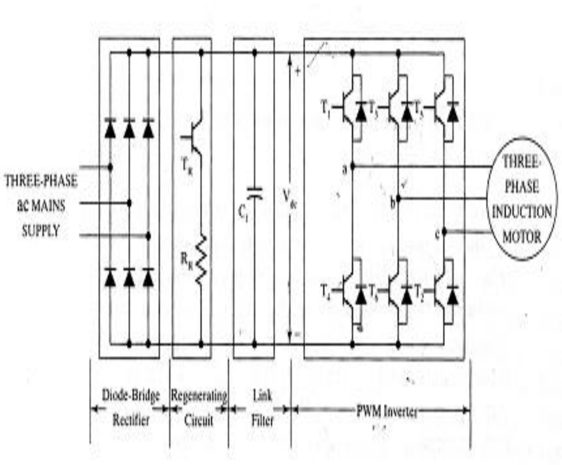

Figure 2: Power-Circuit Configuration of the Induction Motor Drive

Table 1: Inverter Switching States and Machine Voltages

States	S_a	S_b	S_c	V_a	V_b	V_c	V_{ab}	V_{bc}	V_{ca}	V_{as}	V_{bs}	V_{cs}	V_{qs}	V_{ds}
I	1	0	0	V_{dc}	0	0	V_{dc}	0	$-V_{dc}$	$\frac{2}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$\frac{2}{3}V_{dc}$	0
II	1	0	1	V_{dc}	0	V_{dc}	V_{dc}	$-V_{dc}$	0	$\frac{1}{3}V_{dc}$	$-\frac{2}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$\frac{V_{dc}}{\sqrt{3}}$
III	0	0	1	0	0	V_{dc}	0	$-V_{dc}$	V_{dc}	$-\frac{1}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$\frac{2}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$\frac{V_{dc}}{\sqrt{3}}$
IV	0	1	1	0	V_{dc}	V_{dc}	$-V_{dc}$	0	V_{dc}	$-\frac{2}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$-\frac{2}{3}V_{dc}$	0
V	0	1	0	0	V_{dc}	0	$-V_{dc}$	V_{dc}	0	$-\frac{1}{3}V_{dc}$	$\frac{2}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$-\frac{V_{dc}}{\sqrt{3}}$
VI	1	1	0	V_{dc}	V_{dc}	0	0	V_{dc}	$-V_{dc}$	$\frac{1}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$-\frac{2}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$-\frac{V_{dc}}{\sqrt{3}}$
VII	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VIII	1	1	1	V_{dc}	V_{dc}	V_{dc}	0	0	0	0	0	0	0	0

And machine phase voltages for a balanced system are

$$V_{as} = \frac{(V_{ab} - V_{ca})}{3}$$

$$V_{bs} = \frac{(V_{bc} - V_{ab})}{3} \qquad (8)$$

$$V_{cs} = \frac{(V_{ca} - V_{bc})}{3}$$

And the stator q and d voltages for each phase are

$$V_{qs} = V_{as}$$

$$V_{ds} = \frac{1}{\sqrt{3}}(V_{cs} - V_{ds}) = \frac{1}{\sqrt{3}}V_{cb} \qquad (9)$$

Flux control

A uniform rotating stator flux is desirable, and it occupies one of the sextants (in the phasor diagram shown in Fig. 3) at any time. The stator-flux phasor has a magnitude of λ_s, with an instantaneous position of θ_{fs}. The corresponding d and q axes components are λ_{ds} and λ_{qs}, respectively.

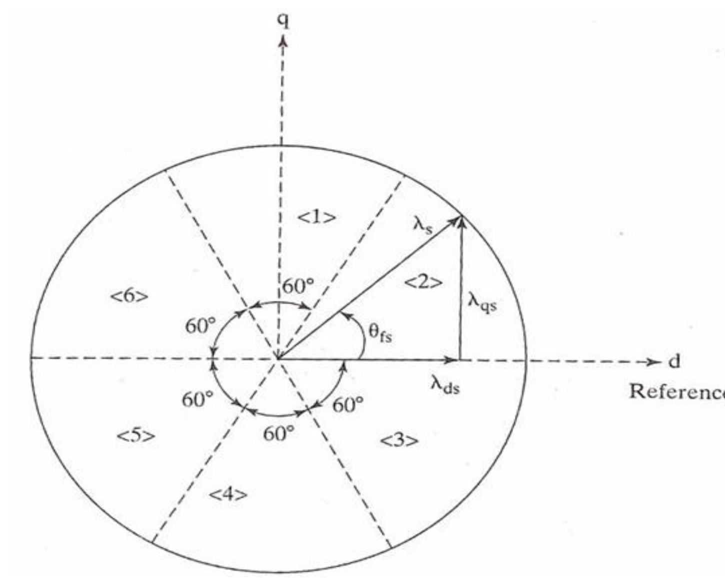

Figure 3: Division of Sextant for Stator Flux-Linkages Identification

Torque Control

Torque control is exercised by comparison of the command torque to the torque measured from the stator flux linkages and stator currents as

$$T_e = \frac{3}{2}\frac{P}{2}\left(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}\right) \qquad (10)$$

The error torque is processed through a window comparator to procedure digital out-puts, S_T, as follows as given in the table 2.

Table 2: Generation of S_T

Condition	S_T
$(T_e^* - T_e) > \delta T_e$	1
$-\delta T_e < (T_e^* - T_e) < \delta T_e$	0
$(T_e^* - T_e) < -\delta T_e$	−1

Combining the flux error output S_λ, the torque error output ST, and the sextant of the phasor S_θ a switching table can be realized to obtain the switching states of the inverter, and it is given in Table 3.

Table 3: Switching states for possible S_λ, S_T, and S_θ

		S_θ					
S_λ	S_T	<1>	<2>	<3>	<4>	<5>	<6>
1	1	VI (1,1,0)	I (1,0,0)	II (1,0,1)	III (0,0,1)	IV (0,1,1)	V (0,1,0)
1	0	VIII (1,1,1)	VII (0,0,0)	VIII (1,1,1)	VII (0,0,0)	VIII (1,1,1)	VII (0,0,0)
1	−1	II (1,0,1)	III (0,0,1)	IV (0,1,1)	V (0,1,0)	VI (1,1,0)	I (1,0,0)
0	1	V (0,1,0)	VI (1,1,0)	I (1,0,0)	II (1,0,1)	III (0,0,1)	IV (0,1,1)
0	0	VII (0,0,0)	VIII (1,1,1)	VII (0,0,0)	VIII (1,1,1)	VII (0,0,0)	VIII (1,1,1)
0	−1	III (0,0,1)	IV (0,1,1)	V (0,1,0)	VI (1,1,0)	I (1,0,0)	II (1,0,1)

DTC Schematic

The following assumption are made for simplification,

1. The machine is linear i.e. saturation in the magnetic circuit is disregarded.
2. The air gap of the machine is uniform and the electromagnetic field is sinusoidal distributed i.e. the effect of space harmonic and their effect on torque and induced voltages is neglected.
3. Parameter of the machine remain constant

The damping coefficient associated with the mechanical rotational system of the machine and mechanical load is neglected.

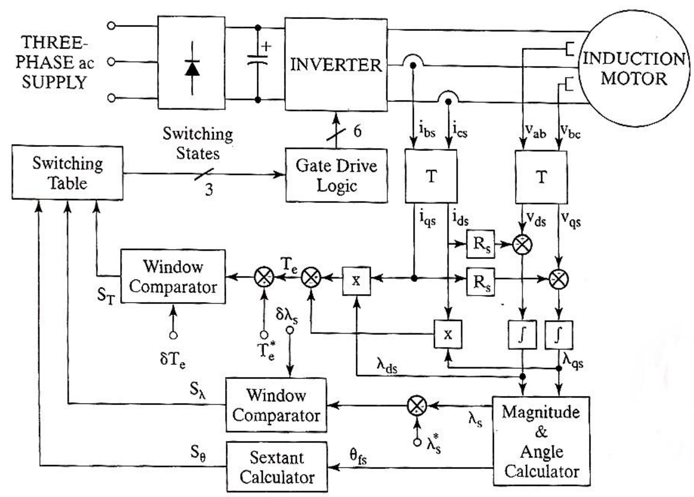

Figure 4: Block diagram schematic of the direct torque (self) induction motor drive

Simulations and Results

For the scheme R_r, L_s, L_r, L_m, J, P, T_{load} used for initialization, are as given in the Appendix A. The MATLAB code has been written for implementation of DTC for the induction motor model taken from [1]. The mathematical model consists of differential equations in terms of machine and motor parameters. The main parts of the direct torque control of induction motor are induction motor, voltage source inverter (VSI) and the functional blocks like adaptive motor model, hysteresis controller and optimum pulse selector.

After tuning the PI controller gains the various response curves of the induction motor drive system for the combinations K_pL=0.020, K_iL=0.06, T=0.01 are shown below

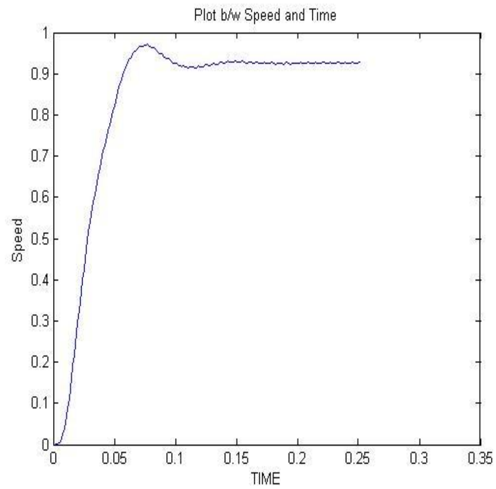

Figure 5: Plot between Speed and time

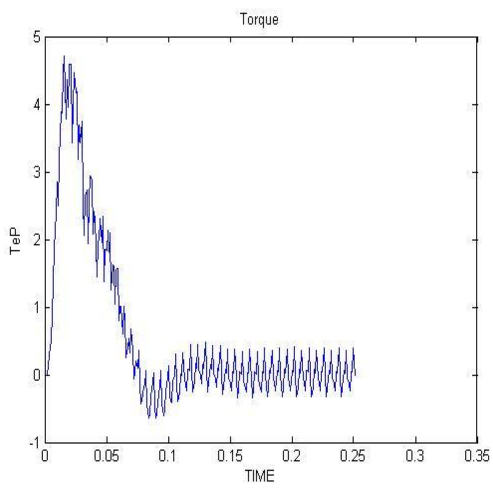

Figure 6: Plot between Torque and time

Appendix A

Motor specifications: Power rating 5 HP, Max. Voltage 200 volt, Frequency 60 Hz, Stator resistance 0.183 Ω, Rotor resistance 0.277 Ω, Mutual inductance 0.0538 H, Stator self-inductance 0.0.0553 H, Rotor self inductance 0.05606 H, Number of poles 4, Moment of inertia 0.01667 kg-m^2.

The motor is at standstill. A set of balanced three-phase voltages at 70.7% of rated values at 60 Hz is applied.

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