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Analysis of Direct Torque Control using Space Vector Modulation for Three Phase Induction Motor

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Article Info	Abstract
	This paper presents the results of an investigation into the suitability of a Direct Torque Control of three phase Induction motor. It is considered as an alternative to the field oriented control (FOC) or vector control technique. They aim to control effectively the torque and flux. Direct Torque Control (DTC) uses an induction motor model to predict the voltage required to achieve a desired output torque. By using only current and voltage measurements, it is possible to estimate the instantaneous stator flux and output torque. An induction motor model is then used to predict the voltage required to drive the flux and torque to the demanded values within a fixed time period. This calculated voltage is then synthesized using Space Vector Modulation (SVM). Torque control of an induction machine based on DTC strategy has been developed and a comprehensive study is described. The performance of this control method has been demonstrated by simulations performed using a versatile simulation package, Matlab. **Key Words:** Direct torque control, Space vector modulation

Introduction

In the mid 1980s. an advanced scalar control technique known as direct torque and flux control (DTFC or DTC) or direct self-control (DSC) was introduced for voltage-fed PWM inverter drives. This technique was claimed to have nearly comparable performance with vector-controlled drives. Recently, the scheme was introduced in commercial products by a major company and therefore created wide interest. The scheme, as the name indicates, is the direct control of the torque and stator flux of a drive by inverter voltage space vector selection through a lookup table.

In this paper, the Direct Torque Control method and the three-level Space Vector Modulation technique that were used are explained. Simulation results from Matlab/Simulink are presented.

Direct Torque Control

Induction motor torque control has traditionally been achieved using Field Oriented Control (FOC). This involves the transformation of the stator currents into a synchronously rotating dq reference frame that is typically aligned to the rotor flux [3]. In this reference frame, the torque and flux producing components of the stator current are decoupled. A hystersis controller is then used to regulate the output voltage to achieve the required stator current and therefore torque. This hystersis controller limits the transient response of the torque controller.

Direct Torque Control (DTC) uses an induction motor model to predict the voltage required to achieve a desired output torque [4]. By using only current and voltage measurements, it is possible to estimate the instantaneous

stator flux and output torque. An induction motor model is then used to predict the voltage required to drive the flux and torque to the demanded values within a fixed time period. This calculated voltage is then synthesized using Space Vector Modulation (SVM). The stator flux vector, $\bar{\lambda}_s$ and the torque produced by the motor, Tem , can be estimated using (1) and (2) respectively. These only require knowledge of the previously applied voltage vector, measured stator current, and stator resistance.

$$\bar{\lambda}_s = \int (\bar{V}_s - r_s \bar{I}_s)\, dt \qquad (1)$$

$$T_{em} = \frac{3}{2}\frac{P}{2}(\bar{\lambda}_s \times \bar{I}_s) \qquad (2)$$

Once the current stator flux magnitude and output torque are known, the change required in order to reach the demanded values by the end of the current switching period can be determined. An equivalent circuit of the induction motor in a stationary dq reference frame is shown in Figure 1. Over a short time period, the change in torque is related to the change in current and from the equivalent circuit, equation (3) can be obtained. The voltage $\bar{E}$ can also be determined by using the stator flux and current vectors.

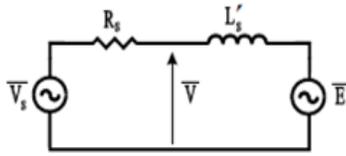$$\Delta I_s = \frac{\bar{V} - \bar{E}}{L_s}\, \Delta t \qquad (3)$$

Figure 1: Equivalent Circuit of Induction Motor in dq reference frame.

By combining (2) and (3), an expression for the change in torque can be obtained as shown in (4).Equation (1) can also be rewritten as an expression for the change in the stator flux, as shown in (5).

$$\Delta T_{em} = \frac{3P}{2Q}\frac{\Delta t}{L_s'}\left(\bar{\lambda}_s \times (\bar{V} - E)\right) \qquad (4)$$

$$\Delta \lambda_s = (\bar{V}_s - n\bar{I}_s)\Delta t = \bar{V}\Delta t \qquad (5)$$

These two equations can be solved to find the smallest voltage vector, $\bar{V}$ required to drive both the torque and flux to the demand values. The required stator voltage can be calculated by adding on the voltage drop across the stator resistance calculated using the current measured from the last cycle.

As shown in Figure 2, the voltage required to drive the error in the torque and flux to zero is calculated directly. The calculated voltage is then synthesized using Space Vector Modulation. If the inverter is not capable of generating the required voltage then the voltage vector which will drive the torque and flux towards the demand value is chosen and held for the complete cycle.
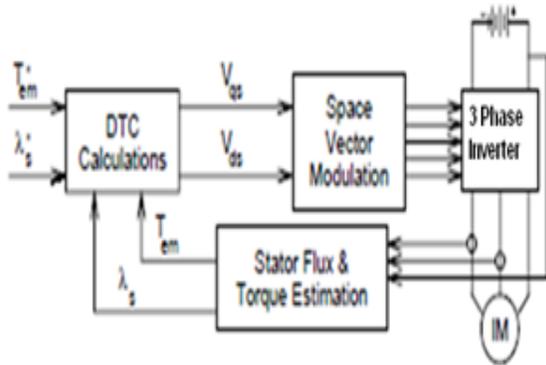

Figure 2: DTC using Space Vector Modulation Block Diagram

Control Strategy of DTC

The block diagram for direct torque and flux control is shown in Figure 3 & Figure 4 explains the control strategy. The speed control loop and the flux program as a function of speed are shown as usual and will not be discussed. The command stator flux ψs* and torque Te* magnitudes are compared with the respective estimated values and the errors

are processed through hysteresis-band controllers, as shown. The flux loop controller has two levels of digital output according to the following relations:

$$H_\psi = 1 \text{ for } E_\psi > +HB_\psi \qquad (6)$$

$$H_\psi = -1 \text{ for } E_\psi < -HB_\psi \qquad (7)$$

where 2HBψ = total hysteresis-band width of the flux Controller. The circular trajectory of the command flux vector ψs* with the hysteresis band rotates in an anti-clockwise direction as shown in Figure 4 (a). The actual stator flux ψs is constrained within the hysteresis band and it tracks the command flux in a zigzag path [7]. The torque control loop has three levels of digital output, which have the following relations:

$$H_{Te} = 1 \text{ for } E_{Te} > +HB_{Te} \qquad (8)$$

$$H_{Te} = -1 \text{ for } E_{Te} < -HB_{Te} \qquad (9)$$

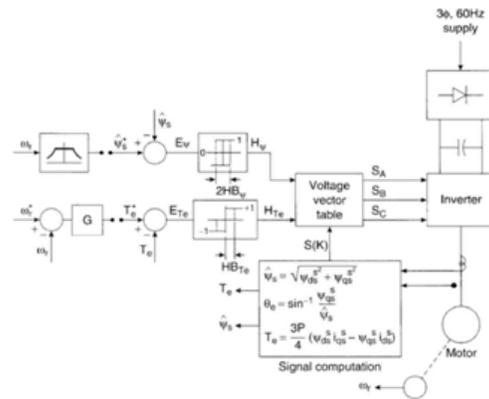$$H_{Te} = 0 \text{ for } -HB_{Te} < E_{Te} < +HB_{Te} \qquad (10)$$

Figure 3: Direct torque and flux control block diagram

The feedback flux and torque are calculated from the machine terminal voltages and currents. The signal computation block also calculates the sector number S(k) in which the flux vector ψs lies. There are six sectors (each π/3 angle wide), as indicated in Figure 4 (a). The voltage vector table block in Figure 3 receives the input signals H_ψ H_{Te}, and S(k) and generates the appropriate control voltage vector (switching states). The inverter voltage vectors (six active and two zero states) and a typical ψs are shown in Figure 4 (b).
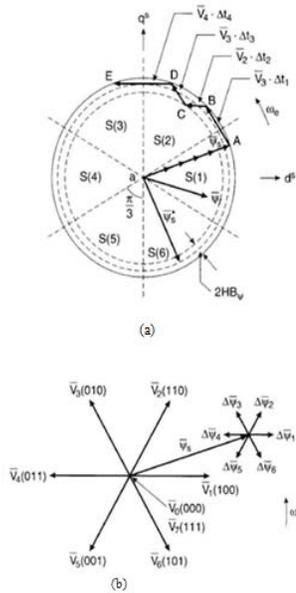
(a)

(b)

Figure 4 (a) Trajectory of stator flux vector in DTC control,
(b) Inverter voltage vector and corresponding stator flux
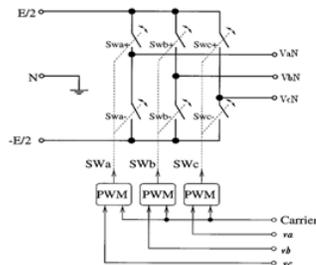variation in time Δt

Space vector modulation

Figure 5: Three phase PWM Inverter

For the three-phase two-level PWM inverter as shown in Figure 5 the switch function is defined by

$$S_{Wi} = \begin{cases} 1, & \text{the upper switch } S_{Wi+} \text{ is on} \\ & \text{and the bottom switch } S_{Wi-} \text{ is off;} \\ 0, & \text{the upper switch } S_{Wi+} \text{ is off} \\ & \text{and the bottom switch } S_{Wi-} \text{ is on.} \end{cases}$$

where i = a, b, c; "1" denotes E/2 at the inverter output (a, b, c) with reference to point N; "0" denotes –E/2; N is the neutral point of the dc bus.

There are eight switch states $(S_i = [S_{Wa}, S_{Wb}, S_{Wc}])$, i=0,1,....7 (as shown in Figure 6). The output voltages of the inverter are composed by these eight switch states. Define eight voltage vectors $\overline{V_0}$ = [000],... $\overline{V_7}$ = [111]corresponding to the switch states , $\overline{S_1}$, ..., $\overline{S_7}$, respectively. The lengths of

vectors $\overline{V_1}$, ..., $\overline{V_6}$ are unity and the lengths of $\overline{V_0}$ and $\overline{V_7}$ are zero, and these eight vectors form the voltage-vector space as displayed in Figure 6. The voltage-vector space is divided up into six sectors.

In the vector space, according to the equivalence principle, the following operation rules are obeyed:

$$\begin{aligned} \overline{V_1} &= -\overline{V_4} \\ \overline{V_2} &= -\overline{V_5} \\ \overline{V_3} &= -\overline{V_6} \\ \overline{V_0} = \overline{V_7} &= \overline{0} \\ \overline{V_1} + \overline{V_3} + \overline{V_5} &= \overline{0} \end{aligned} \qquad (11)$$
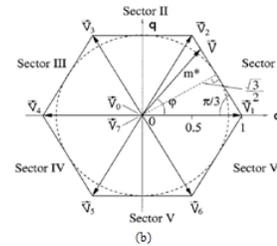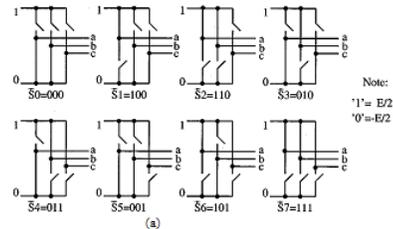

(a)

(b)

Figure 6: Space vectors.
(a) Eight switching states. (b) Voltage vector space.

In one sampling interval, the output voltage vector $\overline{V}$ can be written as

$$\overline{V}(t) = \frac{t_0}{T_s}\overline{V_0} + \frac{t_1}{T_s}\overline{V_1} + ... + \frac{t_7}{T_s}\overline{V_7} \qquad (12)$$

where $t_0, t_1, ... t_7$ time of the vectors $\overline{V_0} ... \overline{V_7}$; $t_0, t_1, ... t_7 \geq 0$; $\sum_{i=0}^{7} t_i = T_s$ and T_s is the sampling time.

According to (6) and (7), the decomposition of $\overline{V}$ into $\overline{V_1}, \overline{V_2} ... \overline{V_7}$ has infinite ways. However, in order to reduce the number of switching actions and make full use of active turn-on time for space vectors, the vector $\overline{V}$ is commonly split into the two nearest adjacent voltage vectors and zero vectors $\overline{V_0}$ and $\overline{V_7}$ in an arbitrary sector. For example, in sector I, in one sampling interval, vector $\overline{V}$ can be expressed as

$$\overline{V} = \frac{T_1}{T_s}\overline{V_1} + \frac{T_2}{T_s}\overline{V_2} + \frac{T_7}{T_s}\overline{V_7} + \frac{T_0}{T_s}\overline{V_0}$$

(13)

Where $T_s - T_1 = T_2 = T_0 + T_7 \geq 0, T_0 \geq 0 \text{ and } T_7 \geq 0$.

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The length and angle of $\vec{V}$ are determined by vectors

$\vec{V_1} \vec{V_2} ... \vec{V_6}$ that are called active vectors, and $\vec{V_0} \vec{V_7}$ are called zero vectors.

Simulation

Simulation have been performed by using matlab7.5. Figure 7 shows the circuit configuration of DTC control of three phase induction motor control.
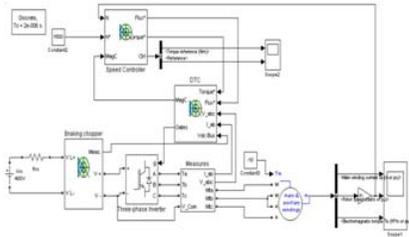
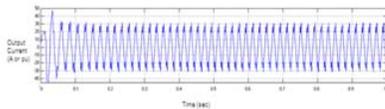Figure 7: DTC Control of 3-Phase Induction Motor
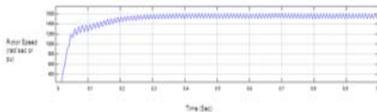
Figure 8: Motor Current Ia
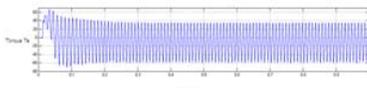
Figure 9: Rotor Speed

Figure 10: Electromagnetic Torque

Figure 8 shows that the initial current was high and steady current was reached at 0.2 sec. After 0.2 sec the current is maintained constant. Figure 9 shows that the rotor speed attain constant speed at 1600 rpm at 0.35 sec. Figure 10 shows the initial high torque and at 0.2 sec steady torque is reached.

Conclusion

Direct Torque Control using Space Vector Modulation was chosen based on its low current distortion and fast torque response. Its high dynamic response is due to the absence of the PI current regulator normally used in torque controllers and its low current distortion is due to the use of Space Vector Modulation to synthesise the demand motor voltage. The performance of this control method has been demonstrated by simulations performed using Matlab / Simulink.

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