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DTC-SVM scheme for Five-level Neutral Point Clamped inverter fed Induction Motor

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ABSTRACT

Direct torque control (DTC) is a control technique in AC drive systems to obtain high performance torque control. This paper proposed direct torque control of induction motor drive using three phase five-level Neutral Point Clamped inverter (NPC). The space vector PWM technique is applied to control the output of the proposed inverter for induction motor drive. The control technique has a constant switching frequency and is generated reference vector of the converter using different sampling period. Dynamic stability (servo and regulatory) of the proposed scheme also done using the proposed inverter. As simulation results using MATLAB/Simulink will show the proposed DTC scheme to control the speed and torque of induction motor drive with SVPWM.

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INTRODUCTION

In the mid-1980s the Direct Torque Control (DTC) principle was developed by Takahashi and Noguchi for low and medium power applications and Direct Self Control (DSC) principle was established by Depen brock for high power applications (I. Takahashi and Y. Ohmori, 1989, I. Takahashi and T. Noguchi, 1986 and M. Depenbrock, 1988). As the name suggests, DTC or DSC regulates the motor torque and flux directly. Direct torque control (DTC) is a control technique used in AC drive systems to obtain high performance torque control. The aim of this work is to enhance the DTC using a space vector modulation technique (SVM) to synthesize the reference voltage vector required to meet the torque and flux demands. The direct torque control (DTC) is one of the actively researched control schemes which are based on the decoupled control of flux and torque, providing a very quick and robust response with a simple control construction in AC drives (Xavier del Toro Garcia, Antoni Arias, Marcel G. Jayne, Phil A. Witting, et.al, 2005 and R. Zaimeddine and E. M. Berkouk, 2004). In this paper propose a DTC scheme using a five-level Neutral Point Clamped (NPC) inverter and space vector modulation control. The torque is controlled in closed loop with estimation of the rotor flux position

Induction Motor Drive Modelling:

Torque control of an asynchronous motor can be achieved on the basis of its model developed in a two axes (α, β) reference frame stationary with the stator winding (R. Zaimeddine and T. Undeland, 2010). In this reference frame and with conventional notations (appendix), the electric mode is described by the following equations:

$$\frac{di_{s\alpha}}{dt} = \frac{1}{\sigma T_r L_s}\varphi_{s\alpha} + \frac{p\Omega}{\sigma L_s}\varphi_{s\beta} - \frac{1}{\sigma}\left(\frac{1}{T_r}+\frac{1}{T_s}\right)i_{s\alpha} - p\Omega i_{s\beta} + \frac{1}{\sigma L_s}V_{s\alpha} \quad (1)$$

$$\frac{di_{s\beta}}{dt} = -\frac{p\Omega}{\sigma L_s}\varphi_{s\alpha} + \frac{1}{\sigma T_r L_s}\varphi_{s\beta} - \frac{1}{\sigma}\left(\frac{1}{T_r}+\frac{1}{T_s}\right)i_{s\beta} + p\Omega i_{s\alpha} + \frac{1}{\sigma L_s}V_{s\beta} \quad (2)$$

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$$\frac{di_{s\alpha}}{dt} = V_{s\alpha} - R_s i_{s\alpha} \quad (3)$$

$$\frac{di_{s\beta}}{dt} = V_{s\beta} - R_s i_{s\beta} \quad (4)$$

$$\varphi_{s\alpha} = L_s i_{s\alpha} + L_m i_{r\alpha} \quad (5)$$

$$\varphi_{s\beta} = L_s i_{s\beta} + L_m i_{r\beta} \quad (6)$$

$$\varphi_{r\alpha} = L_r i_{r\alpha} + L_m i_{s\alpha} \quad (7)$$

$$\varphi_{r\beta} = L_r i_{r\beta} + L_m i_{s\beta} \quad (8)$$

The rotor motion is described by

$$J\frac{d\Omega}{dt} = T_{em} - T_L(\Omega) \quad (9)$$

T_L (Ω) and T_{em} are Load torque and electromagnetic torque developed by the induction motor drive.

Five Level Neutral Point Clamped Inverter:

In recent years, industry has begun to demand higher power equipment, which now reaches the megawatt level. Controlled AC drives in the megawatt range are usually connected to the medium voltage network. MLIs divide the main DC supply voltage into several DC sources, which are used to synthesize an AC voltage from a stepped approximation of the desired sinusoidal waveform. The stepped approximation is also popularly known as the staircase model. The number of stages (cells or capacitors depending on the respective topology) helps decide the power capacity of the converter as a whole. Suitable connections either in series or shunt mode or both are done to achieve higher voltage or current ratings. One of the biggest advantages of using an MLI is, the transformer can be eliminated, and this helps to enhance efficiency and cost effectiveness, the NPC also called DCMLI (Xiaoming Yuan and Ivo Barbi, 1999, M.H. Rashid, 2007). The commutation of the switches permits the addition of the capacitor voltages, which reach high voltage at the output, while the power semiconductors must withstand only reduced voltages. The multilevel inverters can be classified into three types:

1. Diode clamped multilevel inverter
2. Flying capacitor clamped multilevel inverter
3. Cascade capacitor multilevel inverter

Figure. 1 shows the five level neutral point clamped inverter topology. In the NPC topology, the clamping diodes are presented with a common DC link is divided.

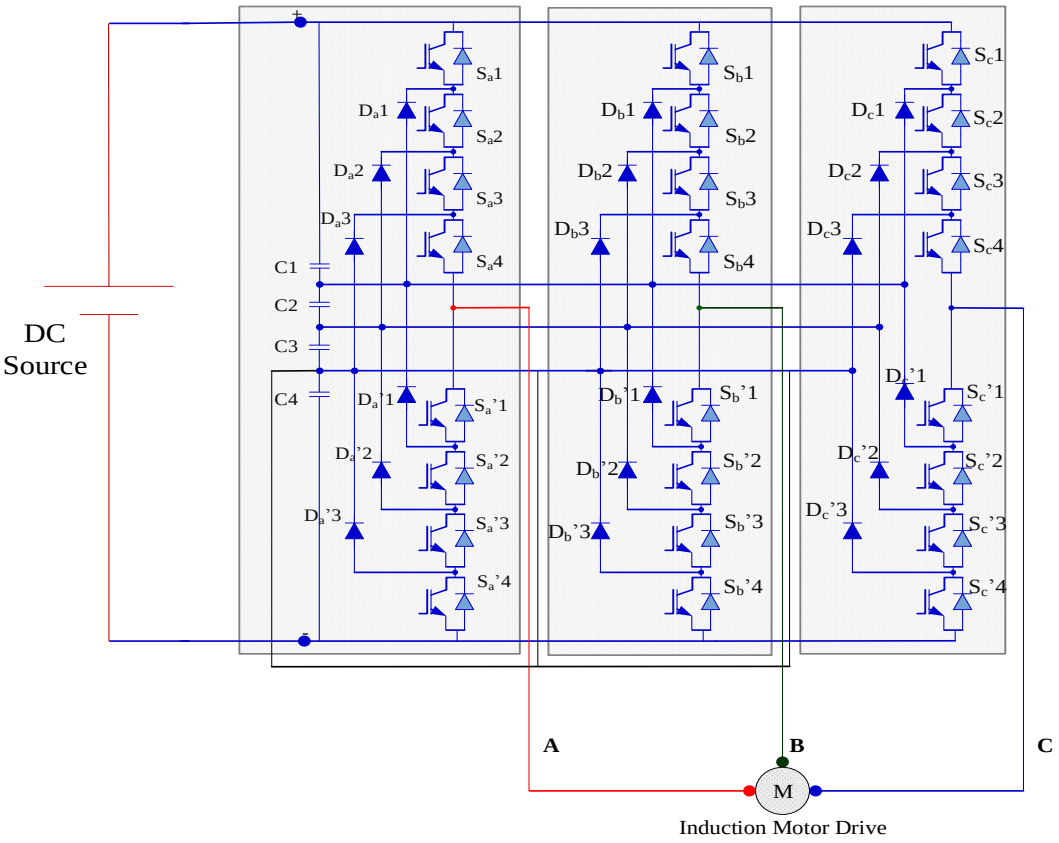

Fig. 1: Schematic diagram of a five-level Neutral Point Clamped inverter

From Figure.1 the DC bus consists of four capacitors, C_1, C_2, C_3 and C_4. For DC-bus voltage V_{dc}, the voltage across each capacitor is $v_{dc}/4$ and through clamping diodes. There are five switch combinations to synthesize five level voltages across A and N.

- For voltage level $V_{AN} = V_{dc}/2$, turn on all upper switches S_a1-S_a4.

- For voltage level $V_{AN} = V_{dc}/4$, turn on three upper switches S_a2-S_a3 and one lower switch S_a1'.
- For voltage level $V_{AN} = 0$, turn on two upper switches S_a3 and S_a4 and two lower switches S_a1' and S_a2'.
- For voltage level $V_{AN} = -V_{dc}/4$, turn on one upper switch S_a4 and three lower switches S_a1' – S_a3'.
- For voltage level $V_{AN} = -V_{dc}/2$, turn on all lower switches S_a1'-S_a4'.

Four complementary switch pairs exist in each phase. The complementary switch pair is defined such that turning on one of the switches will exclude the other from being turned on.

Space Vector Modulation For Five Level Npc Inverter:

PWM strategies are applied to generate acceptable input and output waveforms. Different switching strategies yield distinctive performances, which may be applied in industry. Several switching modulations are available for matrix converters. In this paper, space vector modulation (SVM) is chosen to satisfy the objectives of the design. It is very critical to analyze each of these features in order to match industry demand. SVM switching pattern brings higher dynamic performance to the converter.

Space Vector Modulation (SVM) is one of the vector approaches to PWM technique for three phase inverters. It is the most advanced technique to generate AC signal which produces a high voltage to the motor load with lower total harmonic distortion. In this Space Vector PWM (SVPWM) method, the reference signal is sampled regularly. After sampling each signal the non-zero active switching vectors are adjacent to the reference vector. For variable frequency drive application this is the best technique to implement and provides better results. This is an advanced; computation intensive PWM method. Every switching state can be represented as a vector in the converters α-β Space vector plane. The three phase currents can be transformed into two phase currents in α-β Plane as represented below.

$$\begin{bmatrix} i_\alpha(t) \\ i_\beta(t) \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} \quad (10)$$

According to the space voltage vector representation of the inverter, the voltage diagram can be divided into six (6) sectors as shown in figure 3, and each sector is divided into four (4) triangles. The proposed technique is based on the modulation of a vector reference using the three voltage vectors that construct the triangle where the end of the vector resides. The three vectors are imposed to the motor terminals successively in such away less harmonics components of the output voltage and current are produced. Switching sequences for proposed 5 level NPC inverter is given in table 1 (R. Zaimeddine and T. Undeland, 2010).

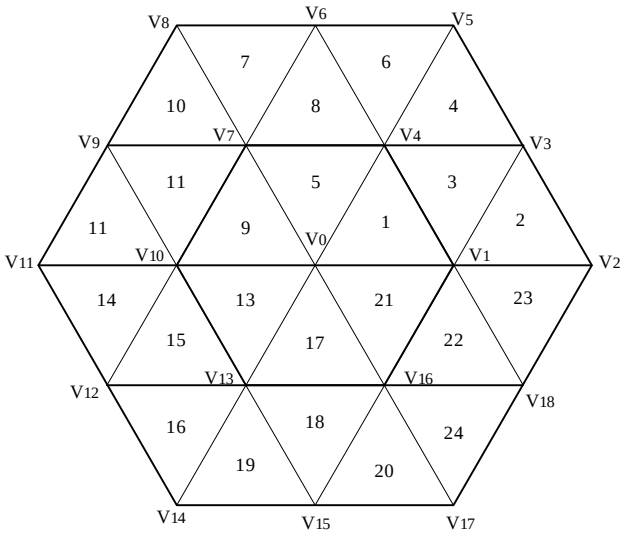

Fig. 2: Five level NPC inverter hexagon with 24 different triangles

The required on-duration of each vector in a specified triangle is determined by the equations (11);

$$\vec{V}_{ref} T_s = t_a \vec{v}_a + t_b \vec{v}_b + t_c \vec{v}_c$$

$$T_e = t_a + t_b + t_c \quad (11)$$

Where, t_a, t_b and t_c are the on- durations of the adjacent vectors.

Table I: switching sequences of five level Neutral Point Clamped inverter

Voltage	Switching State							
	Sa4	Sa3	Sa2	Sa1	Sa4'	Sa3'	Sa2'	Sa1'
V4=4Vdc	1	1	1	1	0	0	0	0
V3=3Vdc	0	1	1	1	1	0	0	0
V2=2Vdc	0	0	1	1	1	1	0	0
V1=1Vdc	0	0	0	1	1	1	1	0
V0=0	0	0	0	0	1	1	1	1

Direct Torque Control Scheme With Space Vector Modulation:

The DTC based induction motor drives were developed and presented more than two decades ago by (I. Takahashi and Y. Ohmori, 1989, M. Depenbrock, 1988). This technique is based on the space vector approach, where the torque and flux of an induction motor can be directly and independently controlled without any coordination transformation. Though the DTC gives fast transient response, it gives large steady state ripples and variable switching frequency of the inverter. To reduce the steady state ripples and to get constant switching frequency of the inverter, the space vector PWM algorithm has been used for the DTC.

A space vector modulation algorithm is required in order to synthesize the reference voltage vector by the adjacent voltage vectors generated by the inverter. We propose in this paper Three DTC scheme using space vector modulation, each scheme will employ different control technique, but its aims still similar which is to obtain the constant switching frequency and reduce the torque ripple (W.U. Xuezh, and L. Huang, 2001, M. Zelechowski, M. P. Kazmierkowski and P. Grabowski, 2002). A DTC-SVM with closed loop torque control can be illustrated by the control block diagram of Figure 3.

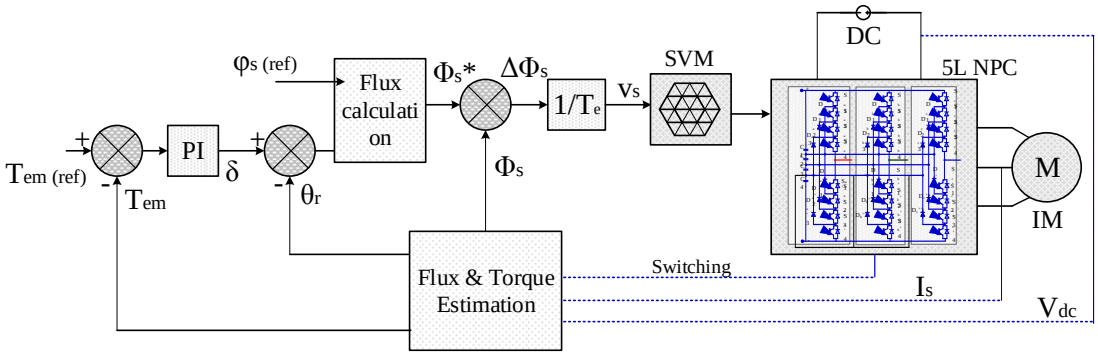

Fig. 3: DTC-SVM with closed loop torque control

The objective of DTC-SVM with closed loop torque control is to select the exact stator voltage vector, Vs that change φ_s to meet the load angle reference, and so the desired torque. With one PI regulator, a simple flux calculator block and no rotating coordinate transformation, making the control strategy a straightforward application of equation (12) (R. Zaimeddine and T. Undeland, 2010, Bimal K. Bose, 2004 and Peter Vas, 1998).

$$T_{em} = \frac{3}{2}\frac{P}{2}\frac{L_m}{\sigma L_s L_r}\varphi_r \varphi_s \sin\delta \quad (12)$$

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \quad (13)$$

Where δ is the angle between the stator (φ_s) and rotor flux linkage space vectors (φ_r) and σ is the leakage coefficient as shown in Figure.4.

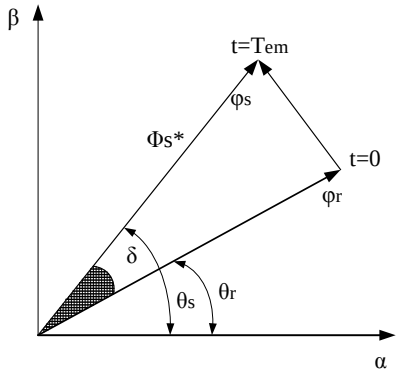

Fig. 4: Flux control principle with closed loop torque control

The PI torque controller actuates over the load angle to meet torque reference, the stator flux calculator block output is given by,

$$\phi_s^* = \phi_s^{ref}\cos(\delta+\theta_r) + j\phi_s^{ref}\sin(\delta+\theta_r) \quad (14)$$

The stator flux reference from the flux calculator block output is compared with estimated flux to obtain the correction error then divided over a sampling period Tem to calculate the reference voltage vector Vs by the following equation:

$$\Delta\phi_S = V_S T_{em} \quad (15)$$

The space vector modulation block performs the defined space vector modulation technique of Vs to obtain the gate drive pulses for the three level inverter. The rotor flux angle θ_r is calculated from the estimated rotor flux ϕ_r in the reference frame related to the stator.

$$\phi_{r\alpha} = \frac{L_r}{L_m}\left(\phi_{s\alpha} - \sigma L_s I_{s\alpha}\right) \quad (16)$$

$$\phi_{r\beta} = \frac{L_r}{L_m}\left(\phi_{s\beta} - \sigma L_s I_{s\beta}\right) \quad (17)$$

$$\theta_r = \arctan\frac{\phi_{r\beta}}{\phi_{r\alpha}} \quad (18)$$

RESULTS AND DISCUSSION

Direct Torque Control – SVM scheme for 5 level NPC inverter controlled induction motor drive has been carried out by using MATLAB/SIMULINK. The simulation parameters and specifications of the induction motor drive are given in appendix. Simulation is carried out in both steady state and dynamic conditions of the motor. Figures 5-12 show the results of DTC-SVM for 5L-NPC inverter fed induction motor drive. Figure.5 shows the voltage response of individual phase voltage (V_a, V_b, V_c) of 5 level Neutral Point Clamped inverter used for induction motor drive.

In case A, steady state analysis is considered the system is simulated for no load condition with set value of 80% of rated speed (ω=251 rad/Sec) of the motor. Responses for speed, torque and flux are given in Figure. 6. from Figure. 6 the system reached its set speed within 0.1 Sec. In Case B and case C dynamic analysis is done to change speed and Load conditions. In case =B, the speed of the induction motor is decremented for 10% of rated speed at t=0. 2 Sec and incremented 10% of rated speed at t=0. 3 Sec. Figure.7 shows the simulated responses of speed, torque and flux of DTC drive for case B. From Figure.7 it is observed that the system reached its set speed value within 30 msec. In case C, Load torque is decremented from the set value (10 N-m) for 50% of at t=0.4 sec and incremented 50% at t=0.45 sec. Figure. 8 shows the simulated responses of speed, torque and flux of DTC drive for case C. From Figure.8 it is observed that the system reached its required torque value within 30 msec without any change in speed.

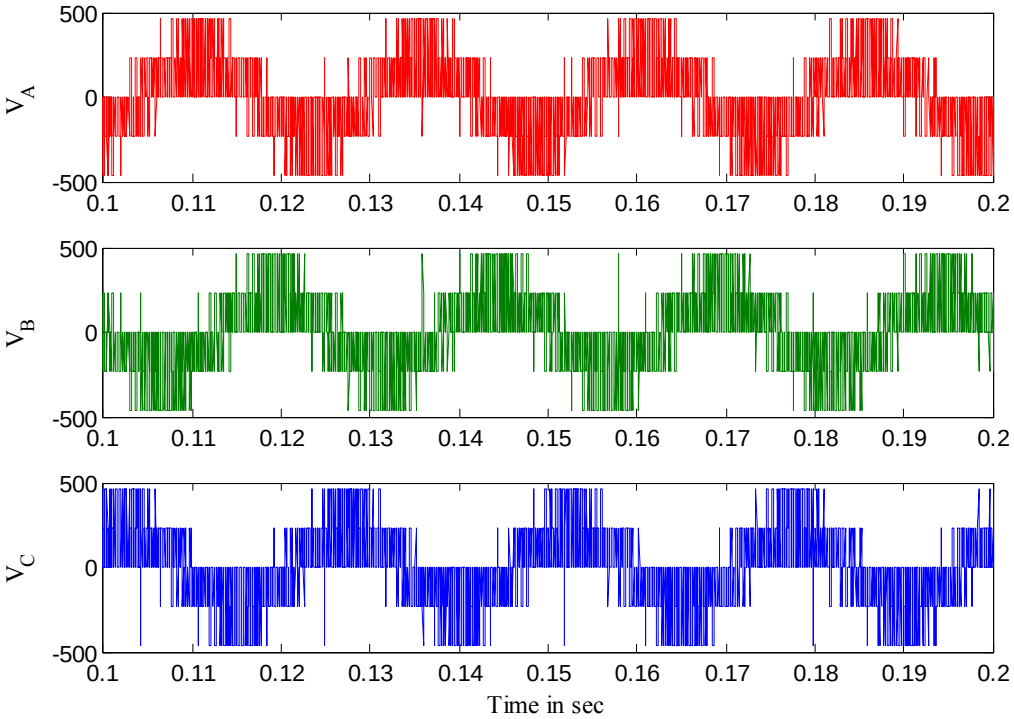

Fig. 5: Simulated voltage response of 5 level NPC inverter used as induction motor drive

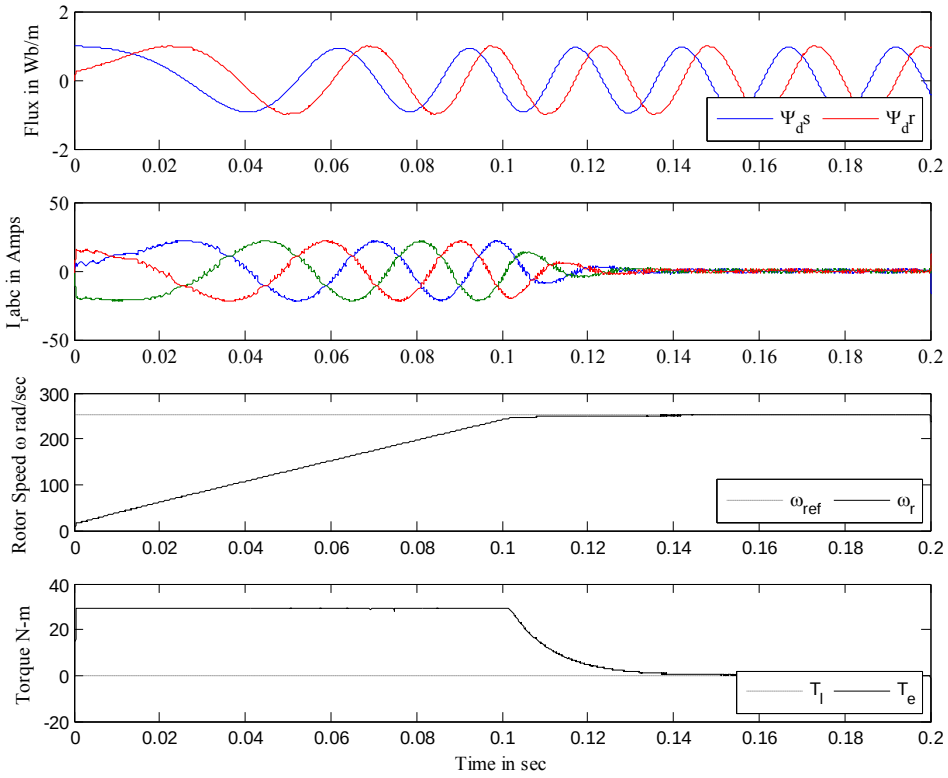

Fig. 6: Simulation results with rated values of the speed, Torque and flux for the case A

Figure. 6 shows the speed and torque response of proposed DTC drive scheme for case A (nominal case). In this case simulated response is obtained for no load condition with set speed of ω=251 rad/sec.

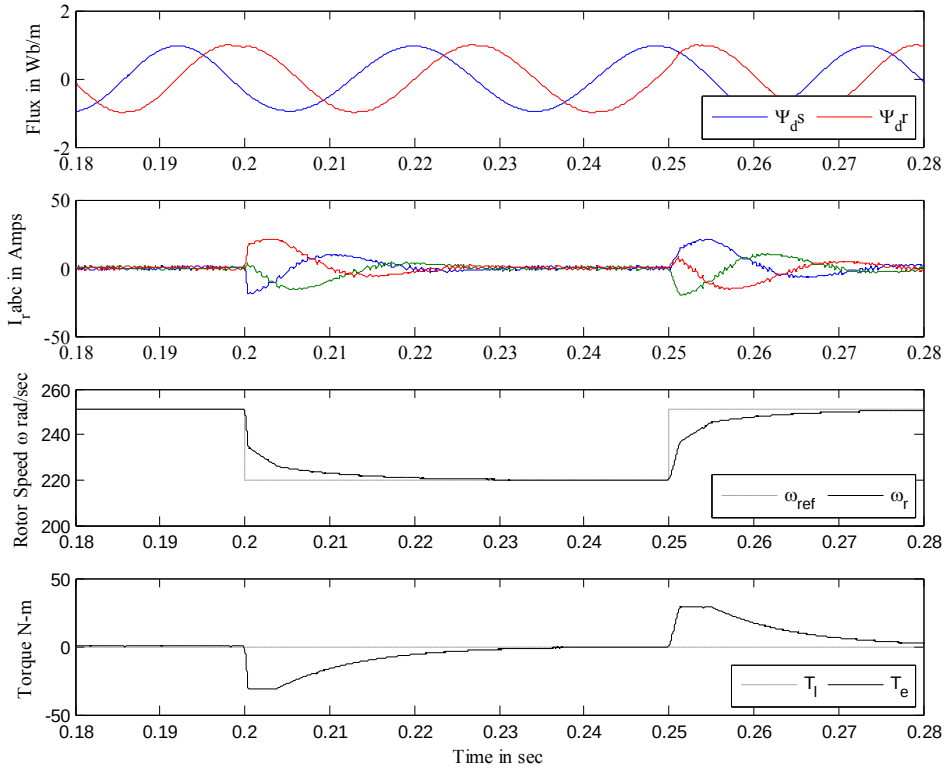

Fig. 7: Simulated response for speed and torque of DTC drive for Change in speed for case B

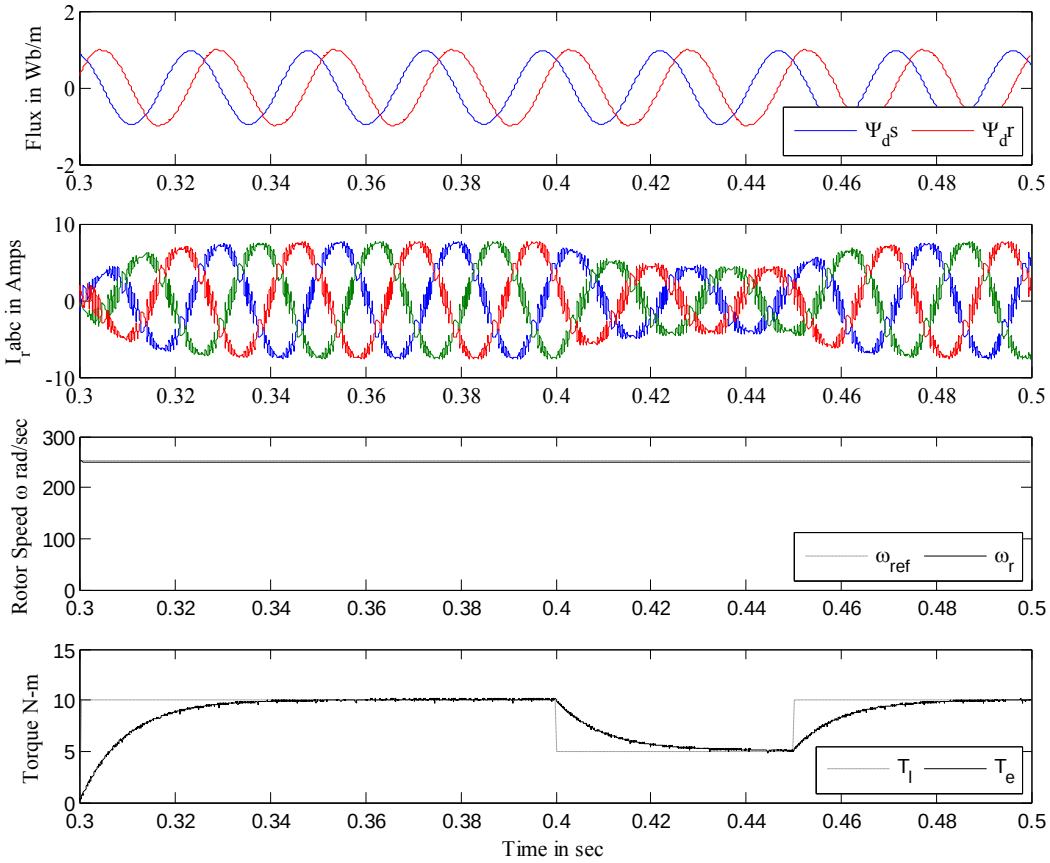

Fig. 8: Simulated response for speed and torque of DTC drive for Change in Load for case C

Stator flux curves of all the 3 cases are given in Figures 5-7. Analysis is carried out speed change as well as load change considerations.

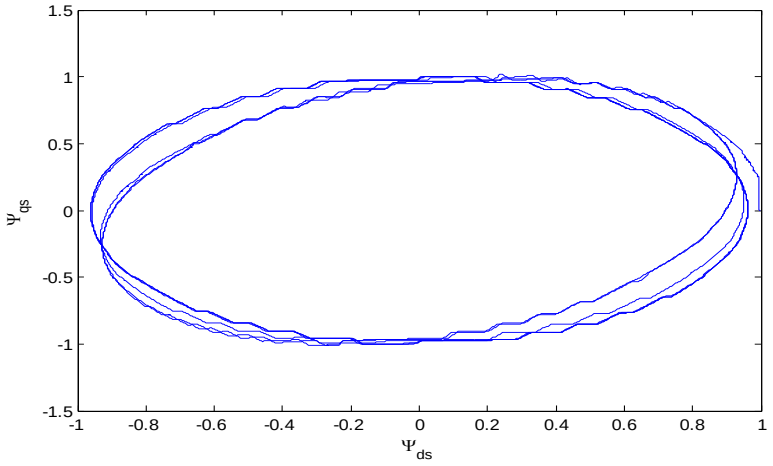

Fig. 9: Circular flux pattern of Induction motor for Case A

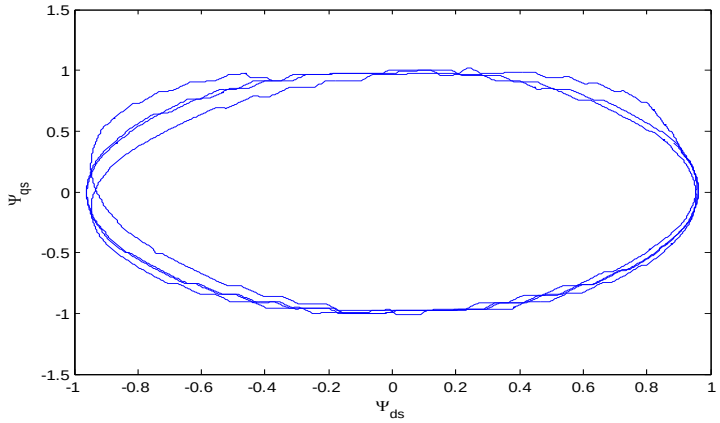

Fig. 10: Circular flux pattern of Induction motor for Case B

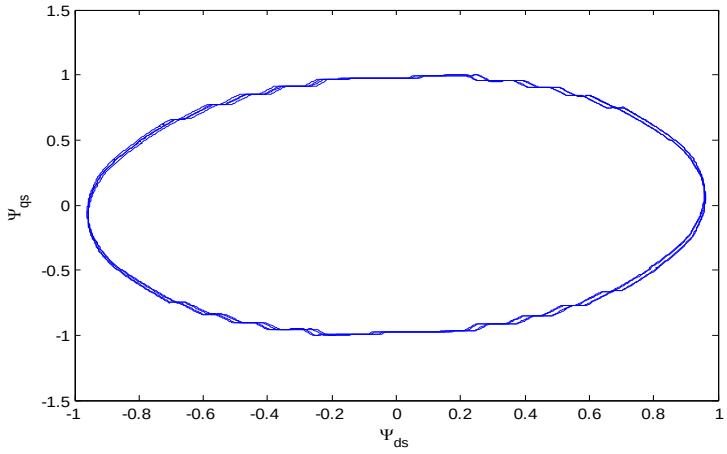

Fig. 11: Circular flux pattern of Induction motor for Case C

Initial stator flux response of proposed DTC drive shown in Figure. 9, Figure.10 shows the change in flux as a result of change in set speed in the case B state and From Figure. 11, it is observed that during load transition period, stable flux curve has produced which indirectly assures no change in speed during load changing conditions.

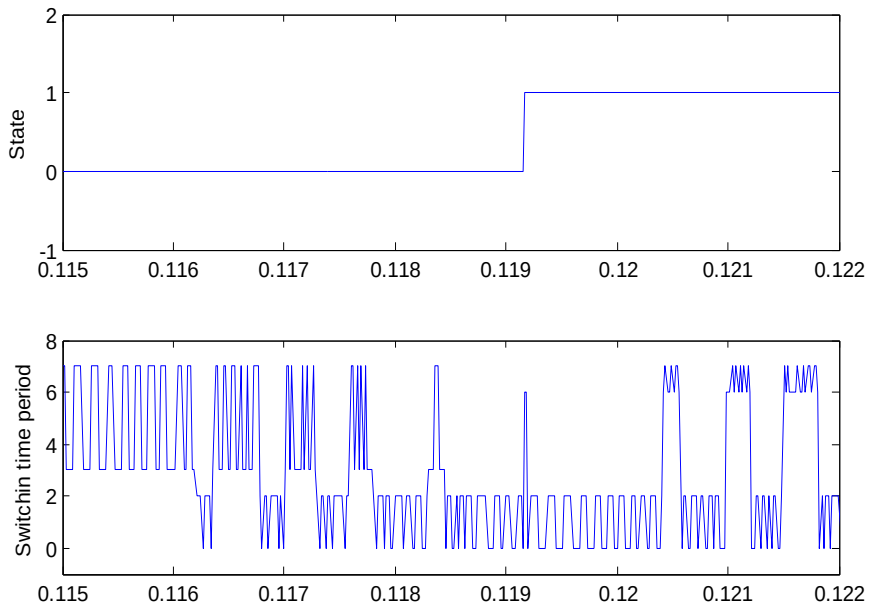

Fig. 12: Simulated response of SVPWM – Switching Time during change in state

Figure.12 shows the time period calculated using Proposed Space vector PWM algorithm from state 1 and state 2.

Conclusion:

Direct torque control using space vector modulation was chosen for its low current distortion due to the SVM control technique and fast torque response. The DTC was introduced to give a fast and good dynamic torque and can be considered as an alternative to the field oriented control FOC technique for any application that requires a quick torque response. It is concluded that the proposed control produces better results for transient and the steady state operation then the conventional control. The neutral point voltage can be easily controlled using space vector modulation technique to solve the usual problem of unbalanced voltages input in five level NPC.

Appendix: Induction Motor parameters

Rated power : 2.2 kW
Rated voltage : 440V
Rated speed : 3000 rpm
Rated frequency : 50 Hz
Rated current : 10A
Stator Resistance : 1.4045Ω
Stator Inductance : 5.839mH
Rotor Resistance : 1.395Ω
Rotor Inductance : 5.839mH
Mutual Inductance: 172.2mH
Rotor inertia : 0.01313 Kg/m^2
No of poles : 2
Sampling period : 50μs
DC link voltage : 700V

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