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PI Controller and Space Vector Modulation based Direct Torque Control of Multi-level Inverter fed Induction Motor

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Abstract
Managing speed and Torque in various applications can raise the AC motor's efficiency and significantly save energy. Direct Torque Control (DTC) is significant among the several methods used to regulate AC motors. It is well known that the DTC of AC motors has very favorable control performance and implementation qualities. The control strategy uses the stator flux field orientation to control Torque and flux. DTC makes it possible to manage speed and Torque over a huge range. With a squirrel-cage induction motor model, a cascaded H bridge multi-level inverter, and a PI controller, this work makes an effort to examine and analyze the characteristics and operating principle of the DTC scheme. MATLAB/SIMULINK simulation results have been used to validate the efficacy and viability of this regulating strategy.

Keywords: Induction motor, Direct Torque Control, Space Vector Modulation, Nine level CHB inverter.

INTRODUCTION

In the past few decades, the revolution of variable speed drives has led to better quality and higher productivity in various industrial applications. Due to the higher cost of maintenance of DC motors and other problems in the usage of DC drives [1-2], researchers have slowly encouraged replacing AC drives in variable-speed drive systems [3-4]. Using high-frequency power inverters, AC motor speed and Torque can be controlled effectively and efficiently [5-6]. More than a decade ago, Direct Torque Control (DTC) was introduced to give fast and good dynamic torque responses and can be considered as an alternative to the Field Oriented Control (FOC) technique [7-9]. Among the problems usually associated with DTC drives, the variable switching frequency of the power devices used for the voltage source inverter and high torque ripples are majorly considered [10-11]. This work aims 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 DTC is one of the actively researched control schemes based on the decoupled control of flux and Torque, providing a very quick and robust response with a simple control construction in AC drives [12-13]. This paper proposes a DTC control scheme for a nine-level Cascaded H-bridge Multi Level Inverter (CHMLI) using space vector modulation control to control the Torque in a closed loop with estimation of the rotor flux position. MATLAB/ Simulink.

INDUCTION MOTOR DRIVE MODELLING

Torque control of an asynchronous motor can be achieved based on its model developed in a two axes (α, β) reference frame stationary with the stator winding [14]. In this reference frame and with conventional notations, the electric mode is described by the following equations:

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

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

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

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

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

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

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

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

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.

CASCADED H BRIDGE NINE LEVEL INVERTER

The proposed nine-level cascaded H-bridge multi-level structure for the direct torque control technique is depicted in Fig. 1. A nine-level, three-phase inverter is created by combining 48 switches and 12 DC sources, or four switches and one DC source for each H-bridge. Each bridge's anti-parallel switches are activated for positive and negative voltage levels. By connecting bridges in series, it is possible to increase or decrease the level by adding voltages. The multi-level voltage source inverters are mostly used in AC power supply sectors. The main benefit of a multi-level inverter is the harmonic reduction in the output waveform that is achieved by maintaining a constant switching frequency or reducing the inverter power output [15]. A multi-level inverter's output voltage waveform comprises different voltage levels. Hence, the multi-level inverter starts at level three. The output Total Harmonic Distortion (THD) reduces approaches zero as the level count rises [16].

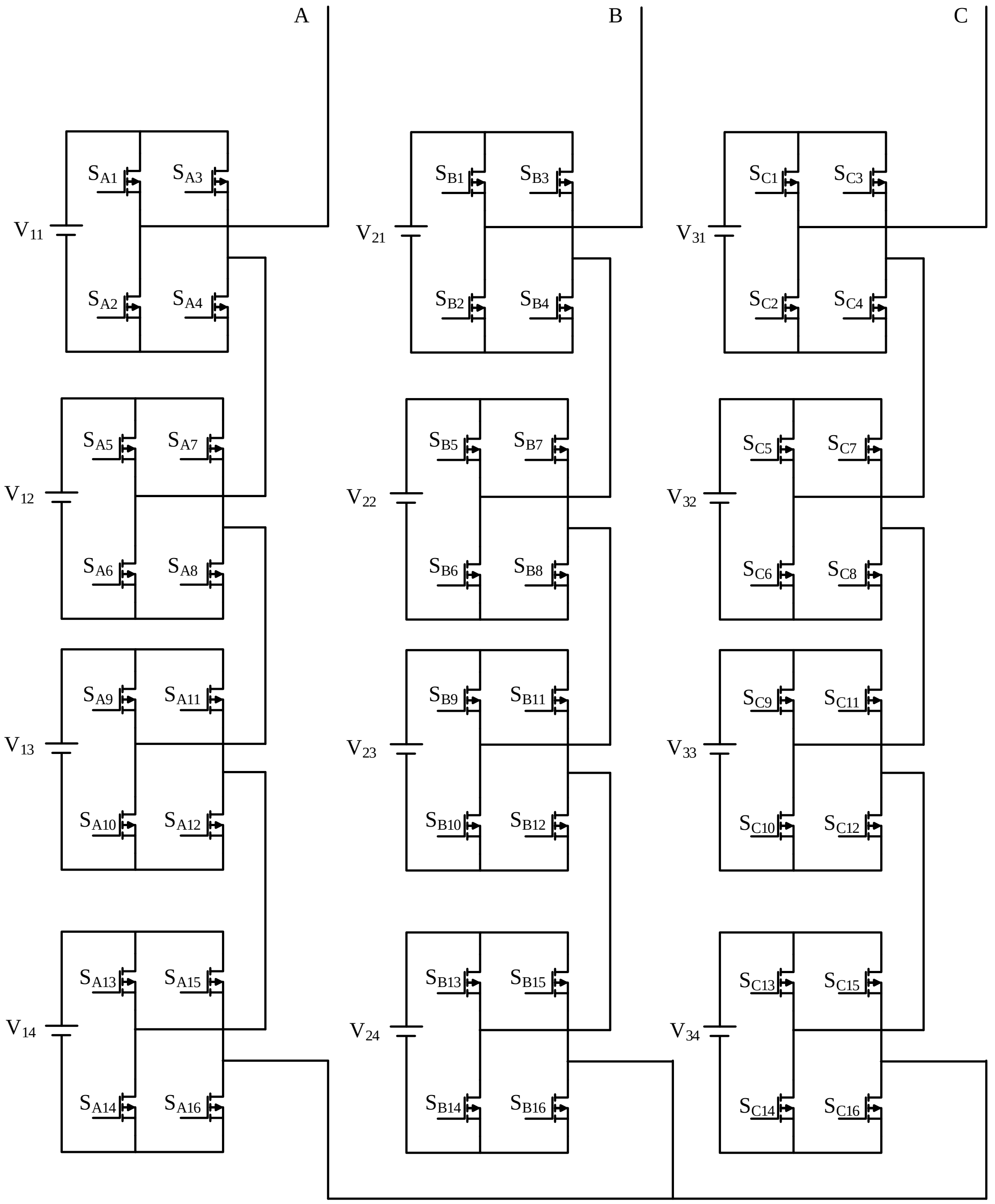

Fig.1: Schematic diagram of a nine-level cascaded H-bridge inverter

Three topologies, the flying capacitor inverter, the diode clamped inverter, and the cascaded H-bridge inverter, divide the multi-level inverters. The property of decreasing the harmonics is shared by all topologies [17]. The flying capacitor inverter design is challenging to implement since each capacitor's voltage varies from the next, making charging challenging [18]. Due to the issue of DC link voltage unbalancing, the diode-clamped inverter, sometimes referred to as a neutral-clamped converter, is not favored [18]. Although the cascaded inverter has a separate DC supply as a drawback, the circuit layout is small, and the voltage-sharing issue is not present. As a result, it is simple to expand and suitable for HVDC and high-power motor driver applications [19].

SPACE VECTOR MODULATION OF NINE-LEVEL CHB INVERTER

To create acceptable input and output waveforms, PWM techniques are used. Different switching tactics produce diverse performances that can be applied in business. For multi-level inverters, several switching modulations are available. This paper uses space vector modulation (SVM) to achieve the design goals. Analyzing each of these qualities is essential if you want to meet market demand. The SVM switching pattern improves the inverter's dynamic performance. One of the vector approaches to the Pulse Width Modulation (PWM) technology for three-phase inverters is Space Vector Modulation (SVM). It benefits from producing an AC signal with minimal total harmonic distortion that delivers a high voltage for the motor load.

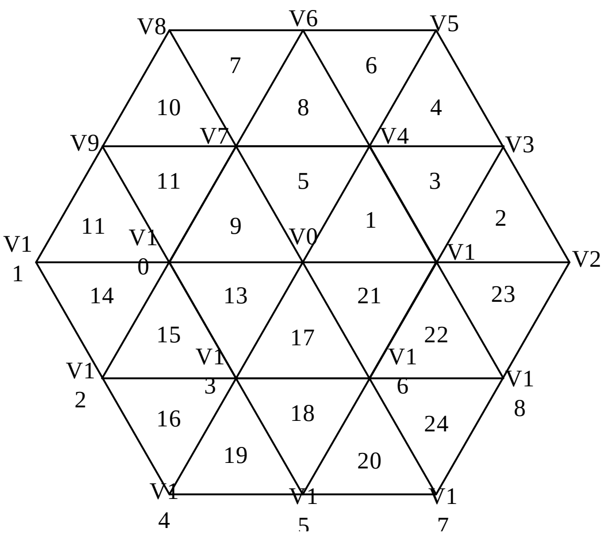

Fig.2: Cascaded H Bridge three-level inverter hexagon with 24 different triangles

This Space Vector PWM (SVPWM) technique samples the reference signal regularly. The active switching vectors that are not zero after sampling each signal are located close to the reference vector. This is the best strategy to use and yields the greatest results for variable frequency drive applications. This PWM technique is sophisticated and computationally expensive. Each switching state can be represented as a vector in the converters' space vector plane. As shown below, the three-phase current can be split into two-phase currents in the -plane.

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

As illustrated in Fig. 2, the voltage diagram can be divided into six (6) sectors, with each sector being divided into four (4) triangles, in accordance with the space voltage vector representation of a three-phase, three-level inverter. The suggested method is based on modulating a reference vector using the three voltage vectors that make up the triangle where the vector's terminus is located. The three vectors are consecutively applied to the motor terminals to provide output voltage and current with less harmonic components. The Cascaded H Bridge nine-level inverter hexagon for sector one is seen in Figure 3 and has 64 triangles. Table 1 [14] lists the proposed nine-level CHB inverter switching patterns.

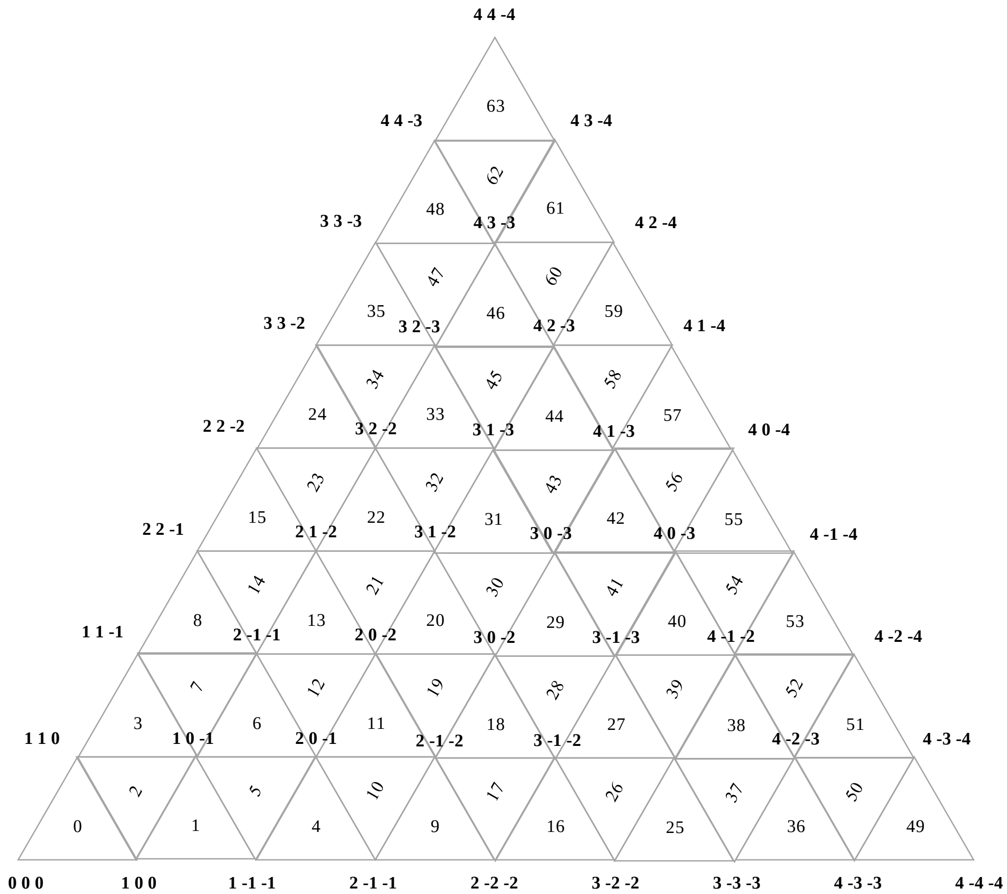

Fig.3: Cascaded H Bridge nine-level inverter hexagon for sector 1 with 64 triangles

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

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

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

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

Table 1 Switching sequences of nine-level cascaded H-bridge inverter

Voltage level for phase A	Sector 1 switching state
V4=4Vdc	(4 -3 -3), (4,-2 -3), (4 -1 -3), (4 0 -3), (4 1-3), (4 2 -3), (4 3 -3), (4 4 -3), (4 -4 -4), (4 -3, -4), (4 -2 -4), (4 -1 -4), (4 0 -4), (4 1 -4), (4 2 -4), (4 3 -4), (4 4 -4)
V3=3Vdc	(3 -2 -2), (3 -1 -2), (3 0 -2), (3 1 -2), (3 2 -2), (3 3 -2), (3 -3 -3), (3 -2 -3), (3 -1 -3), (3 0 -3), (3 1 -3), (3 2 -3), (3 3 -3)
V2=2Vdc	(2 -1 -1), (2 0 -1), (2 1 -1), (2 2 -1), (2 -2 -2), (2 -1 -2), (2 0 -2), (2 1 -2), (2 0 -2), (2 1 -2), (2 2 -2)
V1=1Vdc	(1 0 0), (1 1 0), (1 -1 -1), (1 0 -1), (1 1 -1)
V0=0	(0 0 0)

DIRECT TORQUE CONTROL SCHEME

The DTC-based induction motor drives were developed and presented more than two decades ago by [20-21]. 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 a fast transient response, it gives large steady-state ripples and variable switching frequency of the inverter. The space vector PWM algorithm has been used for the DTC to reduce the steady-state ripples and to get the constant switching frequency of the inverter. A space vector modulation algorithm is required to synthesize the reference voltage vector by the adjacent voltage vectors generated by the inverter. We propose in this paper a novel DTC scheme using space vector modulation to obtain the constant switching frequency and reduced torque ripple [22-23]. The control block diagram of Fig.4 can illustrate a DTC-SVM with closed-loop torque control.

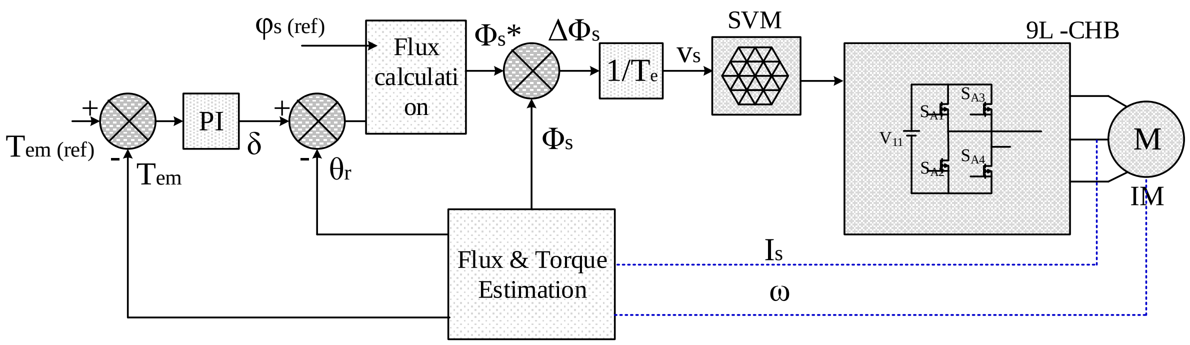

Fig.4: DTC-SVM with closed-loop torque control

The objective of DTC-SVM with closed loop torque control is to select the exact stator voltage vector, V_s, that changes φ_s to meet the load angle reference and so the desired Torque [24]. With one PI regulator as a simple flux calculator block and another for V_d, V_q calculation, which consists of no rotating coordinate transformation, making the control strategy a straightforward application of equation (12) [14], [25-26].

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

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \tag{13}$$

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 Fig.5.

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

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

The stator flux reference of the flux calculator block output is compared with the estimated flux to obtain the correction error, then divided over a sampling period T_{em} to calculate the reference voltage vector V_s by the following equation:

$$\Delta\phi_s = V_s T_{em} \tag{15}$$

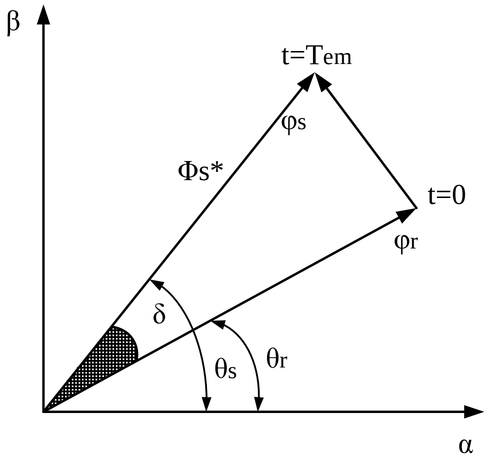

Fig.5: Flux control principle with closed loop torque control

The space vector modulation block performs the defined space vector modulation technique of V_s 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.

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

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

$$\theta_r = \arctan\frac{\phi_{r\beta}}{\phi_{r\alpha}} \tag{18}$$

SIMULATION RESULTS

Direct Torque Control Space Vector Modulation scheme for nine-level cascaded H bridge inverter controlled induction motor drive has been carried out with the help of MATLAB/Simulink power system toolbox. The simulation parameters and specifications of the induction motor drive are in the appendix. Simulation is carried out in both the motor's steady state and dynamic conditions. Figs. 6-13 show DTC-SVM results for a nine-level CHB inverter-fed induction motor drive. Fig.6 shows the voltage response of (V_a, V_b, V_c) nine-level cascaded H-bridge inverter used for induction motor drive. In steady-state analysis, the system is simulated for no-load conditions with a reference speed of 500 rpm. Responses for flux, stator current, speed, and Torque are given in Fig. 7. From Fig.7, it is observed that the system reached its set speed within 0.6 sec. Transient analysis is done for increment and decrement in load-changing conditions. In transient analysis, Torque is first incremented from 100 N-m to 250N-m at t=1 sec.

Further, at 1.5 sec, the Torque is decremented to 150 Nm. Fig. 8 shows the simulated response of stator and rotor flux, stator current, speed, and Torque response of DTC drive sudden increment in load condition. Fig.8 shows that the system (motor) speed kept constant while the required load value was within 20 msec. Fig.9 shows the simulated response of stator and rotor flux, stator current, speed, and Torque response of DTC drive sudden increment in load condition. Fig. 9 shows that the system (motor) speed remained constant while the required load value reached 20 msec.

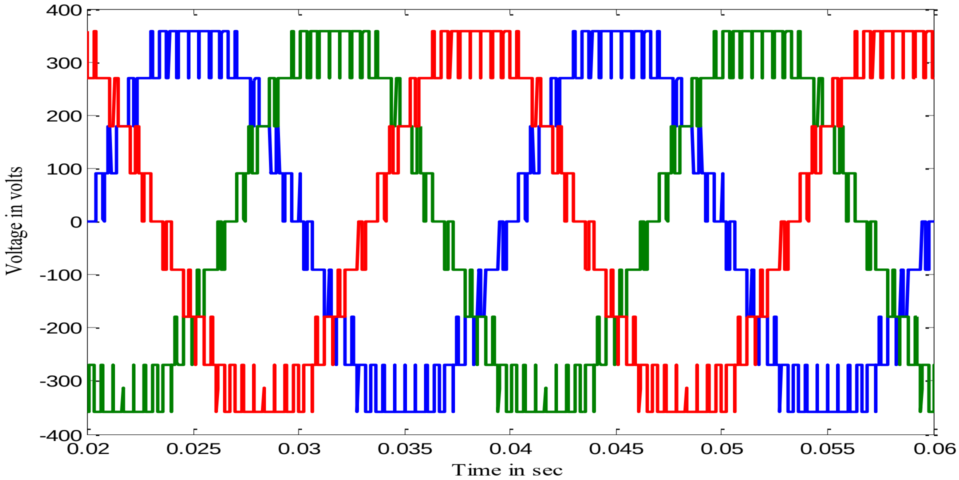

Fig. 6: Simulated voltage response of Cascaded H bridge nine-level inverter used for induction motor drive

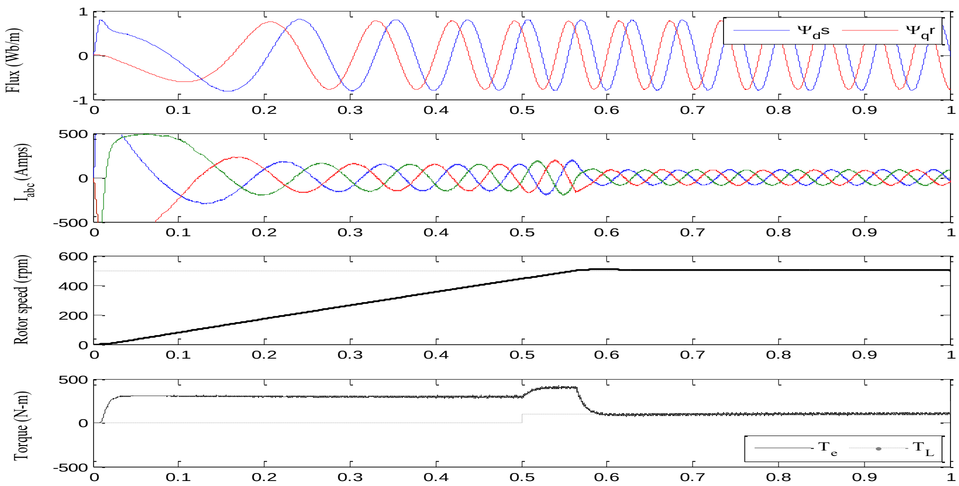

Fig.7: Simulated responses of speed, Torque, current, and flux of nine-level CHB inverter induction motor drive for steady state condition

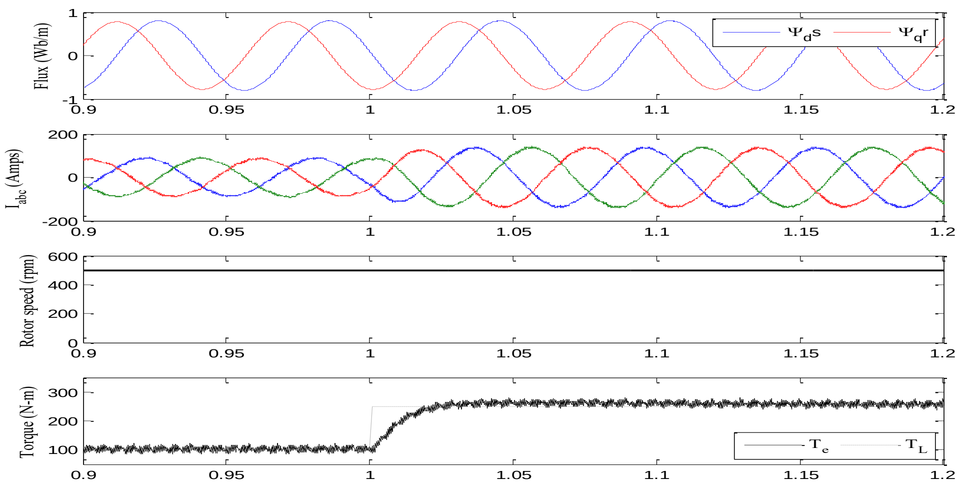

Fig. 8: Simulated responses of speed, torque, current, and flux waveforms of nine-level CHB inverter induction motor drive for increment in load

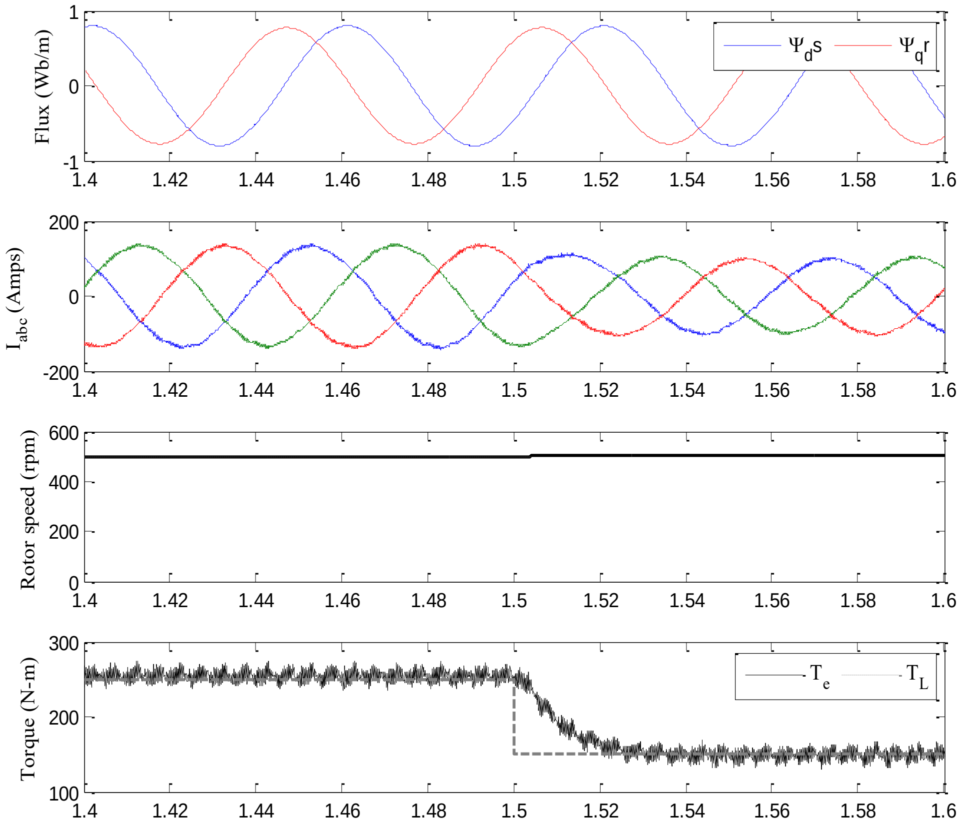

Fig. 9: Simulated responses of speed, torque, current, and flux waveforms of nine-level CHB inverter induction motor drive for decrement in load

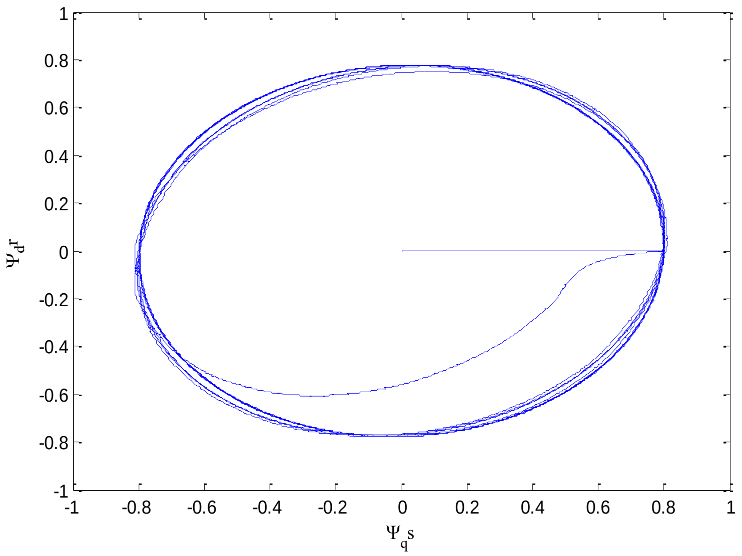

Fig: 10. Circular flux pattern of Induction motor for steady state

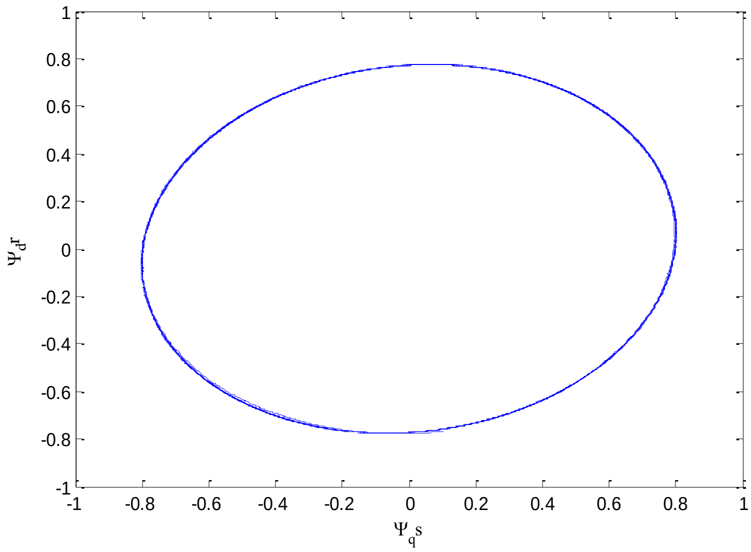

Fig.11: Circular flux pattern of Induction motor for increment in load torque

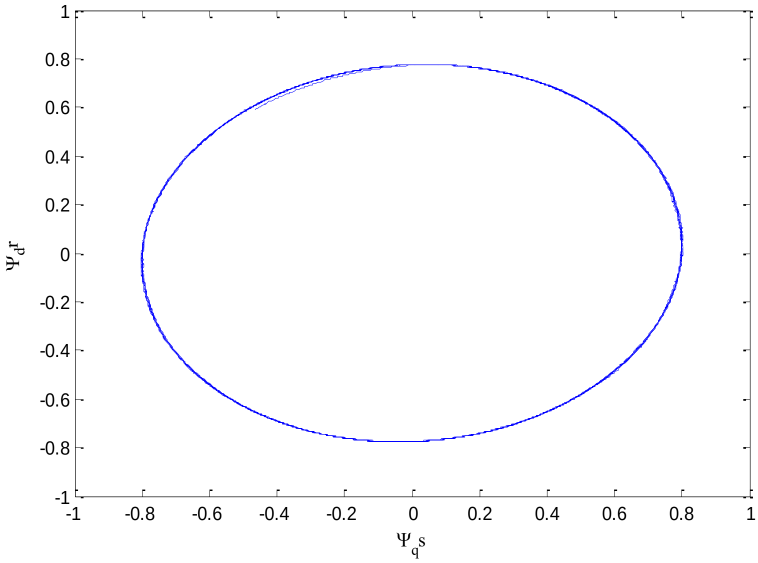

Fig.12: Circular flux pattern of Induction motor for decrement in load torque

Stator flux curves of steady state and dynamic conditions are given in Figs.10-12. Analysis is carried out for load-changing (increment and decrement) conditions. The initial stator flux response of the proposed DTC drive is shown in Fig.10, Fig.11 shows the change in flux as a result of a load increment, and Fig.12 shows a decrement in load torque, it is observed that during the load transition period, stable flux curve (circular) has produced which indirectly assures stability of nine - level cascaded H bridge inverter fed induction motor for dynamic conditions.

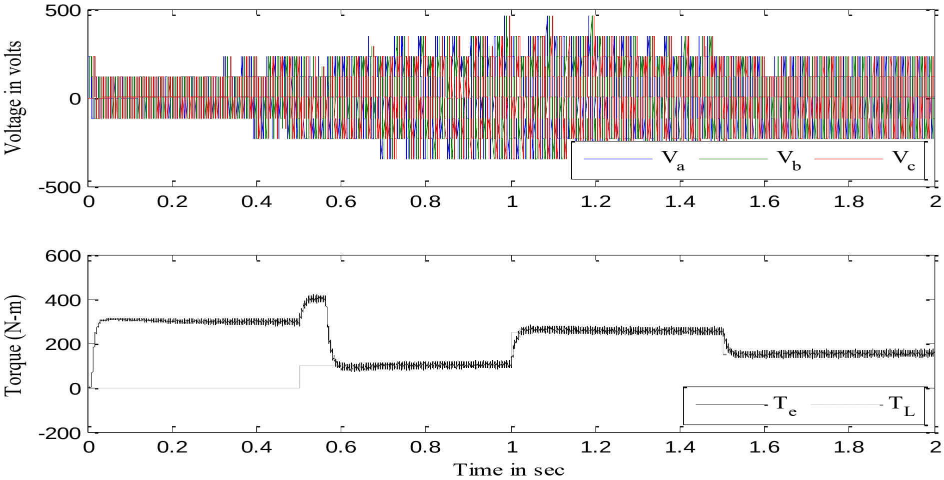

Fig.13: Simulated response of voltage level of nine-level CHB inverter during steady state and dynamic conditions

CONCLUSION

Direct torque control of an induction motor utilizing space vector modulation was chosen due to its quick dynamic torque responses and low current distortion. For any application that requires a quick torque response, the DTC was developed to provide a fast and good dynamic torque and can be viewed as an alternative to the field-oriented control FOC approach. Conclusion: The proposed control outperforms the traditional control with reduced torque ripples in transient and steady-state operation. With space vector modulation, the voltage of the cascaded H bridge's nine levels can be easily regulated to operate an induction motor drive..

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