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DTC Scheme of Cascaded H bridge Nine-Level Inverter Fed Induction Motor

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Abstract

In many applications, the capability of controlling the speed and torque effectively can improve the efficiency of the ac motors and thus lead to large savings in energy. Among the several approaches used to control ac motors, in which the Direct Torque Control (DTC), occupies an important place. DTC of ac motors is known to have very favourable control performance and implementation properties. The control scheme is based on the control of torque and flux utilizing the stator flux field orientation. DTC enables the control of speed and torque over a very broad range. This paper is an attempt to investigate and evaluate the characteristics and operating principle of DTC scheme for squirrel-cage induction motor model with cascaded H bridge multilevel inverter and fuzzy controller. Simulation results have been carried out using MATLAB/SIMULINK to validate the effectiveness and feasibilities of this controlling technique.

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

INTRODUCTION

The past few decades, the revolution of variable speed drives have lead to better quality and higher productivity in various industrial applications. Today, due to the higher cost of maintenance of dc motors and other problems in the usage of dc drives [1-2], the researchers have slowly encouraged the replacement by the ac drives in variable speed drive systems [3-4]. By using the 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 a 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 that are 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]. 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 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 [12-13]. In this paper propose 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 closed loop with estimation of the rotor flux position. MATLAB/ Simulink.

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 [14]. In this reference frame and with conventional notations (appendix), the electric mode is described by the following equations:

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

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

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

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

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

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

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

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

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

Fig.1 shows the proposed nine level cascaded H-bridge multilevel configuration for direct torque control scheme. Each H-bridge consists of 4 switches and one DC source, a total of 48 switches and 12 DC sources employed together to form a nine level three phase inverter. Anti-parallel switches in each bridge is turned on for positive and negative voltage levels. Increment or decrement in level is obtained by adding voltages together by series connection of bridges. The multilevel voltage source inverters mainly finds its application in industries such as AC power supplies. The most important advantage of a multilevel inverter is the harmonic reduction in the output waveform by keeping the switching frequency stable or decreasing the inverter power output [15]. The output voltage waveform of a multilevel inverter is composed of a number of levels of voltages, thus the multilevel starts from three level. As the number of level increases, the output Total Harmonic Distortion (THD) decreases towards zero [16].

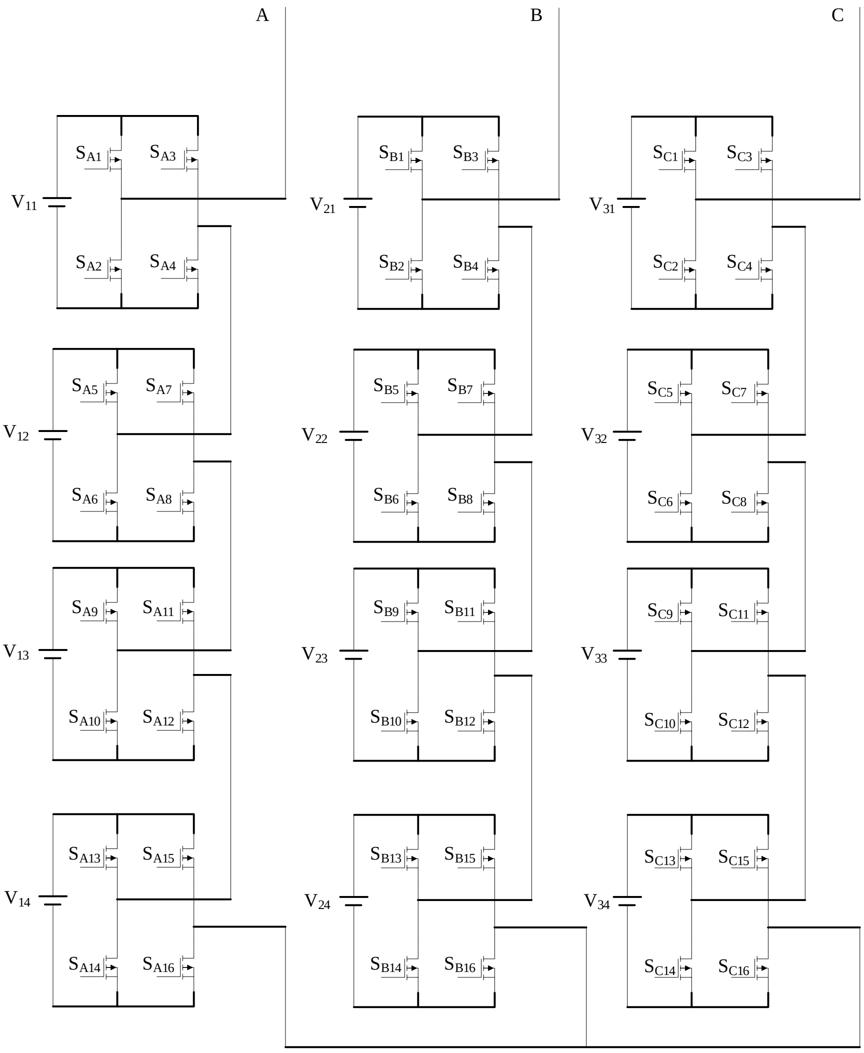


Fig.1: Schematic diagram of a nine-level cascaded H-bridge inverter

The multi-level inverters are basically classified into three topologies which are, the flying capacitor inverter, the diode clamped inverter, and the cascaded H-bridge inverter. All the topologies have the same property of reducing the harmonics [17]. The flying capacitor inverter topology is tedious to realize, because every capacitor voltage is different from the other, therefore charging becomes difficult [18]. The diode clamped inverter which is commonly known as a neutral clamped converter is not preferred because it has the problem of DC link voltage unbalancing [18]. The cascaded inverter has the disadvantage of separate DC source, but circuit layout is compact and the voltage sharing problem is absent. Hence it is easy to expand and applicable in high power motor driver and HVDC applications [17], [19].

SPACE VECTOR MODULATION OF NINE LEVEL CHB INVERTER

PWM strategies are applied to generate acceptable input and output waveforms. Different switching strategies yield distinctive performances, which may be used in industry. Several switching modulations are available for multi-level inverters. In this paper, space vector modulation (SVM) is chosen to satisfy the objectives of the design. It is very critical to analyse each of these features in order to match industry demand. The SVM switching pattern brings higher dynamic performance to the inverter. Space Vector Modulation (SVM) is one of the vector approaches to Pulse Width Modulation (PWM) technique for three phase inverter. It has the advantage of, to generate an AC signal which produces a high voltage to the motor load with lower total harmonic distortion.

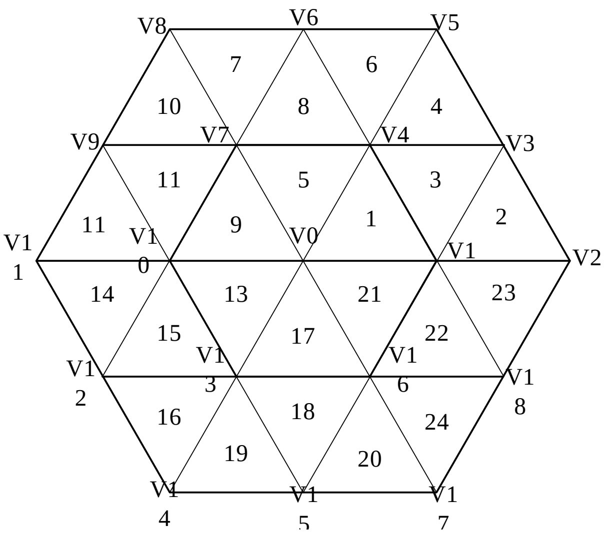


Fig.2: Cascaded H Bridge three - level inverter hexagon with 24 different triangles

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 which 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 current 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 three phase three level inverter, the voltage diagram can be divided into six (6) sectors as shown in Fig.2 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. Fig.3 shows the Cascaded H Bridge nine - level inverter hexagon for sector 1 with 64 triangles the switching sequences for proposed nine level CHB inverter is given in Table 1 [14].

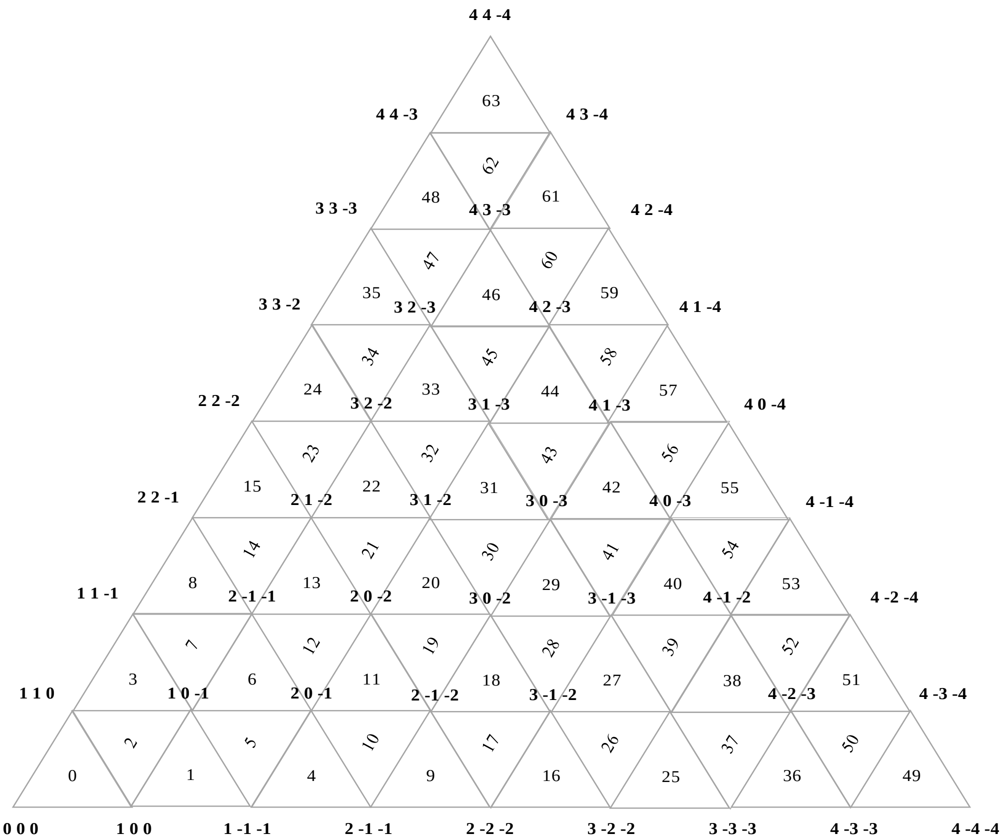


Fig.3: Cascaded H Bridge nine - level inverter hexagon for sector 1 with 64 triangles

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

$$\vec{V}_{ref}T_s = t_a\vec{v}_a + t_b\vec{v}_b + t_c\vec{v}_c \quad T_e = t_a + t_b + t_c \tag{11}$$

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 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 proposes in this paper a novel DTC scheme using space vector modulation, which is to obtain the constant switching frequency and reduced torque ripple [22-23]. A DTC-SVM with closed loop torque control can be illustrated by the control block diagram of Fig.4.

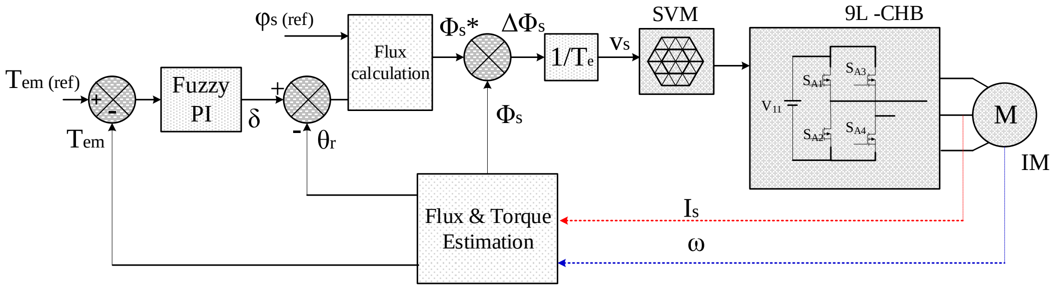


Fig.4: DTC with closed loop torque control

The objective of DTC-SVM with closed loop torque control is to select the exact stator voltage vector, V_s that change φ_s to meet the load angle reference, and so the desired torque [24]. Fuzzy-PI regulator as 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 fuzzy-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 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:

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

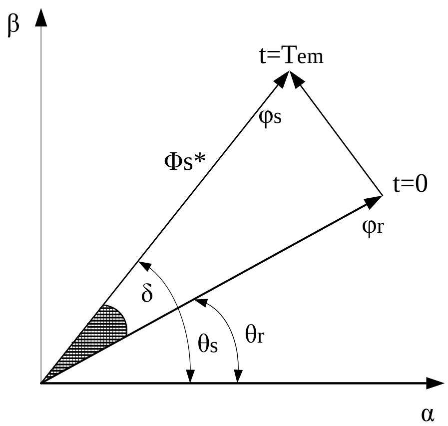


Fig.5: Flux control principle with closed loop torque control

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.

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

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

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

DTC WITH FUZZY LOGIC CONTROLLER

The employment of Fuzzy Logic Controller (FLC) in DTC has provided some improvements in torque and stator flux control and switching frequency [27]. In the literature, FLC can be either added to one part of the DTC-SVM scheme [28] or replacing the hysteresis controller and the look-up table used in DTC-LUT [29] for switching synthesization and neutral-point-voltage balance since a 3-level NPC inverter is used. As in [30], the FLC is located at the outer speed loop and some modification has been made in vector selection such as introducing 2 types of DTC with FLC algorithm in one system in order to suite it with the SVM method. Fig. 4 shows the block diagram of the DTC scheme with FLC.

As in [28], the FLC is added to both the hysteresis controller and the torque and stator flux. By using this modification, the hysteresis cycle becomes wider. It provides a more precise selection of the voltage vector, hence enhancing the performance of torque and stator flux control in a DTC and the proposed inverter. The switching state selections were done by FLC. Some modification has been made to the look-up table in order to suite it with the FLC rules. By using this scheme, the DTC performances are enhanced in terms of reducing flux and torque ripples, and harmonic distortion. Fig. 6 shows the Fuzzy membership function for speed calculation. Fig. 7 shows the Fuzzy surface of k_P and ki. Fig. 8 shows the Fuzzy membership function for theta calculation and Fig. 9 shows the Fuzzy surface for angle (theta) respectively.

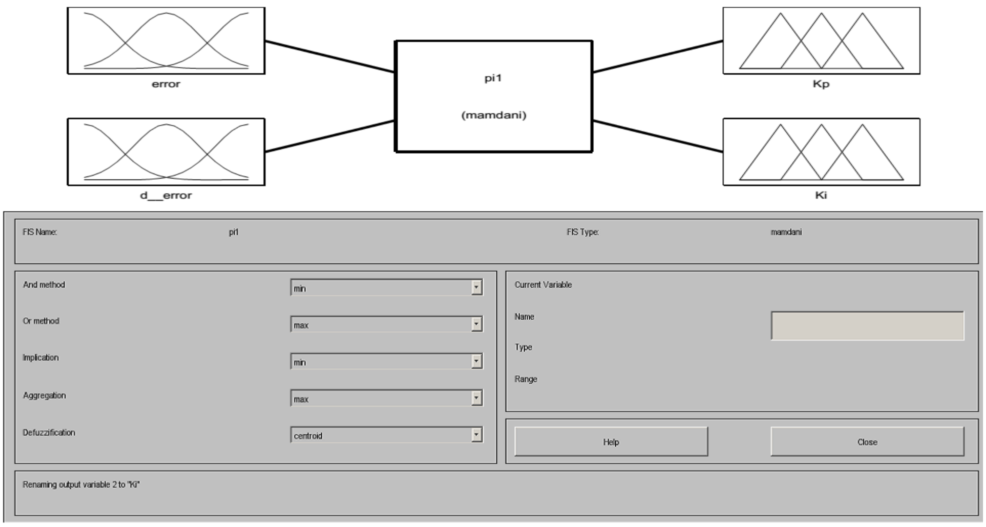
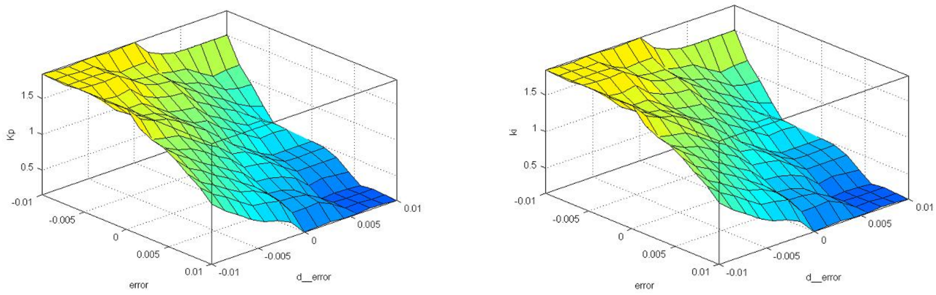


Fig.6: Fuzzy membership function for speed calculation



(a) (b)

Fig. 7: Fuzzy surface a)k_P, b)ki

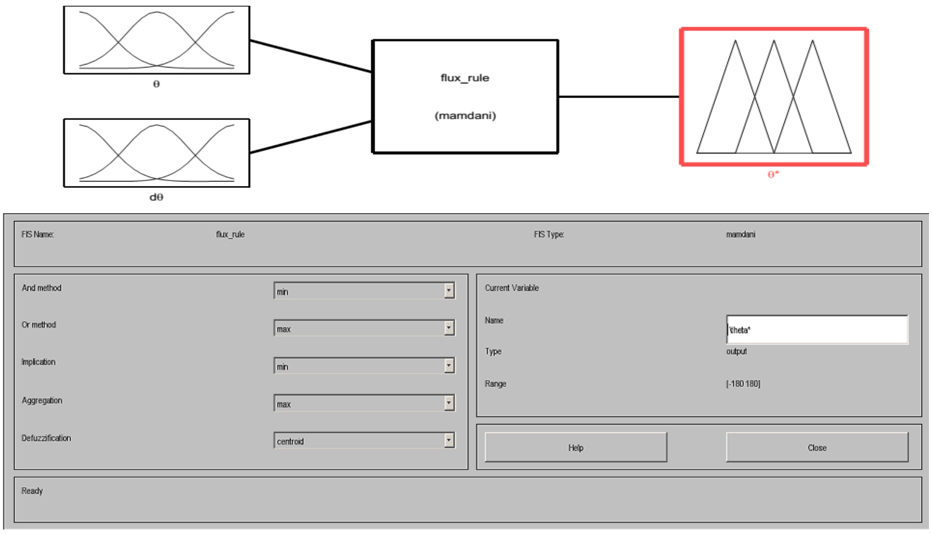


Fig.8: Fuzzy membership function for angle calculation

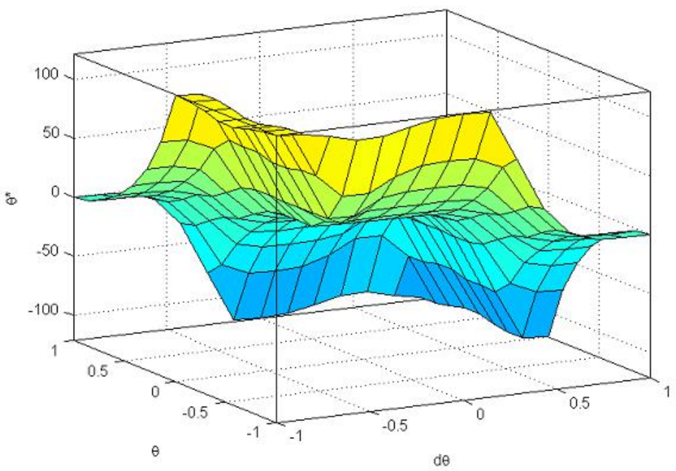


Fig. 9: Fuzzy surface for angle (theta)

Table 2 Fuzzy rule

ω/ dω	NB	NS	Z	PS	PB
NB	PB	PB	PS	PS	Z
NS	PB	PS	PS	Z	NS
Z	PS	PS	Z	NS	NS
PS	PS	Z	NS	NS	NB
PB	Z	NS	NS	NB	NB

SIMULATION RESULTS

Direct Torque Control scheme for nine-level cascaded H bridge inverter controlled induction motor drive has been carried out using fuzzy-PI controller with the help of MATLAB/ Simulink power system toolbox. 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. Figs 10-16 show the results of fuzzy-PI controlled DTC for nine level CHB inverter fed induction motor drive. Fig.10 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 condition with a reference speed of 1000 rpm. Responses for stator current, speed and torque are given in Fig.11. From Fig.11 it is observed that the motor reached its set speed within 0.3 sec. Initially the motor speed is low due to heavy torque more than 200 N-m, then the speed increased gradually and reached its set speed of 1000 rpm within 0.3 sec. similarly the torque reduced and maintained as constant at 100 N-m. Fig.12 shows the simulated speed and torque response of DTC drive sudden increment in load condition. From Fig.12 it is observed that there is a small decrement in motor speed by 600 rpm due to the sudden increment of load torque, after that it back to the reference speed of 100 rpm at 1.2 sec and the torque is kept as 150 N-m. Fig.13 shows the simulated response of stator current, speed and torque response of DTC drive sudden decrement in load condition. From Fig.13, it is observed that the motor speed is slightly reduced due to sudden change in load, again the speed reached its reference speed of 750 rpm at 2.1 sec. Similarly the torque maintained as constant by 150 N-m. Fig.14 shows the overall system responses with increment and decrement in load conditions.

Stator flux curves of steady state and dynamic conditions are given in Figs.15-16. Analysis is carried out for load changing (increment and decrement) conditions. The stator and rotor flux responses of the proposed DTC drive shown in Fig.15 and Fig.16 respectively. it is observed that during 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.

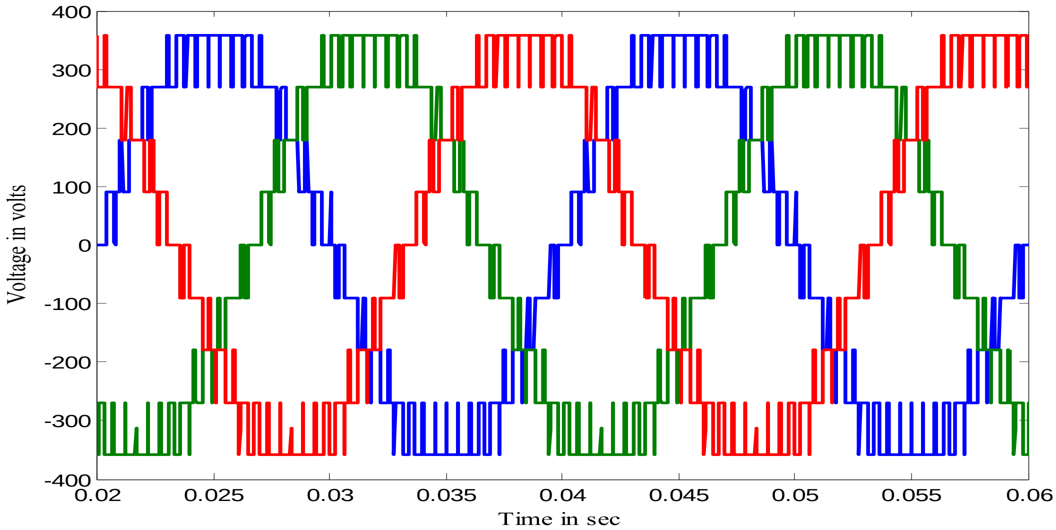


Fig. 10: Simulated voltage response of Cascaded H bridge nine-level inverter used for induction motor drive

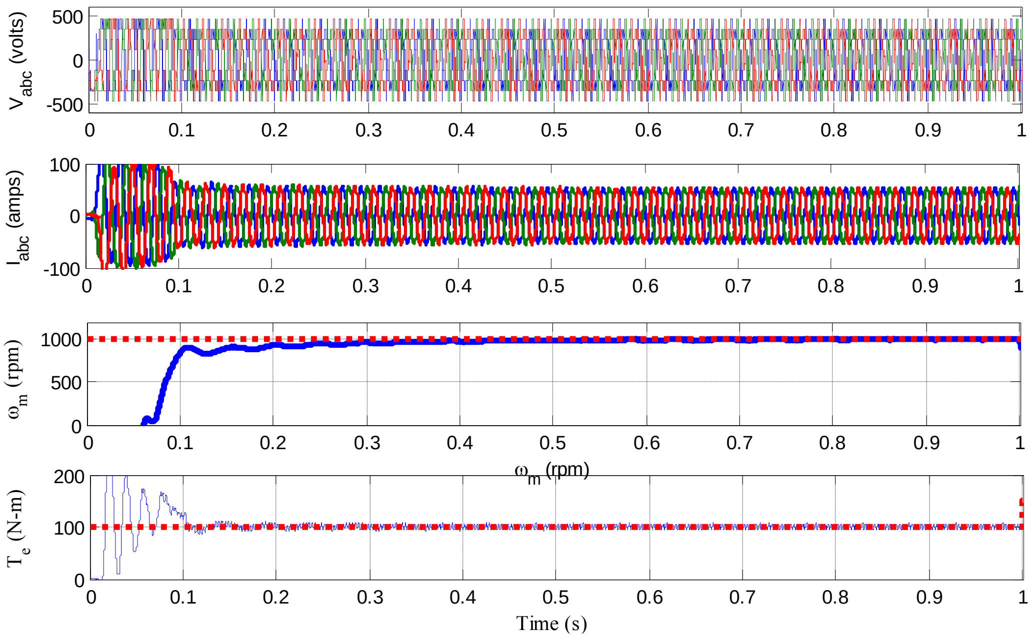


Fig.11: Simulated responses of speed, torque and current of nine-level CHB inverter induction motor drive for steady state condition

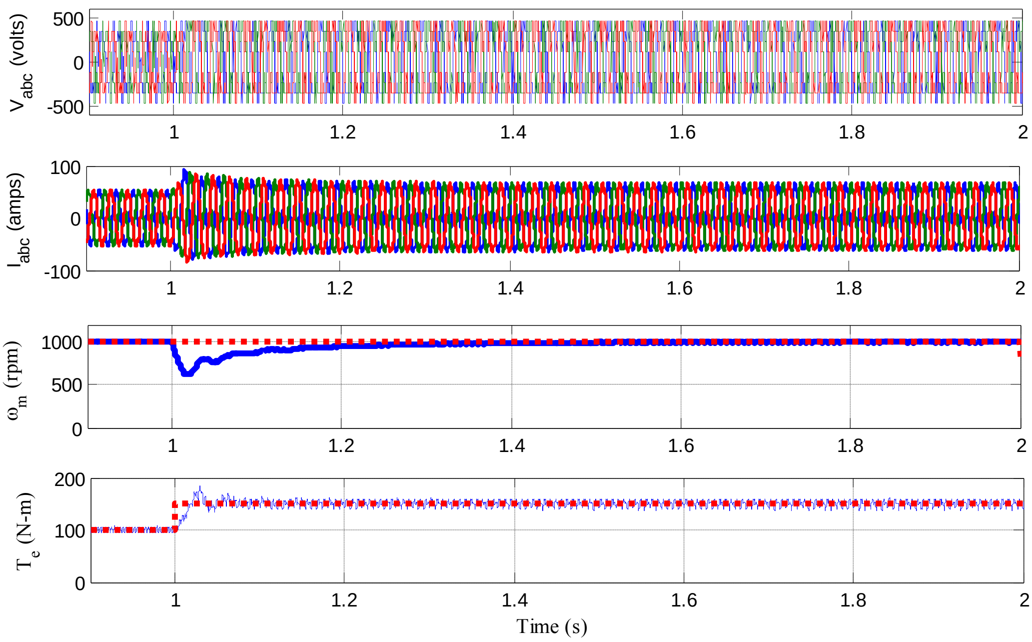


Fig. 12: Simulated responses of speed, torque and current waveforms of nine-level CHB inverter induction motor drive for increment in load

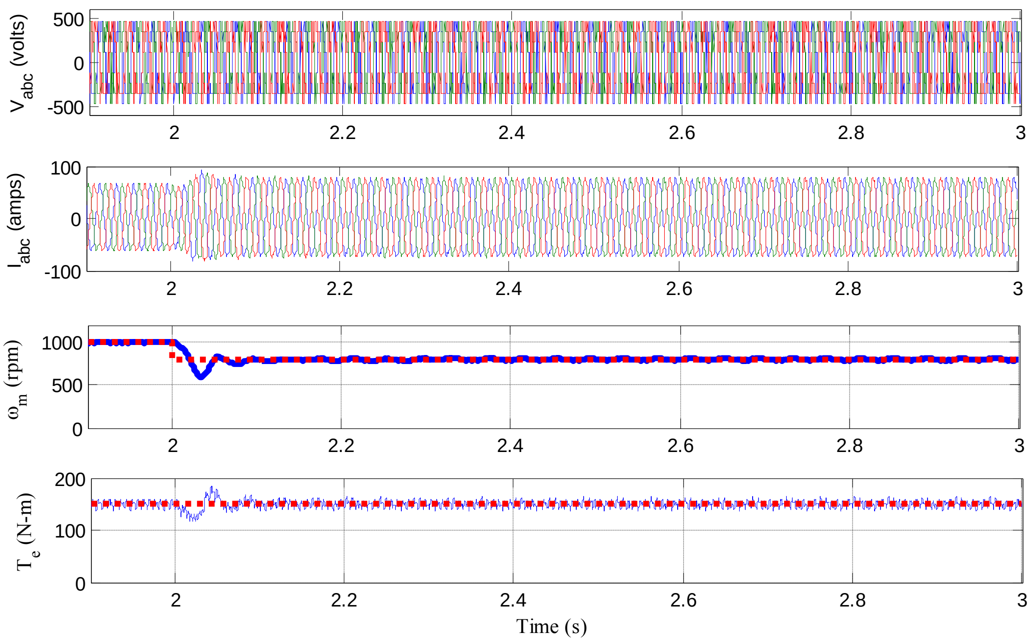


Fig. 13: Simulated responses of speed, torque and current waveforms of nine-level CHB inverter induction motor drive for decrement in load

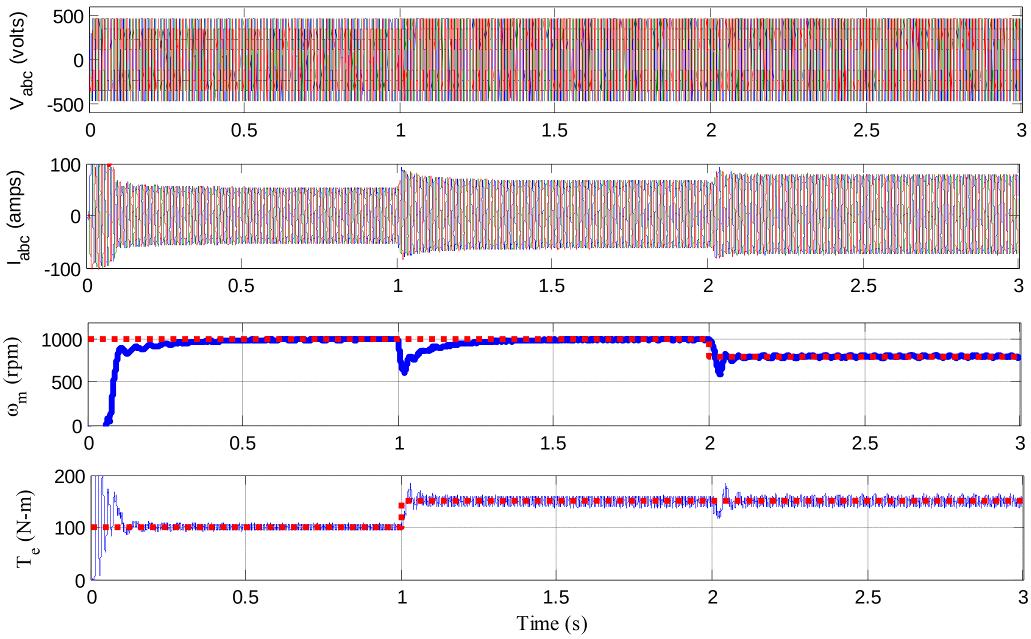


Fig.14: Overall simulated responses of nine-level CHB inverter during steady state and dynamic conditions

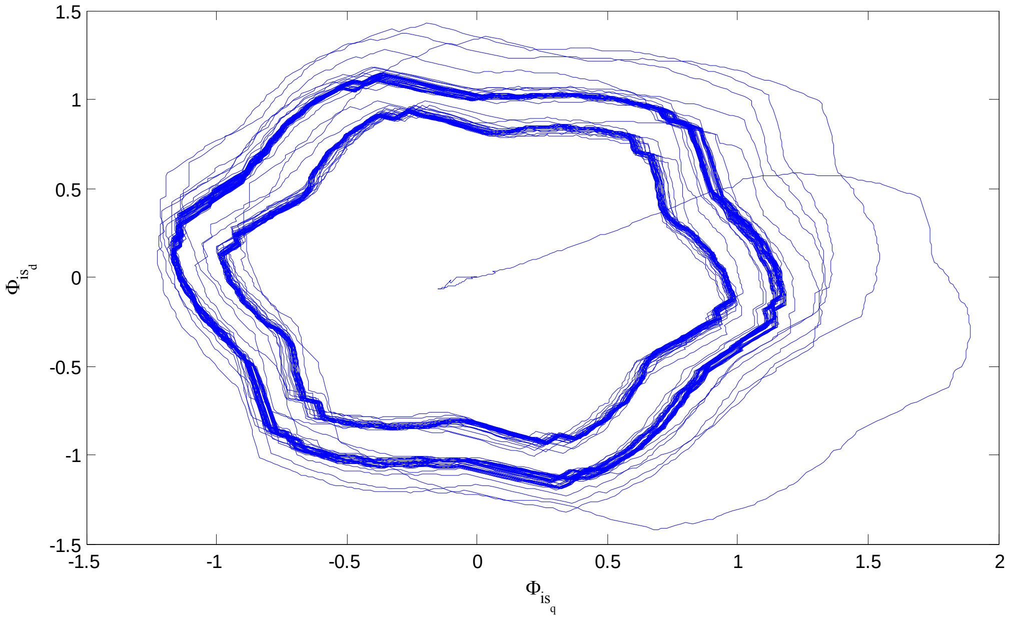


Fig.15: Circular stator flux pattern of Induction motor

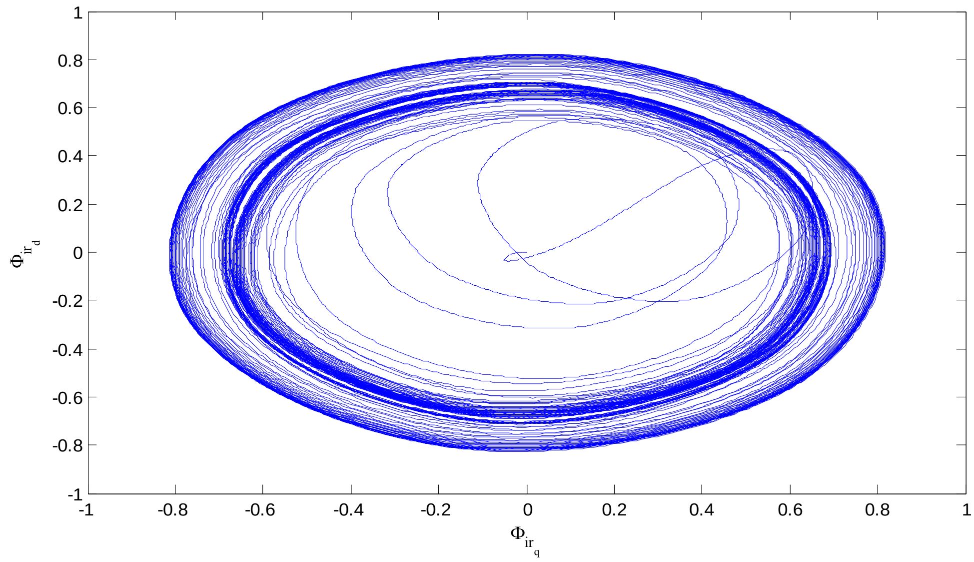


Fig.16: Circular rotor flux pattern of Induction motor

CONCLUSION

Direct torque control of induction motor using fuzzy-PI controller with space vector modulation was chosen for its low current distortion due its fast dynamic torque responses. The DTC was introduced to give a fast and a 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 than the conventional control with less torque ripples. The cascaded H bridge nine-level inverter voltage can be easily controlled with the help of fuzzy-PI controlled operation of induction motor drive.

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APPENDIX

Induction Motor Parameters

Rated power	: 75 kW
Rated voltage	: 400V
Rated speed	: 1000 rpm
Rated frequency	: 50 Hz
Stator Resistance	: 0.03552 Ω
Stator Inductance	: 0.00335 H
Rotor Resistance	: 0.02092 Ω
Rotor Inductance	: 0.000335 H
Mutual Inductance	: 0.0151H
Rotor inertia	: 1.25 Kg/m^2
No of poles	: 2
Friction factor (F)	: 0.03914 (N-m/s)

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