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A Novel Method of Using Direct Torque Control in Bipolar Stepper Motor

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Abstract— Stepper motors are widely used in motion control application, they offer highly precise motion and could be controlled directly with digital pulses and required lesser computation, driver circuitry. The stepper motors are used to offer stepped motion and hence the efficiency is considerably low. As technology advanced the complexities and cost involved in the drivers and computational difficulties were reduced through the developments in power electronics and digital signal processing. Hence in most applications the stepper motors are being replaced by Permanent Magnet Synchronous Motor (PMSM) and Brushless DC motor (BLDC).

This paper proposes a method of applying Direct Torque Control (DTC) used in PMSM for bipolar stepper motor by providing three phase sinusoidal rotating magnetic field. The advantage of the stepper motor is that they have larger number of poles in the rotor hence the synchronous speed of the machine will be low thereby improving the performance and precision of the machine while being used for servo applications. The DTC strategy for stepper motor is relatively simpler and offers better performance when compared to the conventional methods and hence it would be suitable for motion controls in robotic systems where varying velocity and acceleration functions are often encountered. The simulation of Direct Torque Control of stepper motor was done in Matlab/Simulink environment. The concept was observed to be feasible and efficient in the simulation, and it was realized in a two phase bipolar stepper motor using DSPIC30F3011.

Index Terms— Direct Torque Control, Stepper Motor, Permanent Magnet Synchronous Motor

1 Introduction

Nowadays AC motors are replacing DC motors in many industrial applications. Particularly Induction motors are gaining popularity due to their robustness, low maintenance and increased life span. As the induction motor cannot run at synchronous speed any variation in load torque will result in variation in speed. Therefore induction motors are not suitable for precise position control application. Whereas the speed of synchronous motor is equal to the speed of rotating magnetic field produced by stator, hence the name synchronous motors, and speed control is easily achieved by varying the frequency of the applied voltage. Among various types of synchronous motors, Permanent magnet synchronous motor (PMSM) is an automatic choice for robotic and automated systems in the industries because of its performance advantages like are high torque to inertia ratio, high efficiency, high power density, rapid torque response etc.

However, the major problems that are associated with PMSMs, especially when used for servo application, are high investment cost and relatively low precision. In early days Stepper motors were widely used for positioning application since they have characteristics such as low inertia, large torque, does not require any feedback-loop, instant start and rapid stop. Also, the control system and driver circuitry of stepper motors are very simple and are available in cheap rate. Typical applications of stepper motors include positioning in machine-tools, antennae and robotic system. Since they were operated in open loop system stepper motors have their specific problems like dynamic instability, low frequency oscillations at high speeds near the synchronous frequency, low efficiency due to stepped motion etc. To overcome these shortcomings of open –loop system, lot of research is done towards developing a closed-loop system with a suitable control strategy. This paper proposes a method of applying Direct Torque Control (DTC) in bipolar stepper motor by providing sinusoidal rotating magnetic field at the stator which employs a closed loop operation. This will result as a superior control strategy when compared to the conventional strategies like micro-stepping, half stepping and full stepping that used for stepper motors.

Rest of this paper is organized as follows: first we give a short overview about the concept of the proposed work, followed by the basics of stepper motors and its control strategies, variable frequency control of synchronous motors. Then we discuss the application of DTC for bipolar stepper motor along with its simulation in Matlab/Simulink, its implementation in hardware, experimental results. Finally we conclude with a short discussion on the proposed work

2 Concept

Stepper motor have similar construction to that of PMSM except for the non-uniform air gap caused by the teethed construction of the stator core and the Permanent Magnet rotor; stepper motor is salient type and PMSM is non

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salient type. Also number of poles in the rotor is more in stepper motor than in PMSM this will result in lower synchronous speed and accurate positioning of rotor is possible. The estimated position of the rotor will be much closer to that of the actual value and the chances of slip are considerably low. When stator windings of a stepper motor are excited with sinusoidal supply using a conventional H-bridge inverter, the rotating magnetic field is produced which will make the machine to operate with reduced torque ripples. Since the machine is operating in continuous time, the machine can be modeled and the various control strategies used in the PMSMs can also be applied on the stepper motor.

The Direct Torque Control algorithm assumes that the rotor flux of the machine remains a constant and the torque can be controlled directly by controlling the stator voltage. The DTC strategy is relatively simpler and offer better performance when compared to the conventional methods and hence it would be suitable for motion controls in robotic systems where varying velocity and acceleration functions are often encountered. By the application of the proposed strategy we will be able to reduce the constructional complexity as well.

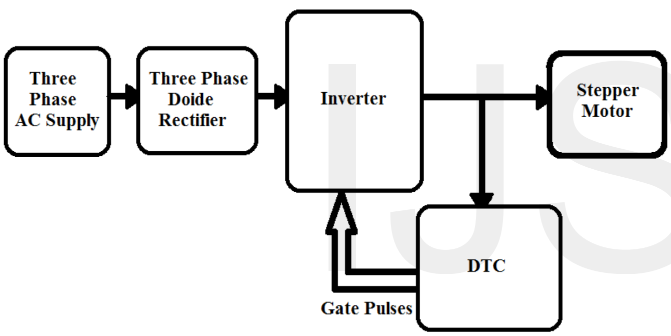

Figure 2.1: Block Diagram of the Concept

3 Stepper Motor and its Control Strategies

Stepper motor is a doubly salient AC synchronous motor. It can be considered as an electromechanical device which converts digital electrical pulses into discrete step of shaft rotation. Stepper motors are generally operated as open loop systems without any feedback. Also, they are low speed- low power devices. Electrical pulse input is directly fed to the stator windings of the stepper motor through a controller which energizes corresponding phases with DC currents and thereby constituting a stepped motion. Rotor is the only moving part which has got no commutator or brushes and these characteristics make the motor quite reliable and robust. As the step angle, number of poles and resolution (number of steps per revolution) of the motor increases the precise position control become much easier.

Basically there are two types of classification for stepper motors; one is based on the construction and other is based on the winding arrangements. Constructionally there are three types of Stepper motors; Variable reluctance Stepper motor, Permanent magnet Stepper motor and Hybrid Stepper motor (Figure 3.1). Based on the winding arrangements there are two types of Stepper motors; Unipolar and Bipolar (shown in figure 3.2).

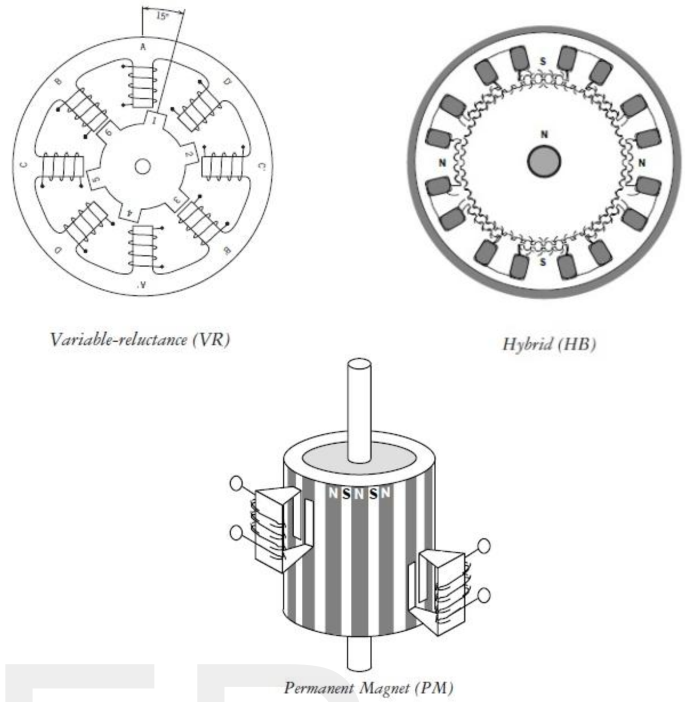

Figure 3.1: Stepper motor Types

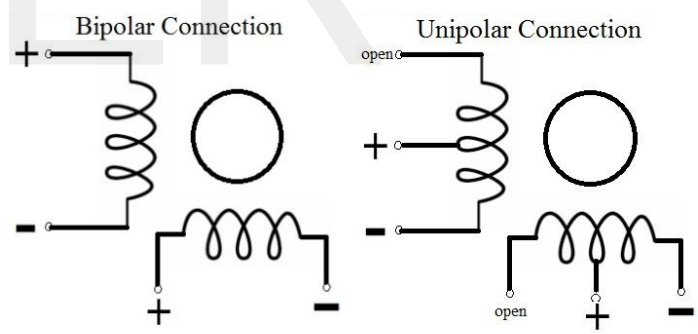

Figure 3.2: Bipolar and Unipolar Connection

Conventionally all types of stepper motors are operated in four modes; they are single phase on mode, Two Phase on mode, Half Stepping and Micro-stepping.

Single Phase on mode (Wave Drive): In this mode only one phase of the motor is excited at a time. Electromagnetic torque developed is much less when compared to other modes of operation. It's is highly unstable at higher speeds. Power consumption is very low and is rarely used.
Two Phase on mode (Full Stepping): In this mode two phase of the motor are excited simultaneously so that the motor will provide its maximum rated torque. Step angle is reduced when compared to Wave drive mode.
Half Stepping: In this mode the motor is operated alternative-

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ly in single phase on mode and two phase on mode so that the rotor advances in half the full step angle. Developed torque is more and is most stable mode operation at higher speeds.

Microstepping: In this mode of operation two phases are energized simultaneously but current distribution is made unequal deliberately. In a two phase stepper motor the current in one phase (say Phase A) is made constant while that in the other phase (say Phase B) is increased in small increments until the maximum current is reached. Then current in Phase A is reduced to zero in very small steps [5]. Thus current in phases A and B are increased and decreased just like a sinusoidal wave (shown in Figure 3.3).

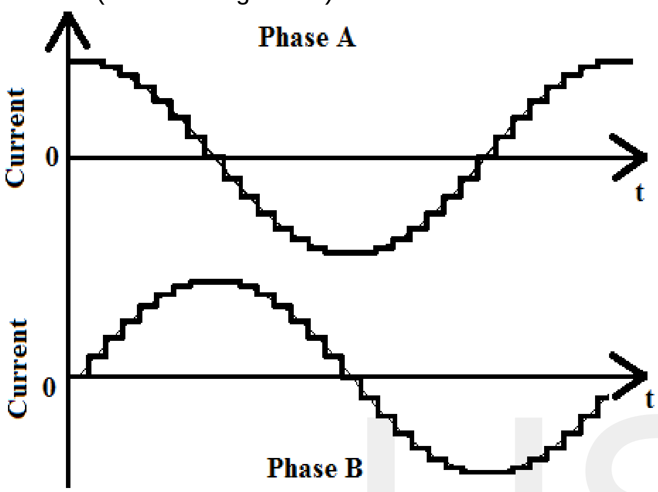

Figure 3.3: Phase Currents in Microstepping Mode

The following Figure 3.4 shows all the operating modes of stepper motor.

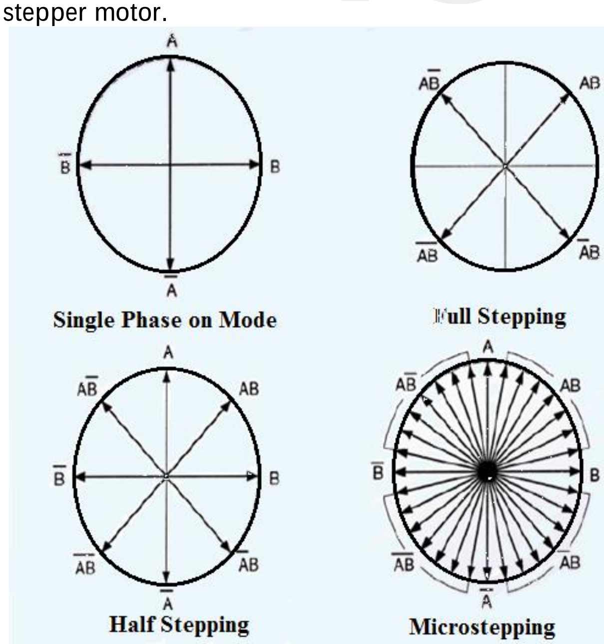

Figure.3.4: Stepper Motor Control Strategies

4 Variable Frequency Contro of Synchroous Motors

As discussed earlier, if it is possible to operate Stepper Motor in continuous time mode, the machine can be modeled and the various control strategies used in the PMSMs or Synchronous motors can also be applied on the stepper motor. Figure 4.1 shows the variable frequency control of AC Synchronous motors in general.

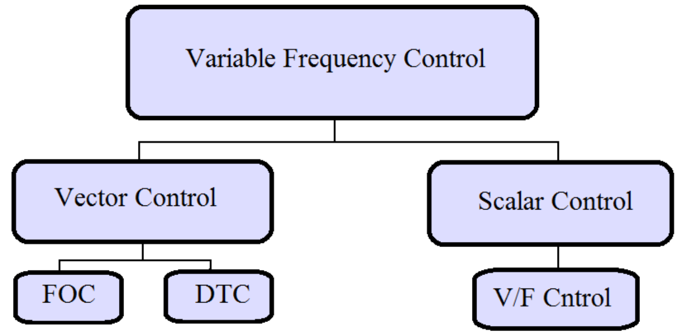

Figure 4.1: Variable Frequency Control

V/F control (Open Loop Control): In open loop control method the ratio of voltage to frequency is kept constant (made equal to one) to maintain the stator flux and motor torque constant at its nominal value at the base speed range. If the V/F ratio is greater than one, the magnetizing flux increases which inturn increases the magnetizing current and this will create additional heating in the stator coils. And if V/F ratio is less than one magnetizing flux decreased, and hence the magnetizing current decreased and the motor will unable to develop the required amount of torque. Eventhough v/f control is the simplest speed control method of Synchronous Motors, as it is an open loop control which does not use any feedback loop; its performance is inferior compared to the vector control methods.

Field Oriented Control (FOC): The vector control is based on the isolation of flux channel (the flux producing component) and torque channel (the torque producing component) from the stator current so that the flux and torque can be controlled independently as in the case of separately excited dc motor. The principle of FOC can be briefly explained as follows: by controlling the inverter switching it is possible to control the magnitude and phase of stator current so that the flux producing component of stator current is aligned along the rotor flux linking vector (phasor diagram1 figure 4.2). This is maintained at all operating condition and hence it is called Field oriented control. In FOC the motor speed control is comprised of two inner current controllers (flux and torque) and one outer speed controller (Figure 4.3). Limitations of FOC are listed below.

- Back EMF flux saturation
- Temperature effect on the magnet
- Torque response under current control is limited by the time constant of the armature
- Dependence on the motor parameters

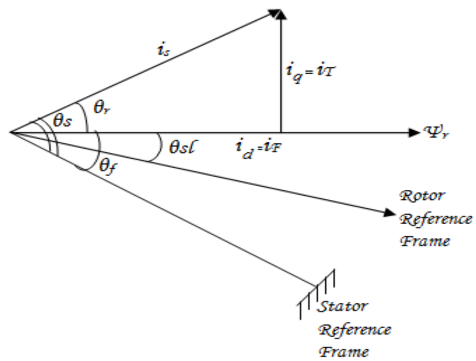

Figure 4.2: Phasor Diagram 1

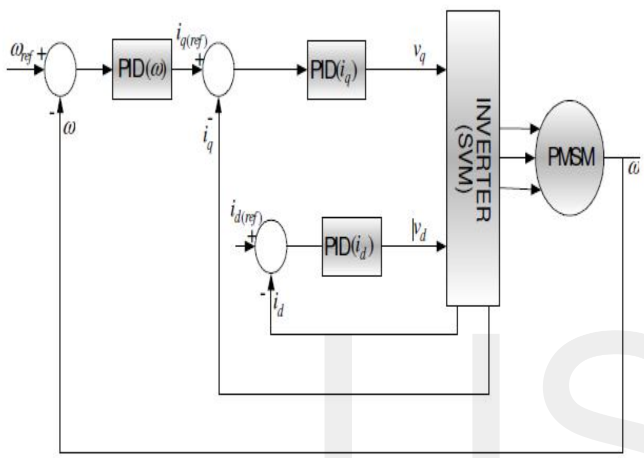

Figure 4.3: FOC Block Diagram

Direct Torque control (DTC): Direct torque control is simple and robust control scheme capable of giving excellent performance. Direct Torque Control (DTC) is also known as Direct Torque and Flux Control (DTFC). It was introduced in 1985-1986 by two German engineers Dr. Blashke and Mr. Depenbrock and was initially applied for induction motors. Later it was made popular by ABB [7].

Features and Benefits of DTC Scheme:

- Control Variables are torque and Stator Flux.
- Quick torque response (a typical torque response time is 1 to 2 ms below 40 Hz)
- Accurate torque control at low frequencies.
- Variable Switching Frequency
- Full load torque at zero speed without any feedback.
- It can provide 1 to 2 percent torque repeatability of the nominal torque across the speed range.
- Torque is linear across the speed range.
- Static and dynamic speed accuracy is more.
- Switching control signals are generated by Hysteresis controller. Traditional PWM controller is not required.
- Current control is not required.
- Less switching loss and higher efficiency.
- Coordinated Transformation is not required
- Steady State Torque Ripple is Low.
- Independent of motor parameter variation.
- Simple Computation/Processin

Principle of DTC: General torque expression with stator and rotor fluxes is given by:

$$T_e = \frac{3}{2}\frac{P}{2}(i_{qs}\psi_{ds} - i_{ds}\psi_{ds}) = \frac{3}{2}\frac{P}{2} i_s \times \psi_s \qquad (4.1)$$

$$i_s = i_{qs} - j i_{ds} \quad \text{And} \quad \psi_s = \psi_{qs} - j\psi_{ds} \qquad (4.2)$$

Where,
ψ_{ds} is the direct axis component of stator flux
T_e is the Electromagnetic Torque
ψ_{qs} is the quadrature axis component of stator flux
i_s is the stator current
ψ_s is the stator flux
i_{ds} is the direct axis component of stator current
i_{qs} is the quadrature axis component of stator current
P is the number of poles

Replacing the stator current vector with rotor ψ_r flux vector

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_s L_r - L_m^{\ 2}}[\psi_{dr}\psi_{qs} - \psi_{qr}\psi_{ds}] \qquad (4.3)$$

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{\sigma L_s L_r}\psi_r \psi_s \sin\delta \qquad (4.4)$$

Where,
L_s is the stator inductance
L_r is the rotor inductance
L_m is the mutual inductance
δ is the load angle or the angle between stator and rotor fluxes
θ is the rotor flux angle
$<\psi_s$ is the stator flux angle

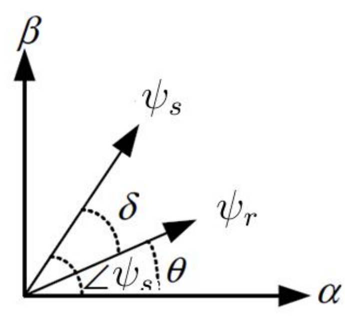

Figure 4.4: Phasor Diagram 2

The basic principle of DTC can be explain using equation 4 and Figure 4.4; if the rotor flux remains constant, the electromagnetic torque can be varied by varying the supply voltage which changes the stator flux and it will finally result in a change in load angle also. ie, electromagnetic torque can

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be directly controlled from the supply end and hence the name Direct Torque Control [7].

5 DTC of Biploar Stepper motor

The basic model of the DTC scheme for stepper motor is shown in Figure 5.1. It consists of torque and stator flux estimators, speed controller, torque and flux hysteresis comparators, a switching table and a voltage source inverter (VSI). Figure 5.2 shows the detailed diagram of DTC for Stepper Motor.

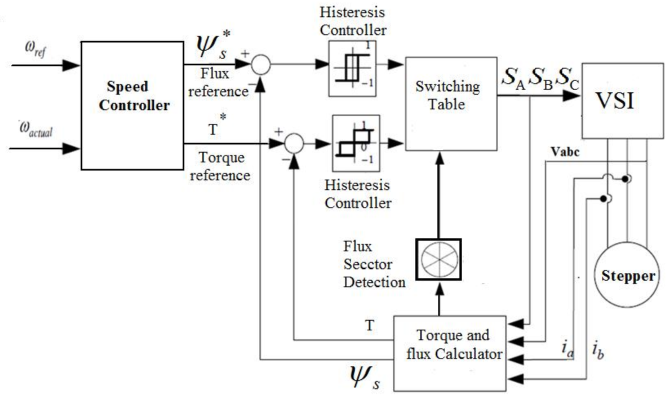

Figure 5.1: Direct Torque Control

Speed controller: The speed controller block consists of a PID controller. The external speed reference signal is compared to the actual speed produced in the motor model. The error signal is then fed to both the PID controller. The outputs of the speed controller are reference signals of flux and torque.

Flux and Torque calculator: Terminal voltages and currents are sensed and given to the Flux and Torque Calculator. These three phase variables are transformed into dq axes variables. Then stator flux and torque are given by the following equations.

$$\psi_{ds} = \int (v_{ds} - R_{ss} i_{ds}) dt \quad (5.1)$$

$$\psi_{qs} = \int (v_{qs} - R_{ss} i_{qs}) dt \quad (5.2)$$

$$\psi_s = \sqrt{(\psi_{ds}^2 + \psi_{qs}^2)} \quad (5.3)$$

$$< \psi_s = \tan^{-1}\left(\frac{\psi_{ds}}{\psi_{qs}}\right) \quad (5.4)$$

$$T_e = \frac{3}{2}\frac{P}{2}(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}) \quad (5.5)$$

Where,
V_{ds} is the direct axis component of stator voltage
V_{qs} is the quadrature axis component of stator voltage
R_{ss} is the resistance of stepper motor referred to stator

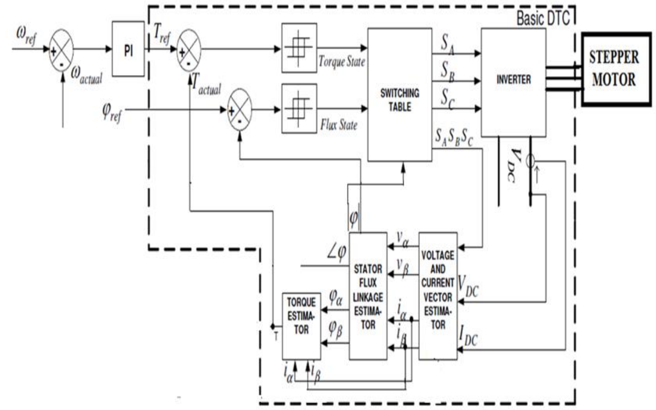

Figure 5.2: Torque Control of Stepper motor

Hysteresis Controllers: Hysteresis Controllers are used to generate switching patters for the inverter. The advantages of hysteresis controllers are:

- Quick current controllability
- Easy implementation
- Unconditioned stability
- Provides excellent dynamic control
- Fastest control with minimum hardware

Flux Hysteresis Controller: Flux Hysteresis Controller is basically a two level Hysteresis Controller. It will has two levels of digital outputs according to the following relations.
where $2HB_\psi$ is the total hysteresis band width of the flux controller.

Condition	Output(H_ψ)
$E_\psi > HB_\psi$	1
$E_\psi < -HB_\psi$	-1

Table 1

Torque Hysteresis Controller: Torque Hysteresis Controller is basically a three level Hysteresis Controller. It will have three levels of digital outputs according to the following relations.

Condition	Output(H_{Te})
$E_\psi > HB_\psi$	1
$E_\psi < -HB_\psi$	-1
$-HB_\psi < E_\psi < HB_\psi$	0

Table 2

Switching table and voltage vectors:

The flux and torque estimator calculates the actual values of flux, torque and angle of stator flux that indicates the sector number in which the flux vector lies. Hence it generates the appropriate control voltage vector for the inverter which affect magnitude and direction of both the torque and flux simultaneously. The zero vectors (V0, V7) short circuit the machine terminals and keep the flux and torque unaltered. The

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drive can easily operate in the four quadrants, and speed loop and field weakening control can be desired. The torque response of the drive is claimed to be comparable with that of a FOC controlled drive.

The switching table receives the inputs from flux hysteresis controller, torque hysteresis controller and sector number and generates voltage vector for the inverter by the lookup table. The inverter voltage vectors (six active and two zero states) and typical stator flux are shown in Figure 5.3. Neglecting the stator resistance R_{ss} of the machine, we can write

$$V_s = \frac{d}{dt}(\psi_s) \quad (5.1)$$

$$\Delta\psi_s = V_s \Delta t \quad (5.2)$$

The above equation shows that ψ_s can be changed by applying stator voltage vector V_s for time increment Δt.

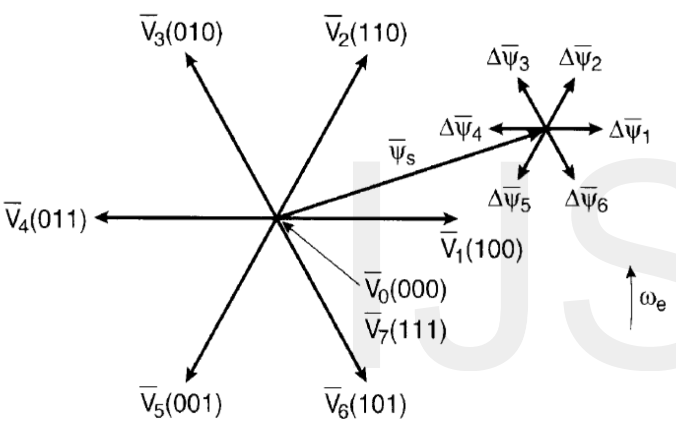

Figure 5.3: Voltage Vectors

6 SIMULATION

The following Figure 6.1 shows the block schematic of simulation of Direct Torque Control of Bipolar Stepper Motor using Mtalab/Simulink.

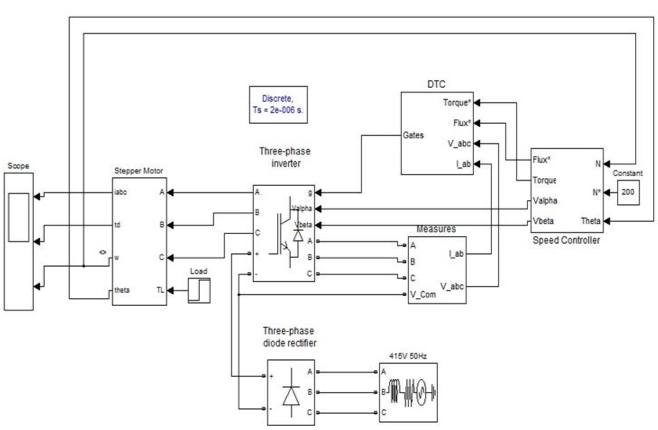

Figure 6.1: Simulation Diagram

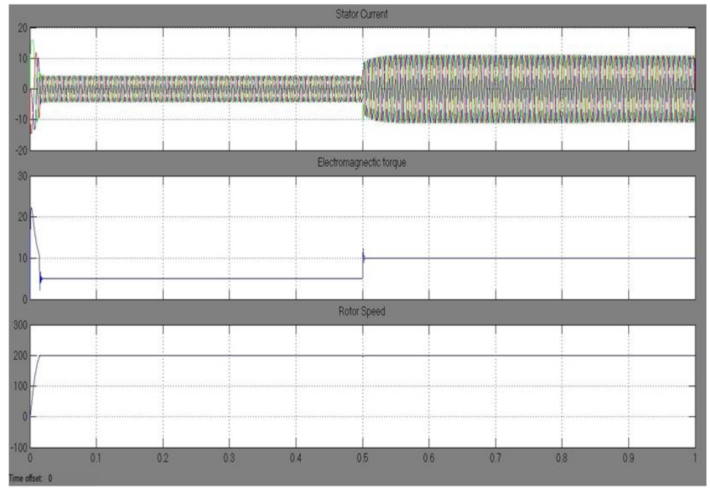

Figure 6.2: Stator Current, T_e, and Speed

The above Figure 6.2 represents the Simulation Result of DTC controlled Stepper Motor. The figure shows the variation of Stator current, Electromagnetic Torque and Speed with respect to time.

In order to achieve steady state performance, the machine needs to undergo transients initially. These transients will appear as pulsation in torque and speed at the time of starting. The transient period will depend upon the mechanical time constant and electrical time constant of the machine which inturn depends on the moment of inertia, friction and motor parameters.

The speed reference given here is 200 rpm and from the simulation it is observed that the actual speed settles to 200 rpm after time 0.02 seconds. The torque waveform is also found to settle to the reference value 5 Nm as the speed reaches 200 rpm. After 0.5 sec load torque changes its value to 10Nm, there is a small dip in the speed curve, but the machine quickly regains its normal speed. As the load torque increases stator current magnitude also increases. From the phase current waveforms we can observe, that the current is sinusoidal in all the three phases after time 0.02 seconds.

7 EXPERIMENTAL SETUP

The Figure 7.1 shows the Block schematic of the Hardware using Motor Controller dspic30f3011, Motor Driver IC L298N. Power Supply required for setting up the Hardware is 24V, 12V, 5V. The stator windings of the two phase bipolar stepper motor are connected to the motor driver IC L289N using six freewheeling diodes (D1-D6).

The motor controller dspic30f3011 is a high performance 16- bit microcontroller specifically designed for motor control applications.

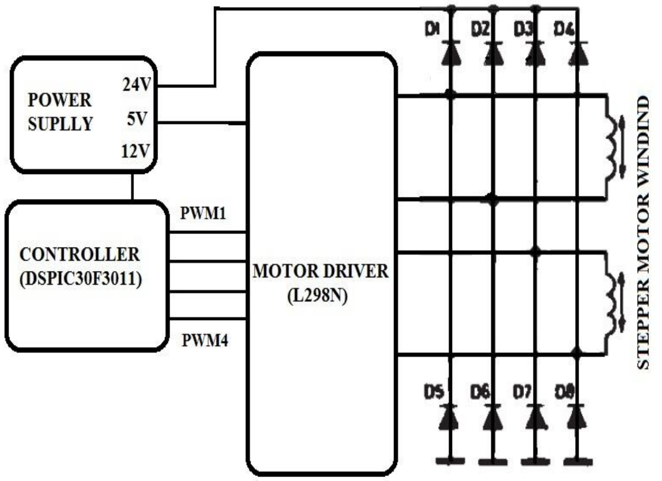

Figure 7.1: Hardware Block Diagram

The important criteria that led to the selection of this particular IC are:
(i) It has got six dedicated pins for motor control PWM outputs
(ii) Separate engine to execute motor control algorithms
(iii) It is easily available.
L298N is a 15 pin motor driver IC which is conventionally used to drive relays, solenoids, DC motors and stepper motors. It's a high current, high voltage dual full bridge driver. Operating voltage of L298N is in the range of 4-35V.

The following Figure 7.2 shows the experimental setup of the proposed system. The Stepper Motor used here is a Two Phase Hybrid motor. Each of the two stator windings of the stepper motor has three tappings, which indicate that the motor can be used both as bipolar and unipolar. In bipolar connection, bidirectional current flows through the entire winding and in unipolar connection a center tap is added between the two leads and unidirectional current flows in each half of the winding.

Specification of Stepper Motor Used: Minebea-17PM-K 1.8 HYBRID

- Step Angle... 1.8
- Step Angle Accuracy.......................... +/-5%
- Rated Voltage (V)................................ 4.40
- Rated current/phase (A)...................... 0.8
- Winding Resistance/phase (ohm)....... 5.50

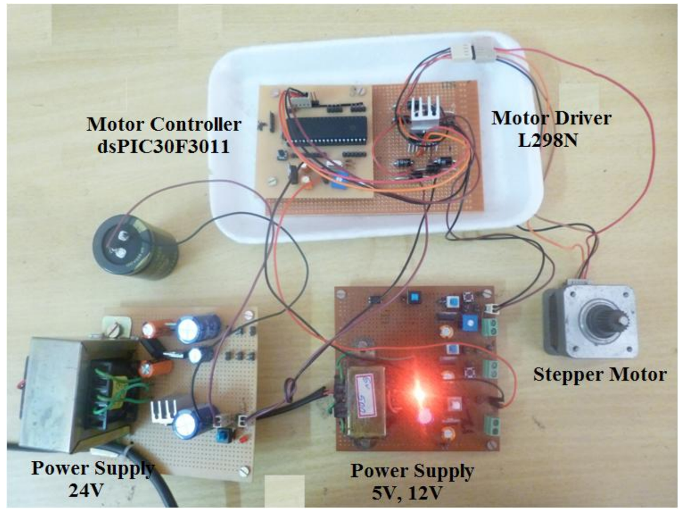

Figure 7.2: Experimental Setup

Experimental Results: When Sinusoidal pulse width modulated waveforms, phase shifted by 90 degree (shown in Figure 7.3), was generated and given to motor driver IC, smooth and continuous rotation of the motor was observed with reduced vibrations. Input current drawn by the motor is 0.4A in the steady state when compared to conventional full stepping methods which consumes around 0.6A. The input power consumed by the drive is reduced upto 40% and hence the efficiency increases. The PWM output frequency is in the range of 5-50Hz. The motor exhibits smooth speed control in the range of 10-120rpm. During the experiment it was observed that the desired speed of 100rpm is achieved in less than 2 seconds. Synchronous speed of the motor was low due to large number of poles. The stator current waveforms shown in Figure 7.4 that are phase shifted by 180 degree have less amounts of ripples.

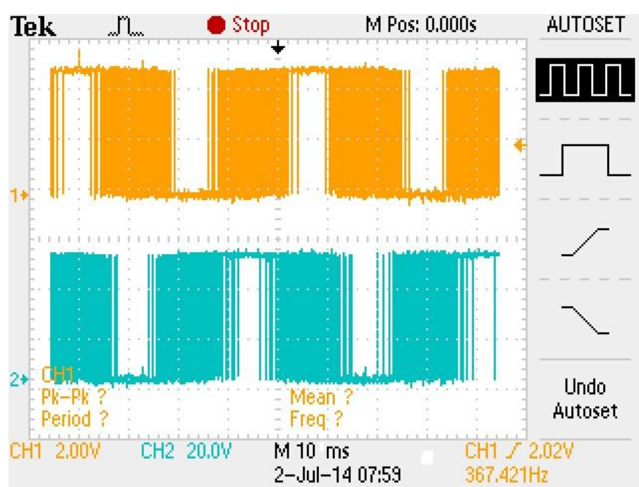

Figure 7.3: 90degree Phase Shifted PW

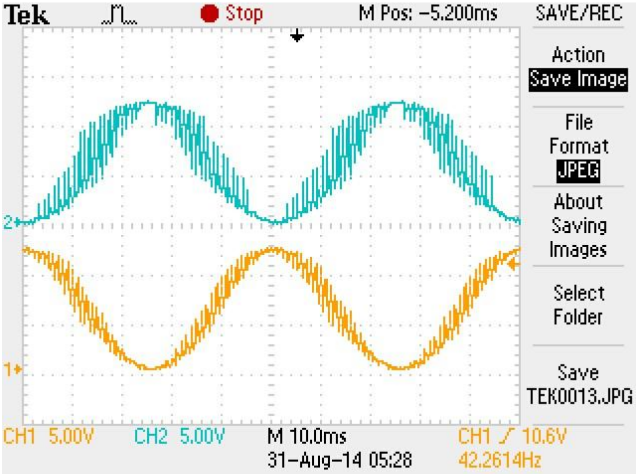

Figure 7.4: Stator Current Waveforms

8 CONCLUSION

When bipolar stepper motors are provided with sinusoidal voltage of line frequency at the stator, a smooth rotating magnetic field is produced and the machine tends to operate without any torque ripples. ie, the rotor rotates continuously in synchronous speed rather than discrete steps. Therefore the stepper motor can be modeled as synchronous motor (PMSM) and the various control strategies used in the PMSMs can also be applied on the stepper motor. Direct torque control is simple and robust control system capable of giving high performance. If torque response quickness, robustness and precision are to be secured Direct Torque Control is more suitable than any other control system. DTC being more crude has advantage of not having to compute applied current/voltage vectors, which significantly reduces the computational burden. This allows a simple and cheap processor to perform the computational task.

The proposed control strategy is simulated Matlab/Simulink environment. The simulation based on Matlab/Simulink is convenient enough to study the performance of the control system and the parameter dependences in the system. The concept was observed to be feasible and efficient in the simulation, and it was realized in a two phase bipolar stepper motor using DSPIC30F3011.

Acknowledgment

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