A Novel Vector Control Strategy For Bipolar Stepper Motor

Mr. Jijo Paul , Prof. Dominic Mathew

Abstract— The requirement of precise control in servo applications used in the digital systems led to the development of stepper motors. The precise and zero backlash operation of steppers extended its reach to various position control applications. The lack of requirement of sensors for position control applications was one of the main reasons for preferring stepper motors. Since the stepper motors were driven using digital pulses the motor moved in discrete steps of fixed angles and this caused torque pulsations in the machine. The advent of Micro-stepping strategy was a revolutionary change to this scenario, which helped to achieve a continuous smooth torque performance with reduced ripples, but this led to the requirement of a position sensor feedback for precise control. In robotic applications, continuous motion with a steady torque is preferred over stepped motion with pulsating torque. The paper proposes a novel control technique for stepper motors with reduced torque ripple and improved efficiency with the application of a vector control strategy analogous to PM Synchronous Motors. The proposed strategy was implemented and tested on a hybrid stepper motor. The proposed system can be used in position control applications, process automation, Robotics etc.

Index Terms— Vector Control, Stepper Motor

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1 INTRODUCTION

Stepper motors evolved in the early 1960s as a replacement for servos in the computer peripheral industry for applications requiring precise position control at an affordable price [1]. Two reasons attributing to the popularity of stepper-based designs are their ability to achieve accurate position control without the requirement of position feedback (open- loop control), and the fact that they can be driven by squarewaves, which can easily be supplied by a digital controller. However, controlling them is often more difficult than other motors, as they are frequently plagued by resonance and acoustic noise problems.

Generally, microstepping with current proportional and integral (PI) feedback loops is used to maintain desired currents in industrial applications [2]. Microstepping is used to improve the resolution and increase the motion stability of stepper motors. Several feedback control methods were developed in order to improve the current tracking performance of microstepping. However, the PI controllers cannot efficiently compensate for the effects of back-emfs and inductances. A motor control strategy for Permanent magnet stepper motors using nonlinear torque modulation is proposed in [3]. The method comprises of a nonlinear Current tracking controller, a commutation scheme and a non linear torque modulator. The paper intends to overcome the difficulties of positioning errors that arise due to the mechanical dynamics of the machine in the conventional and contemporary micro stepping strategies as in [4]. author proposes a control

strategy similar to Field oriented control (FOC) to optimize the energy efficiency of the stepper motor. [5] Suggests optimal and suboptimal control algorithms for stepper motor drives employing closed loop control. The modification in the control strategy was analyzed to provide better acceleration and minimum positioning time for the hybrid stepper motor drives compared to the contemporary strategies. The control algorithm was implemented on Intel EV80C196KB control card supported by a PC hence requires complex processing system similar to the methods in [6], [7].A control strategy for position control using nonlinear torque modulation for control over an extensive speed range is proposed in [8]. This system comprises of a nonlinear torque modulator a commutation scheme and a nonlinear current controller. The system uses a control strategy of Field oriented control (FOC) and Field weakening control (FWC) to construct a desired current profile for torque generation without the use of a DQ transformation. The proposed scheme of FOC and FWC are similar to that of the micro-stepping and is observed to offer better performance compared to the conventional strategy of micro-stepping.

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2 FIELD ORIENTED CONTROL

A brushless Permanent Magnet Synchronous Motor (PMSM) has a wound stator, a permanent magnet rotor assembly and internal or external devices to sense rotor position. The sensing devices provide position feedback for adjusting frequency and amplitude of stator voltage reference properly, to maintain smooth rotation of the Permanent magnet rotor.

The combination of outer windings and inner permanent magnet rotor offers the advantages of low rotor inertia, efficient heat dissipation, and reduction of the motor size. Moreover, the elimination of brushes reduces noise, EMI generation and avoids the need of brush maintenance.
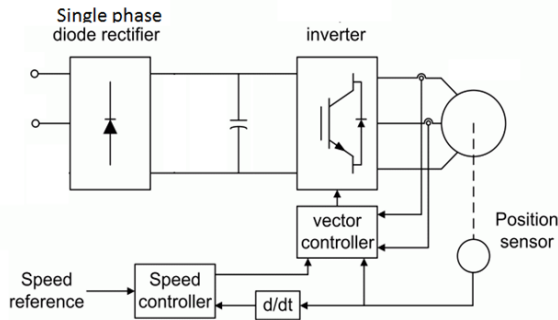

Figure 2.1: Block Diagram of FOC in PMSM

During acceleration or deceleration the stator field speed is controlled in such a way that the rotor follows the stator speed. If the rotor cannot follow synchronous speed of stator it will pull out and stall. The angle between the rotor field and the stator field must be equal to 90 degree to obtain the highest mutual torque production. This synchronization requires knowing the rotor position in order to generate the right stator field. The stator magnetic field can be made to have any direction and magnitude by combining the contribution of different stator phases to produce the resulting stator flux. In order to achieve better dynamic performance, a more complex scheme needs to be applied, to control the PM motor. With the mathematical processing power offered by the microcontrollers, we can implement advanced control strategies, which use mathematical transformations in order to decouple the torque generation and the magnetization functions in PM motors. Fig2.1 shows the block diagram of Field orientated control (FOC).

This algorithm maintains efficiency in a wide range of speeds and takes into consideration torque changes and varying load conditions by controlling the flux directly from the rotor coordinates. The Field Orientated Control consists of controlling the stator currents represented by a vector. This control is based on projections which transform a three phase time and speed dependent system into a two co-ordinate (d and q co-ordinates) time invariant system.

Fig 2.2 shows a block diagram depicting the implementation of vector control in PM Synchronous motor. These projections lead to a structure similar to that of a DC machine control. Field orientated controlled machines need two constants as input references: the torque component (aligned with the q co-ordinate) and the flux component (aligned with d co-ordinate). This strategy implemented in PM synchronous motors can also be applied in PM Stepper Motors as derived below.
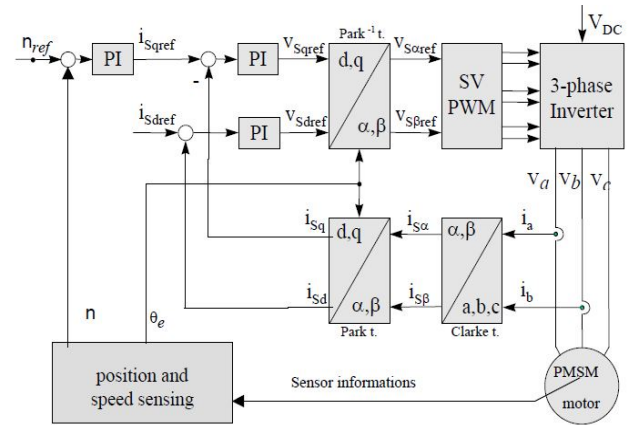

Figure 2.2: FOC control strategy in PMSM

$$V_{qs} = R_{qs}i_{qs} + p\psi_{sd} + \omega_r\psi_{ds} \qquad (1)$$

$$V_{ds} = R_{ds}i_{qs} + p\psi_{ds} - \omega_s\psi_{ds} \qquad (2)$$

$$R_{qs} = R_{ds} = R_s \qquad (3)$$

$$\psi_{qs} = L_q i_{qs} + L_m i_{qr} \qquad (4)$$

$$\psi_{ds} = L_d i_{ds} + L_m i_{dr} \qquad (5)$$

Permanent magnet excitation can be modeled as a constant current source, i_{fr}

$$i_{dr} = i_{fr} \qquad (6)$$

$$i_{qr} = 0 \qquad (7)$$

$$\psi_{qs} = L_q i_{qs} \qquad (8)$$

$$\psi_{ds} = L_d i_{ds} + L_m i_{fr} \qquad (9)$$

$$\psi_{ds} = L_d i_{ds} + \psi_{af} \qquad (10)$$

Where ψ_{af} is the rotor flux linking constant

$$T_e = \frac{3}{2}\frac{P}{2}(\psi_{ds}i_{qs} - \psi_{qs}i_{ds}) \qquad (11)$$

$$T_e = \frac{3}{2}\frac{P}{2}(\psi_{af}i_{qs} + (L_d - L_q)i_{qs}i_{dr}) \qquad (12)$$

As Field Orientated Control is simply based on projections the control structure handles instantaneous electrical quantities. This makes the control accurate in every working operation (steady state and transient) and independent of the limited bandwidth mathematical model. The FOC thus solves the classic scheme problems, in the following ways:

1. The ease of reaching constant reference (torque component and flux component of the stator current)
2. The ease of applying direct torque control because in the (d,q) reference frame the expression of the torque is:

$$T_e = \frac{3}{2}\frac{P}{2}(\psi_{ds}i_{qs} - \psi_{qs}i_{ds}) \qquad (13)$$

By maintaining the amplitude of the rotor flux (ψ_r) at a fixed value we have a linear relationship between torque and torque component (i_{sq}). We can then control the torque by controlling the torque component of stator current vector.

3 VECTOR CONTROL STRATEGY

The field oriented control algorithm was implemented on a PM synchronous motor as shown in Fig 3.1. The system uses a speed reference input; the machine tries to achieve the reference speed based on the control algorithm. The input reference speed is compared with the feedback speed and the generated error is fed to a PI controller. The output of the PI controller is compared with the I_q reference generated in the processor. The generated error is fed to the Park inverse transform unit through a PI controller as I_q
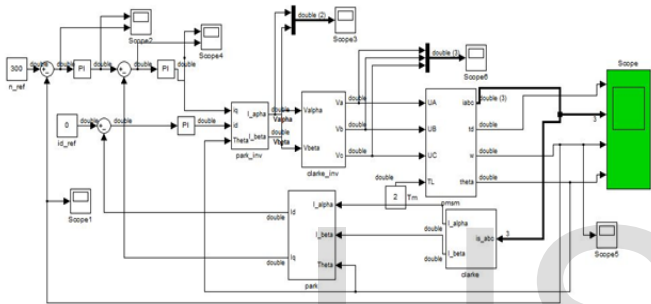

Figure 3.1: Vector control of PM Synchronous Motor

In the field oriented control of PM synchronous motor we provide the I_d reference input as zero. The Id input that is generated in the processor is compared with constant input and is fed to the inverse Parks Transformation unit through a PI controller. The θ input is fed back from the motor output. Using the inputs the I_q, I_d, and θ the I_a and I_β are processed. The I_a and I_β components differ in space by 90 degree and are sinusoidal. These are fed to the inverse Clarkes transformation unit to process V_a, V_b, and V_c. Based on the inputs the three phase PWM for the motor is generated, for the purpose Space Vector Modulation can be employed. Using the current feed backs taken from the inputs given to the motor we can process the I_a and I_β components using Clarkes transformation. Using a Parks transformation block the I_q and I_d components can be processed.

WAVEFORMS

The output waveforms of the vector control employed in PM synchronous motor can be obtained as shown in Fig 3.2. The torque waveform is smooth and free from transients. The machine consumes high amount of current during the turn on period but the system is free from current transients and the waveforms are smooth. The current waveforms exhibit 120 degrees phase shift and exhibits a smooth transition while ascending to the base frequency. The dynamic response of the machine is very good and the machine achieves the base speed of 300rpm in 0.028 secs.
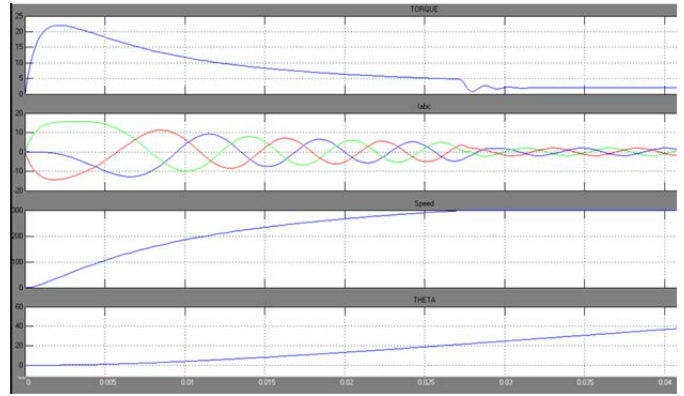

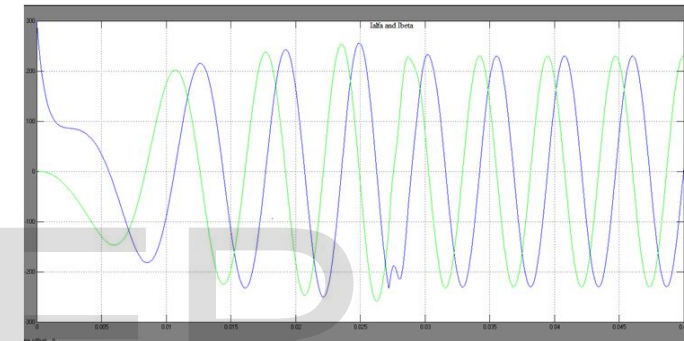Figure 3.2: Output waveforms for vector control in PMSM

Figure 3.3: I_a and I_β components from the inverse park transformation block

Fig 3.3 shows the I_a and I_β components generated in the inverse Parks transformation Unit. The waveforms were observed to be sinusoidal and displaced in space by 90 degree. The outputs were available from 0.005secs. This shows that even from lower speeds the I_a and I_β components can be processed to generate the input for the machine. For the control of bipolar PM stepper motors we use the I_a and I_β components as the reference to generate the input for the machine.

Open loop control of PM Stepper motor

In order to simulate the bipolar stepper motor in open loop mode the circuit was set up as shown in Fig 3.4. For the open loop control of PM stepper motor we use sinusoidal voltage sources as reference inputs phase shifted by 90 degree. To generate the sine PWM we use reference input Discrete PWM generator. Based on the reference inputs, the discrete PWM generator produces the PWM outputs for the inverter. The inverter provides the input to the PM stepper motor. This is the analysis of motor control using micro-stepping strategy.

The waveforms observed during the open loop control of stepper motor are shown in Fig 3.5. The generated waves are not sinusoidal due to the saliency of the rotor and non sinusoidal air gap flux distribution in the machine. The reference input PWM has a fundamental frequency of 20 Hz. The machine generates a steady uniform torque; the torque waveform has slight fluctuations due to the following reasons. Saliency of the rotor construc-

tion creates the fringes in the generated torque and the ripple is uniform. The larger ripple generated is due to the saliency of the stator construction, this noise is reflected in the speed curve also, these pulsations could cause observable noise in the motor operation.
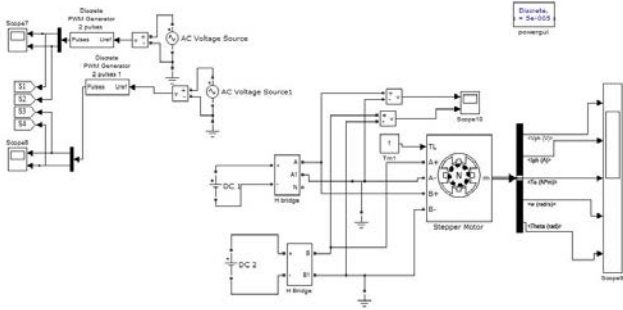

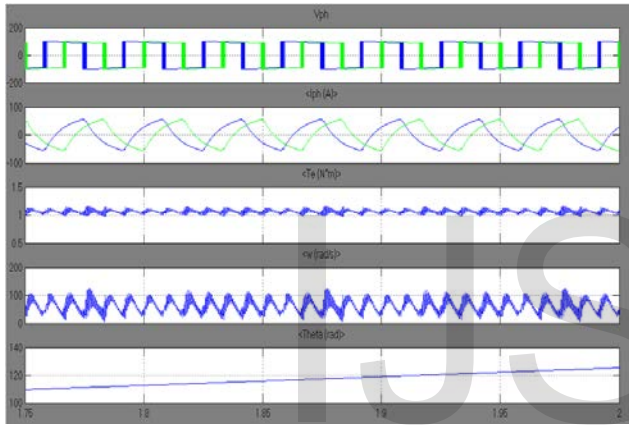Figure 3.4: Circuit of open loop control of PM stepper motor

Figure 3.5: Waveforms observed in open loop control of PM stepper motor

Closed loop control of PM Stepper motor
The circuit for closed loop control of stepper motor is shown in Fig 3.6. The system uses a speed reference input; the machine tries to achieve the reference speed based on the control algorithm.
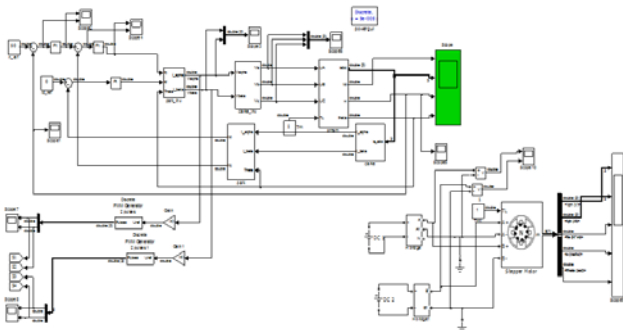

Figure 3.6 : Circuit of closed loop control of PM stepper motor

The input reference speed is compared with the feedback speed and the generated error is fed to a PI controller. The output of the PI controller is compared with the I_q reference generated in the processor. The generated error is fed to the Park inverse transform unit through a PI controller as I_q. In the field oriented control of PM synchronous motor we provide the Id reference input as zero. The Id input that is generated in the processor is compared with constant input and is fed to the inverse Parks Transformation unit through a PI controller. The theta input is fed back from the motor output. Using the inputs the I_q and I_d and theta the I_a and I_β are processed. The I_a and I_β components differ in space by 90degress and are sinusoidal. The waves I_a and I_β are taken as the reference inputs to generate the sine PWM required for the motor.
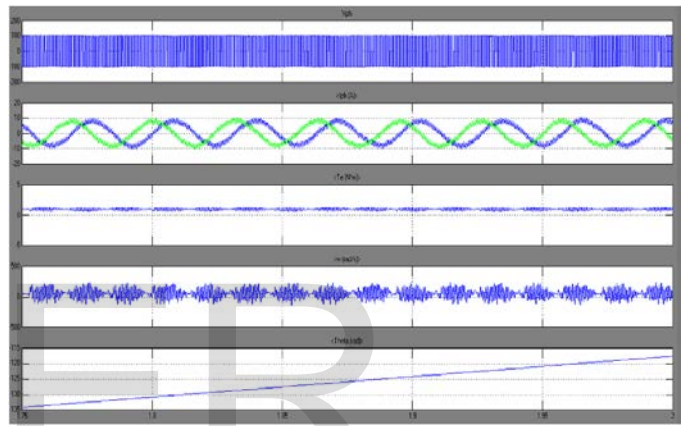
WAVEFORMS

Figure 3.7: Waveforms observed in closed loop control of PM stepper motor

The waveforms in the machine when a closed loop control is employed are shown in Fig 3.7. The input PWM generates a sinusoidal input current with 90 deg phase difference. The input current is fairly continuous and ripple free the torque generated in the machine is continuous the torque wave have shot fringes due the non uniform air gap at the rotor teeth, but the effects of the saliency of the stator construction are minimal in the closed loop system. By modifying the control strategies and improving the feedback mechanisms the difficulties of torque ripple and noises in the machine can be reduced

4 HARDWARE IMPLEMENTATION

The basic system overview of the proposed system hardware is demonstrated in the Fig 4.4. The single phase AC input to the rectifier is fed from a step down transformer to attain the required voltage level (12V or 24V) for the motor. The system uses an uncontrolled diode bridge rectifier this is followed by a voltage regulator (7824) and a filter capacitor to regulate the output voltage that is fed to the inverter circuit. The inverter circuit converts the regulated DC to a sinusoidal wave of desired frequency based on the PWM gating from the gate driver circuit. The gate driver circuit is constituted by IRS2110 (independent high and low channel gate driver IC). The Stepper motor requires two independent alternating current excitations at their phases, to achieve

this four half bridge circuits are required as shown in Fig 4.2.

The Vector control algorithm is the core of the system, the respective computations and the control algorithm is carried out in the control unit. The FOC algorithm is implemented on dsPIC30F3011 the controller provides the required PWM for the operation of the inverter and the control algorithm computations are also handled within the microcontroller simultaneously. The feedback from the encoder is received in the dsPIC; the position θ obtained from the encoder can be differentiated to obtain the speed of the reference input to the system is also given into the system. The reference input is given as an analog input using a potentiometer, which is converted into the respective digital value using ADC. The current feedback from the respective winding is fed to the ADC of microcontroller to track the phase current waveforms to continuously monitor the motor parameters.

The ADC result for AN7 that is converted to binary is left shifted to convert them to fractional values, which simplifies the mathematics. The two fractional values are multiplied using the fractional MPY instruction. The result of the multiplication operation is a fractional value that can be used to scale the modulation voltage between 0 and 100%. This value is stored in the "Amplitude" variable. Together, the "\Frequency" and \Amplitude" values specify the input parameters for the sine wave generation. The value of Amplitude is limited, so that over modulation will not occur in the PWM modulation routine. In the processing, the ADC processing occurs at a 500-Hz rate to generate new voltage and frequency values. The frequency processing only needs to be executed when the motor speed needs to be changed.
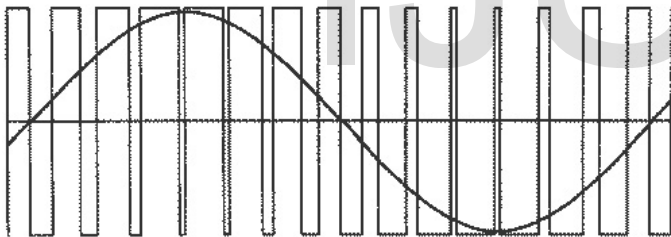

Figure 4.1: The generation of sine wave by averaging the PWM using sine table.

The PWM is configured for a 5 KHz carrier frequency, complementary outputs and the use of dead time. The required amount of dead time depends on the power circuit that is used to drive the motor. A 64-entry sine wave look-up table is used to drive the motor in this case. The resultant is obtained as shown in Fig 10.

The Modulation subroutine is called in each PWM period to calculate the duty cycle for each of three motor phases. This subroutine is written to save and restore all working registers so that it can be reused in other applications. The function first loads pointers to the sine look-up table and various variables and constants associated with the modulation routine. The sine table is stored in the program memory space to conserve RAM.
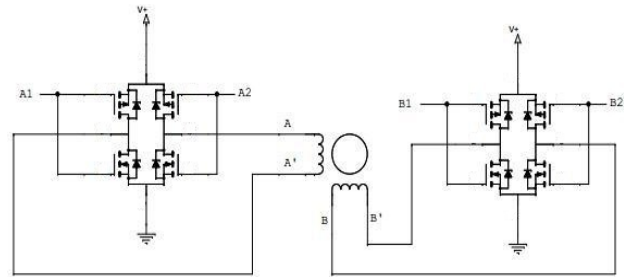

Figure 4.2: Inverter and motor drive

Fig 4.3 shows the overview of the inverter setup used for driving the bipolar stepper motor. The gate driver circuit is used for amplification; it also provides optical isolation between control circuit and power circuit.
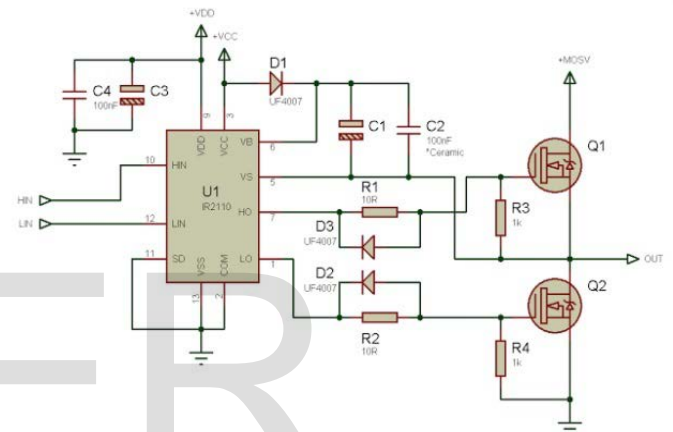

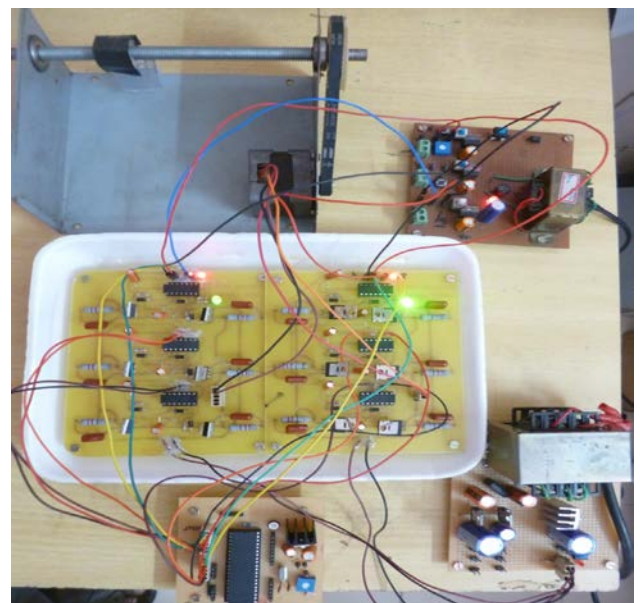Figure 4.3: IR2110 circuit used to drive a half bridge of the inverter.

Figure 4.4: Hardware setup.

Two gate drivers (IR2110) are used which provide switching signals for all 4 switches in the inverter. The circuit of gate driver IR2110 IC is shown in the Fig 4.3. The IR2110 is a high

voltage, high speed power MOSFET and IGBT drivers with independent high and low side referenced output channels. Logic inputs are compatible with standard CMOS or LSTTL output, down to 3.3V logic.

5 EXPERIMENTAL RESULTS

The figure shows the complimentary PWMs for Phase A, it can be observed that the PWM have a phase difference of 180 degree. The PWM are also having a dead band of 8 micro-seconds.

The slight curving in the edges of the pulse occur due to the charging delay caused at the Gate (Due to gate capacitance and path resistance) this time is limited to 1micro seconds using filter arrangements.
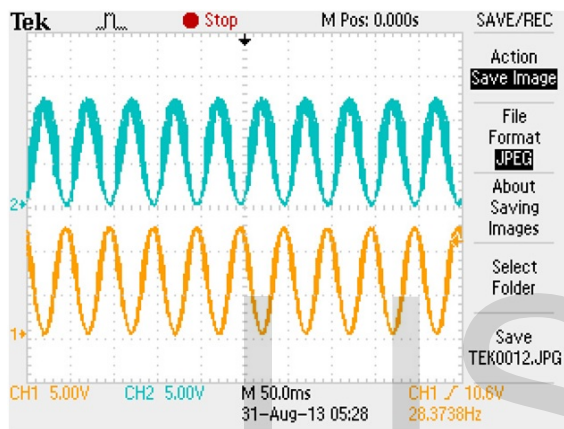

Figure 5.1: The complimentary PWMs for a half-bridge with dead-band
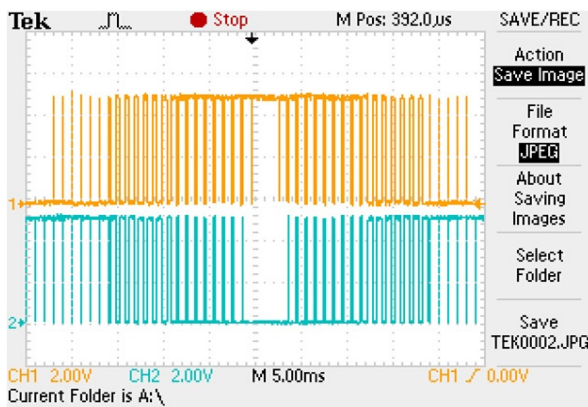

Figure 5.2: The PWM input to the upper and lower switch

The machine offers smooth noise free operation in the steady state and transient state, the machine achieves a speed of 120rpm from zero speed in less than 1.5sec. The machine transits from 20rpm to 80rpm in a time span less than 0.8sec. The transients during start up were observed to be less than 2.5times the full load current of 1.2A. The machine operation was smooth and free from mechanical vibrations.
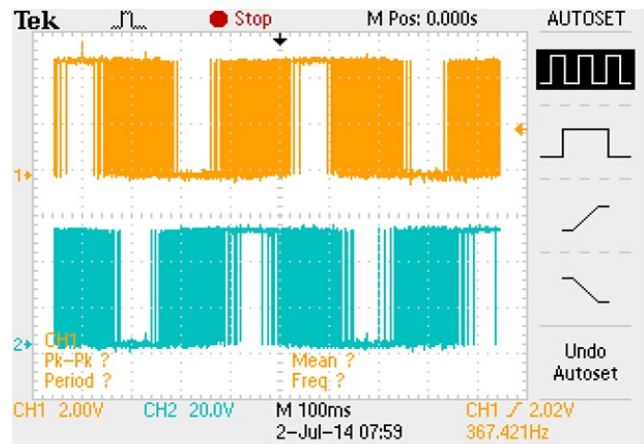

Figure 5.3: PWM fed to phase A and PhaseB

6 CONCLUSION

The difficulties associated with employing stepper motors for precise servo applications are discussed in this paper. The conventional micro-stepping technique was adopted as a technique to develop continuous torque in the machine and the outputs of the machine were observed in the open loop mode. Based on the inferences from the open loop control a Vector control algorithm was employed in the system to enhance the performance of the machine. The new control strategy gave superior results compared to the open loop control mode in the transient state as well as in the steady state operating conditions. The dynamic response of the machine seemed to be improved and the machine seemed to achieve steady performance in duration of less than 0.5 sec. Based on the observed results this new control strategy could be used as a viable control option for precise servo positioning applications. Since the torque ripples were considerably reduced the power consumption of the machine could also be lowered to considerable extend. The concept was evaluated using simulations and implemented experimentally on two phase bipolar stepper motor. From the observations it can be perceived that the motor will be able to provide smooth performance and can be implemented in a precise position control applications.

Acknowledgment

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