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Power Factor Improvement of Vector Controlled PMSM Drives

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ABSTRACT: The field oriented control of Permanent Magnet Synchronous Machine (PMSM) is investigated. The rotor magnetic field position information is obtained from the shaft position sensor. Robust instantaneous torque control is achieved with the help of sensored field oriented control. The modulation technique employed to drive the inverter switches is chosen to be Space Vector Modulation (SVM) for the ease of digital implementation and better dc bus utilization. The DC bus for the inverter is obtained from a boost converter fed by a single phase diode bridge rectifier. Power factor correction is performed in the front end boost converter of the drive; therefore unity power factor operation is achieved. The overall system is modelled in MATLAB/Simulink environment. The performance of the PFC unit is analyzed under different loading conditions and it is found that the power factor lies close to unity. The torque response under various loading conditions are found to be instantaneous and in line with the principle of vector control. A prototype to assess the performance of PFC is attempted using PFC IC and the experimental results are obtained.

KEYWORDS: Surface Permanent magnet synchronous motors, sensored torque feedback power factor correction, robust control, efficient control, space vector modulation, field oriented control, boost converter.

I.INTRODUCTION

In recent years, Permanent Magnet Synchronous Motors are applied in several areas such as traction, automobiles and robotics technology. The advantage of PMSM drive is high efficiency, high torque to power ratio. The drive is said to achieve high efficiency if Maximum Torque per Ampere (MTPA) conditions are met. Every drive essentially consists of two control loops namely outer speed controller and inner current controller. The design of these control loops is critical. The controller should take into account the effect of load variations and parameter variations. Accurate mathematical model is needed in describing the dynamics of the system when conventional controllers are employed. In PMSM, the stator excitation must be synchronized with the rotor position, which requires a rotor position sensor or a position estimation algorithm. The PMSM Drive consists of a classical three phase bridge inverter fed by a DC bus which is usually generated from a diode bridge rectifier. Power quality issues are predominant at higher power levels due to the presence of a front end diode bridge rectifier. The primary reason being the harmonic distortion in input current waveform. This could be overcome by the use of a boost converter based power factor correction circuit.

The work of Krishnan [7] gives an overview of the PMSM control and it has arrived at the conditions for MTPA. The modulation scheme with maximum dc bus utilization is SVM which is described in depth in the work of Neacsu et. Al[8]. The issues in practical implementation were discussed in detail in the work of Asri et al[2]. The power quality issues and its associated solutions are illustrated in the work of Bhim Singh et. al[3]. Power factor correction using analog ICs were discussed in [5]. The MATLAB/Simulink simulation guidelines were illustrated in the text by Ong [9].

This paper is organized as follows. Section II explains the mathematical model of PMSM in rotating dq reference frame and it outlines the equations that govern the dynamics of the PMSM. Section III describes the control techniques available for PMSM. Section IV details about the principle of vector control in general and field orientation conditions are outlined in this section. Section V describes the operation of the power factor correction circuit and explains the design procedure. Section VI describes about the SVM and current regulated PWM using SVM. The MATLAB/Simulink simulations and experimental results are described in Section VII and VIII.

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II. PMSM MODEL

The mathematical model of PMSM is obtained by applying Kirchhoff's Voltage law for the stator windings. Unlike other motors that carry winding in the rotor, PMSM consist of permanent magnets, this drastically reduced the simultaneous equations that needs to be solved into half. To ease the control design, it is a conventional practice to express the voltage equations in synchronously rotating reference (dq) frame with d-axis aligned with the rotor magnetic field. The electrical and mechanical equations of the PMSM in the dq frame are as follows:

$$v_d = R_s i_d + \frac{d\lambda_d}{dt} - \omega_r \lambda_q \quad (1)$$

$$v_q = R_s i_q + \frac{d\lambda_q}{dt} - \omega_r \lambda_d \quad (2)$$

With

$$\lambda_d = L_d i_d + \lambda_{af} \quad (3)$$

$$\lambda_q = L_q i_q \quad (4)$$

Where v_d, v_q, i_d, i_q, λ_d, λ_q are d,q axis stator voltages, currents and flux linkages respectively. L_d, L_q are d, q axis inductances. λ_{af} represents mutual flux due to the permanent magnet in the rotor. R_s represents stator per phase resistance and ω_r is the rotor speed in rad/s.

The motor dynamics are characterized by,

$$p\frac{d\omega_r}{dt} = \frac{1}{J}\left(T_e - T_L - B\omega_r\right) \quad (5)$$

Where T_e, T_L represents electromagnetic torque developed by the motor and load torque applied to the motor. B represents the viscous frictional coefficient. J is the moment of inertia of the rotor about the motor axis. The motor is assumed to have p poles.

The torque developed by the motor is given by,

$$T_e = 1.5p\left(\lambda_{af} i_q + \left(L_d - L_q\right) i_d i_q\right) \quad (6)$$

It can be observed from eq. that there are two components in torque. The first component is called as synchronous torque and the second term is called reluctance torque.

III. CONTROL OF PMSM

In general, PMSM Control methods can be subdivided into two categories, one is scalar control and another one is vector control. In scalar control the magnitude and frequency of the stator voltage is adjusted to vary the speed of the motor. It is well suited for motors driving constant loads as scalar control offers excellent steady state performance.

For dynamically varying loads, the performance of scalar control is poor. In such cases, vector control offers excellent dynamic response. The idea of vector control is inspired from the ease of torque control in separately excited DC Motor. The superiority of vector control is essentially due to the control of magnitude, phase and frequency of the stator currents. Vector control requires the machine variables to be expressed in complex domain using transformations. Hence this control technique demands heavy computational power at high speeds which is easily provided by modern commercial processors.

IV. VECTOR CONTROL OF PMSM

As already stated, the vector control is inspired from separately excited DC motor torque control. The principle reason for the ease of torque control in DC motor is that, the torque and magnetizing flux producing components are decoupled by design. Hence vector control on any motor tries to decouple the torque and magnetizing flux producing components. From eq.it can be noted that the torque is a non-linear equation expressed in terms of currents. Under field orientation conditions (i_d=0), the equation reduces to

$$T_e = 1.5p\left(\lambda_{af} i_q\right) \quad (7)$$

From the above equation it can be deduced that the q-axis component of stator current is responsible for torque production under constant flux operation. Hence a vector controlled drive essentially consists of a current regulated

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PWM inverter that regulates the current in the machine windings at command values (i_d^*,i_q^*). The d-axis command current is 0 at constant power region of the drive and hence the machine is operated under rated flux. The q-axis command current is derived from a speed controller which is usually a PI controller.

At the heart of vector control is current regulated PWM inverter. There are numerous ways suggested to implement a current regulated PWM inverter. [4] suggests that the use synchronous frame based space vector modulated inverter proves to be beneficial for vector control. The stator currents are measured and transformed to dq frame using the position information obtained from rotor position sensors. They are compared with the command values (i_d^*,i_q^*) and fed to a current regulator. Usually a PI regulator is employed for obtaining zero steady state error. The overall block diagram is illustrated in Fig1.

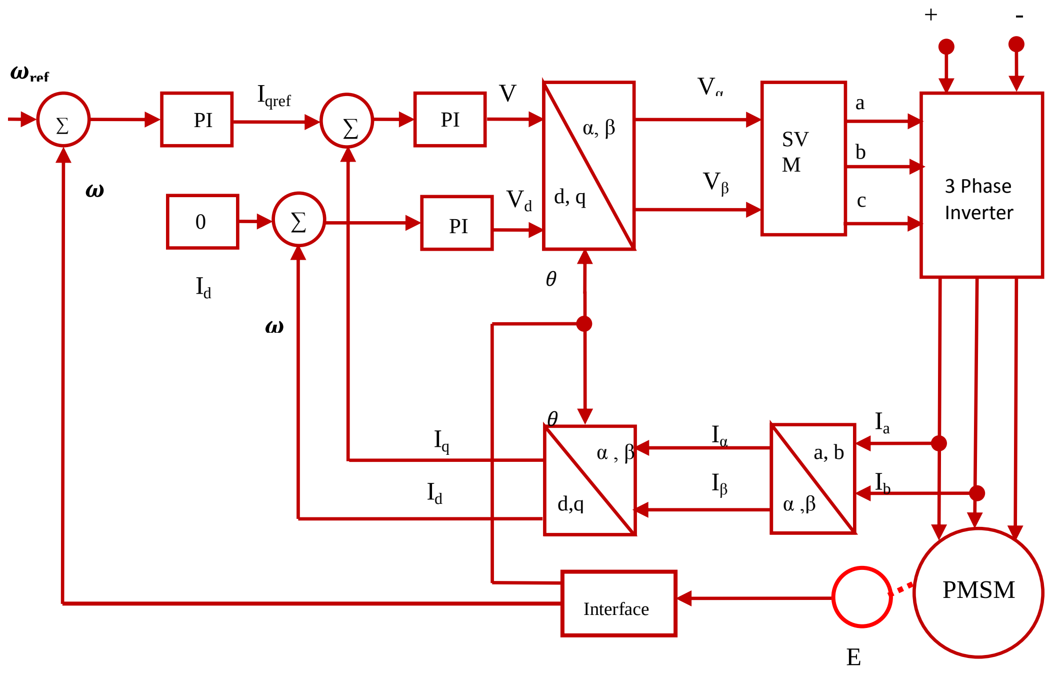

Figure 1 Block diagram of vector controlled PMSM drive

V. POWER FACTOR CORRECTION

In order to overcome the power quality issues of diode bridge rectifier, a boost converter fed by a diode bridge rectifier is used to create DC bus for the inverter. The boost converter is triggered such that the inductor current follows the waveform of a rectified input voltage waveform. This achieves unity power factor at the input side. The control is performed as follows, the output dc voltage is measured and compared with the reference value and the error is fed to a PI regulator. The output of the PI regulator is multiplied with the rectified input voltage waveform scaled appropriately. This is the reference current for the inductor. The actual dc bus current is measured and compared with the reference current and error is generator. By comparing the error with a triangular carrier wave PWM pulses are generated.

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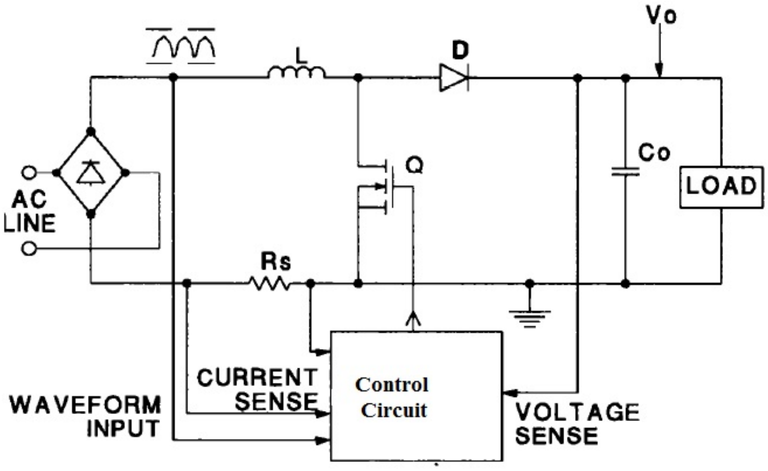

Figure 2 Power factor correction circuit

Design of Boost Converter:

The design of boost converter is based on the specifications of the converter. Let the operating requirements be as follows:
Output Power [Pout (Max)] = 250W
Vin Range: 80-270Vac
Output Voltage: 400V
Switching Frequency: 100 kHz

Inductor Selection:

The inductor is selected based on peak inductor current, ripple current, and maximum allowable duty cycle values. The peak inductor current is evaluated from output power and minimum AC_{rms} voltage and assumed efficiency of the converter.

$$I_{ACPeakmax} = \frac{\sqrt{2} \times P \times \eta}{V_{ACmin}} \tag{8}$$

Ripple Current:

Ripple current is assumed to be 20% of the peak current.

$$L = \frac{V_{ACnom} \times \sqrt{2} \times DutyMax}{f_{SW} \times \Delta I} \tag{9}$$

Maximum allowable duty cycle is given as,

$$Dutymax = \frac{V_{DC} - V_{ACmin} \times \sqrt{2}}{V_{DC}} \tag{10}$$

Capacitor Design:

The capacitor is selected based on the output power and holdup time as given by the following relation.

$$C = \frac{2 \times P \times T_{holdup}}{V_{DC}^{2} - V_{DC\,min}^{2}} \tag{11}$$

Typically the capacitance is usually in the range of 1 to 2uF per watt.
The overall block diagram of power factor correction circuit is given below.

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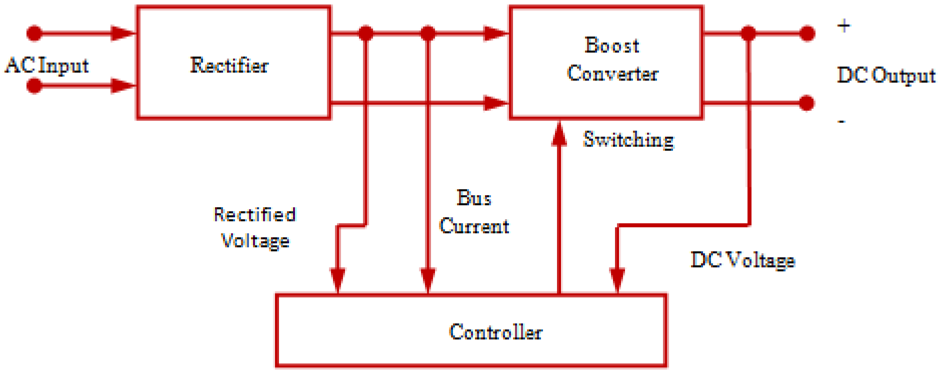

Figure 3 Block diagram of power factor correction circuit

VI. SVM BASED CURRENT REGULATED PWM INVERTER

Space vector modulation (SVM) is a pulse width modulation (PWM) technique employed for three level inverters.Although highly computational, the efficiency of the Inverter is better than any other modulation technique. It is due to the fact that the maximum DC bus utilization is possible by Space Vector Modulation technique. For a DC voltage of Vdc volts, the maximum RMS line-line inverter voltage obtained is 0.707Vdc. Moreover the Harmonics in the steady state instantaneous current waveforms are minimized.

The overall block diagram of the PMSM drive is illustrated below.

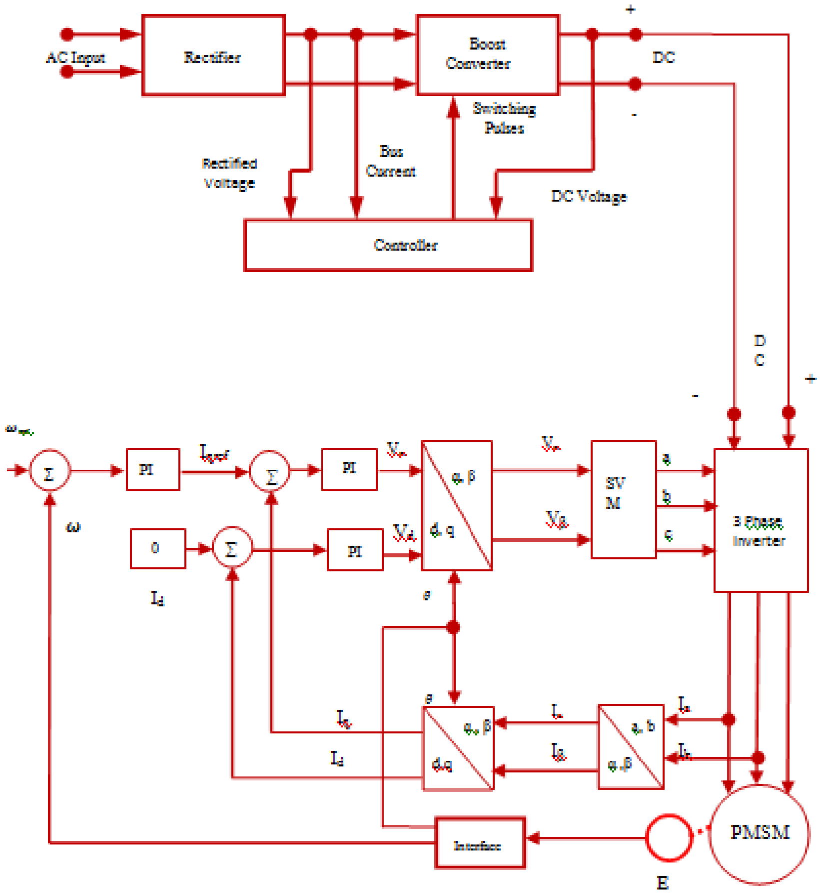

Figure 4 Overall block diagram of the PMSM drive

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VII. MATLAB/SIMULINK SIMULATION

The system is simulated in MATLAB/Simulink environment. The motor parameters for the PMSM are given in Table I

TABLE I PMSM simulation parameters

SL.NO.	PARAMETER	VALUE
1	Number of poles, p	4
2	Amplitude of flux induced by permanent magnets of rotor in stator phases, λ	0.175Wb
3	Resistance of stator winding, R	2.875Ω
4	d and q axis inductances, $L_d$and L_q	8.5mH
5	Inertia, J	0.0008kg/m^2
6	Friction coefficient, F	0.001Nms

The figure below shows the Simulink model for power factor correction circuit. It can be seen that the output DC Voltage, input AC voltage and DC bus currents are measured and fed to the controller and the controller produces PWM output.

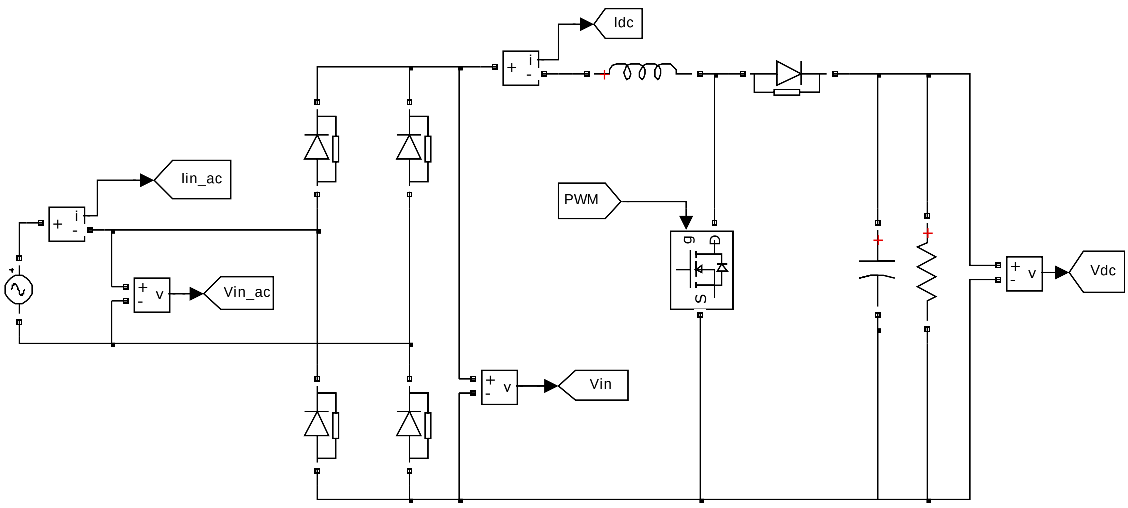

Figure 5 MATLAB/Simulation model of boost converter type PFC Circuit.

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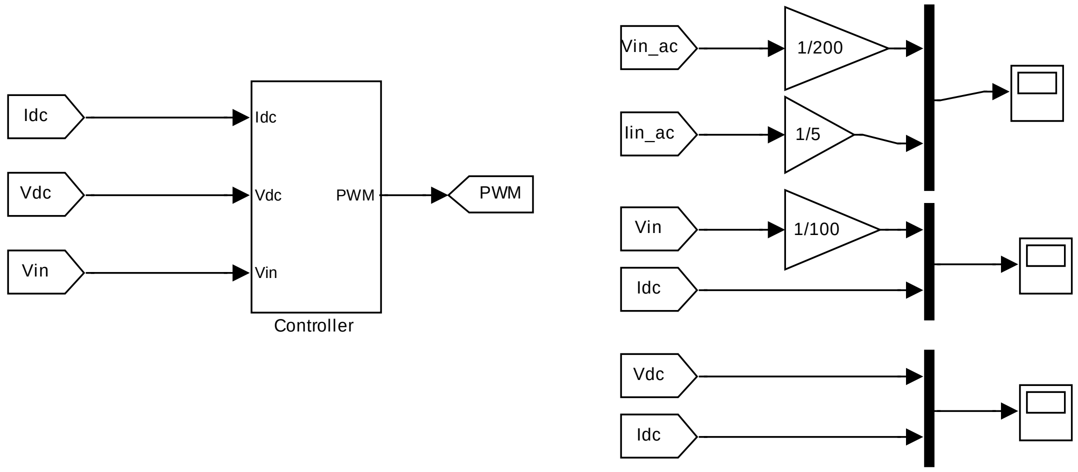

Figure 6 PWM generation logic for the Simulator Boost converter

The figure below illustrates the simulation of space vector modulation. The SVM algorithm takes DC Voltage, real (alpha) and imaginary (beta) components of the reference space vector as inputs and produces the gate pulses as outputs. The duty cycle calculator block calculates the duty cycles of the vectors. Based on the sector in which the reference vector lies, the relevant active space vectors are employed.

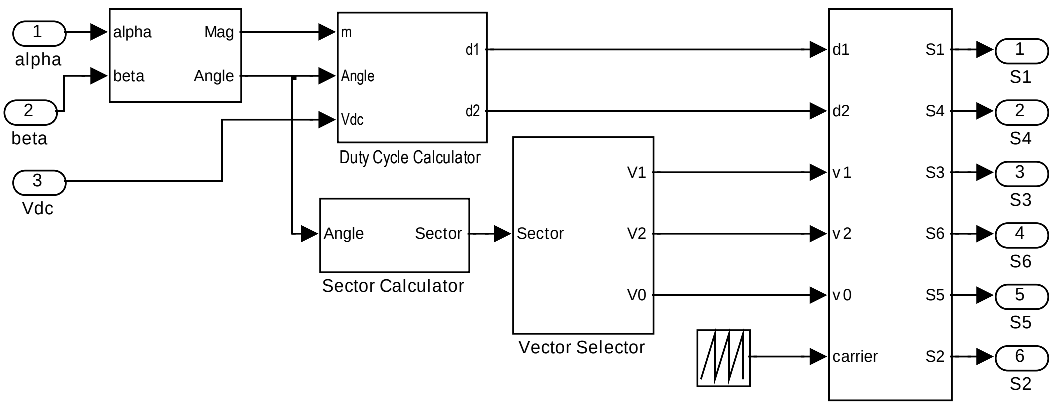

Figure 7 MATLAB/Simulink Model for Space Vector Modulation

The overall simulation including the boost converter based power factor correction circuit is illustrated below.

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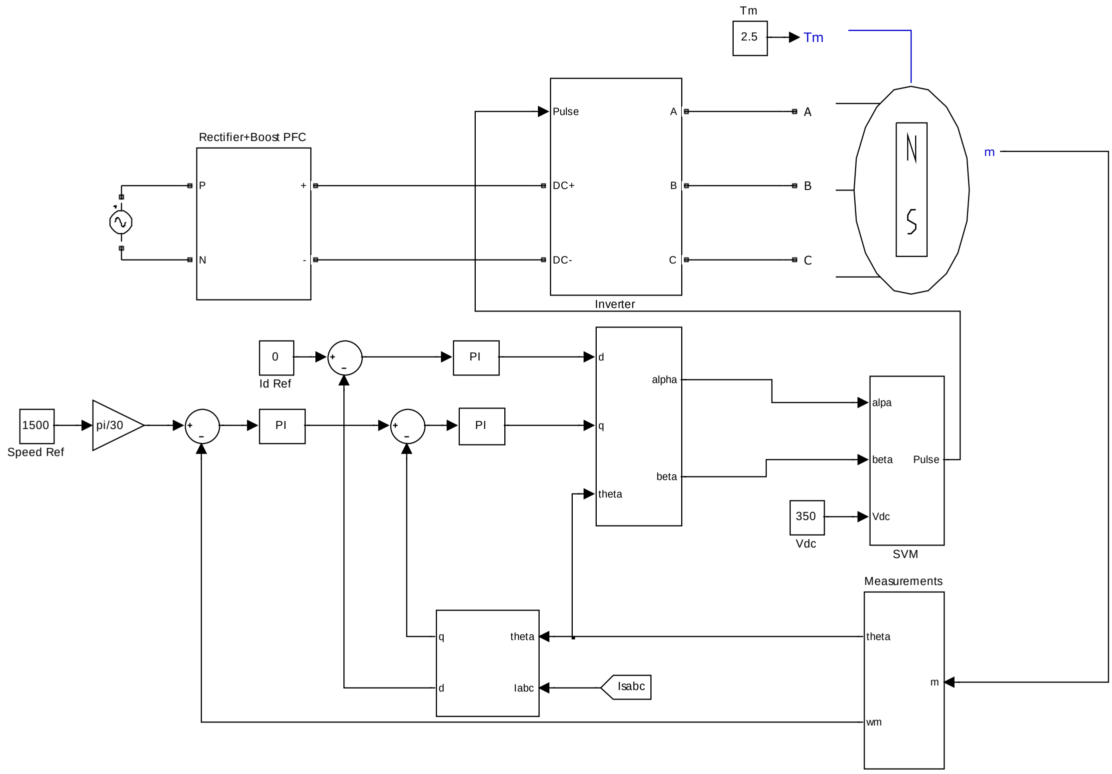

Figure 8 MATLAB/Simulink model of Power factor improvement of Vector controlled PMSM Drive.

Simulation Results

The boost converter is simulated with the designed values and the results are obtained. For proper visualization of the waveforms the variable are appropriately scales. The figure below shows the input voltage and input current waveforms.

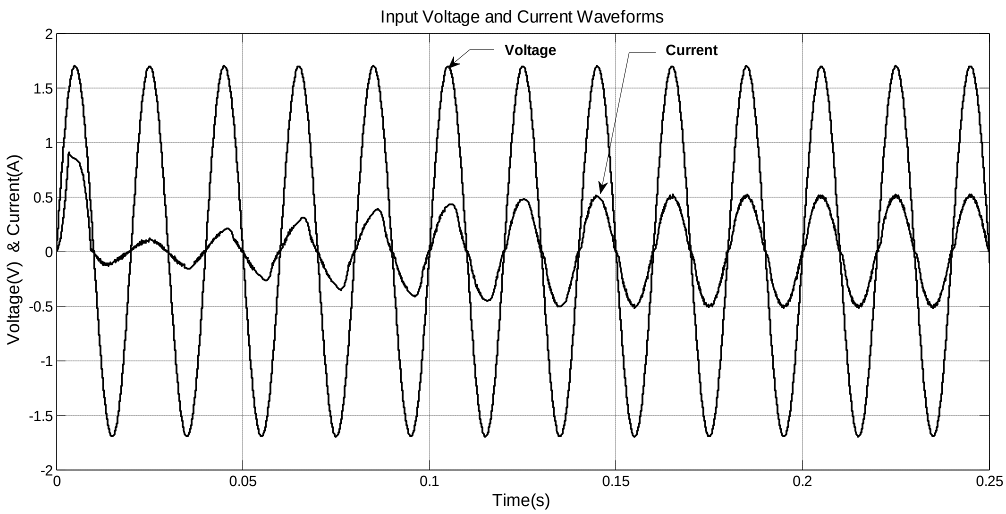

Figure 9 Input AC voltage and current waveforms

It can be observed that the voltage and current waveforms are in phase which establishes unity power factor operation. The initial rise in input current is due to the charging of the DC bus capacitor. The below figure show the rectified

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voltage and inductor current. It should be observed that the inductor current waveform and rectified voltage waveforms are similar in shape.

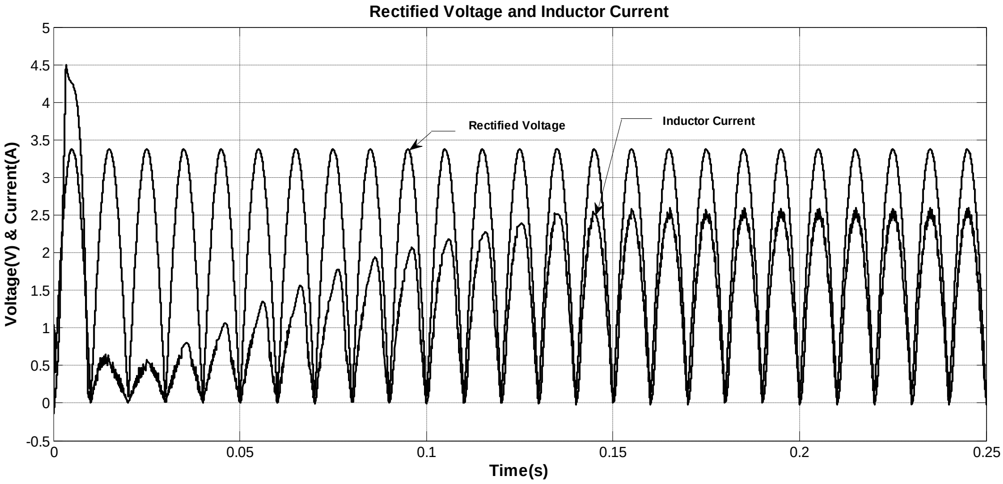

Figure 10 Rectified voltage and inductor current waveforms

The output voltage waveform is illustrated below, it shows that the output DC voltage is regulated and maintained at 400V.

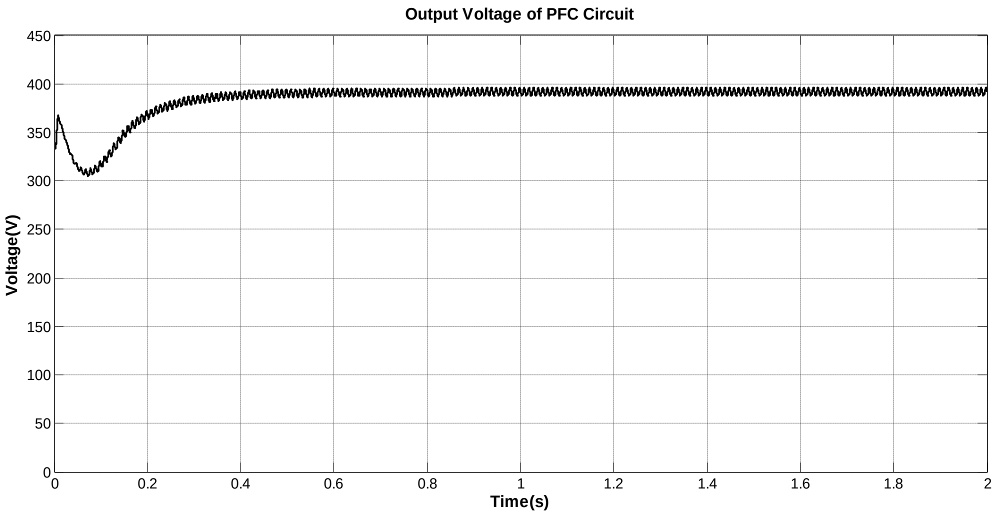

Figure 11 output voltage of PFC circuit

Figurebelow shows the input AC voltage, rectified voltage and output DC voltage waveforms.The performance of the PFC circuit is tested by varying the load resistance and the THD of input current is calculated in each case and tabulated in Table 1

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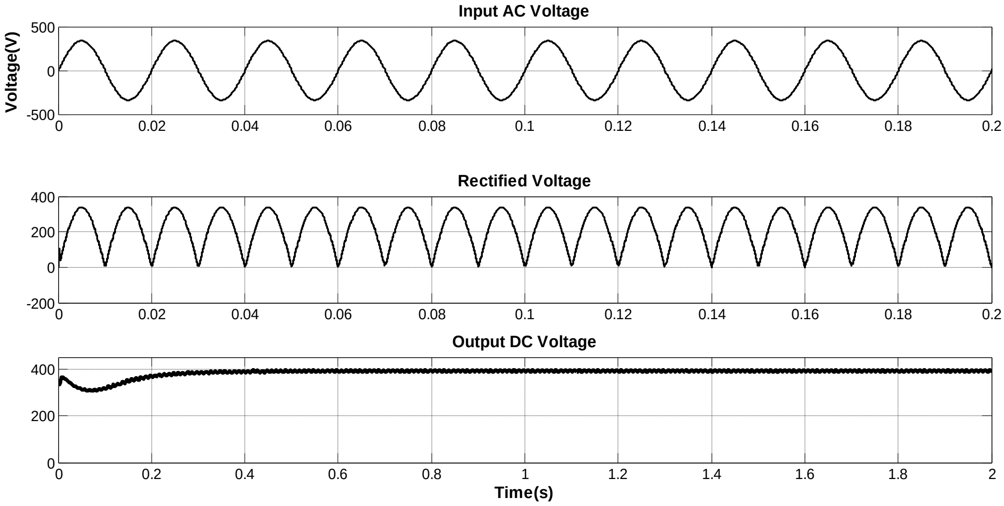

Figure 12 Input voltage,Rectified voltage and output DC voltage waveforms

TABLE II Simulation Results

Sl.No.	**PARAMETERS**	**LOAD**			
		384W	**356W**	**334W**	**252W**
1	DC Output voltage (V)	391	462	516	504
2	Load current(A)	0.98	0.77	0.646	0.502
3	Distortion factor	0.9984	0.9983	0.9982	0.9986
4	Displacement factor	0.9998	0.9999	0.9998	1.000
5	Power factor	0.9982	0.9982	0.9980	0.9986

The performance of the drive is assessed by varying the load torques at various instants. The variation of load torque is shown below and the drive is expected to drive the load torque maintaining the set speed.

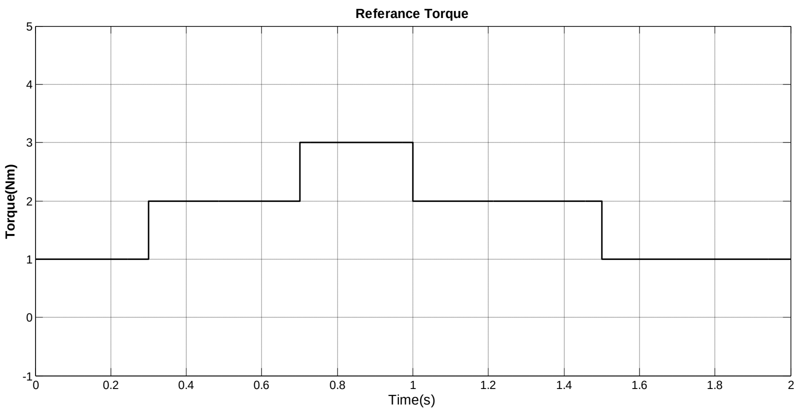

Figure 13 Referance torque

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The figure below illustrates the speed of the PMSM in rotations per minute and electromagnetic torque developed by the motor. It is fairly obvious to see that the electromagnetic torque meets the load torque maintaining the set speed of 1500 RPM.

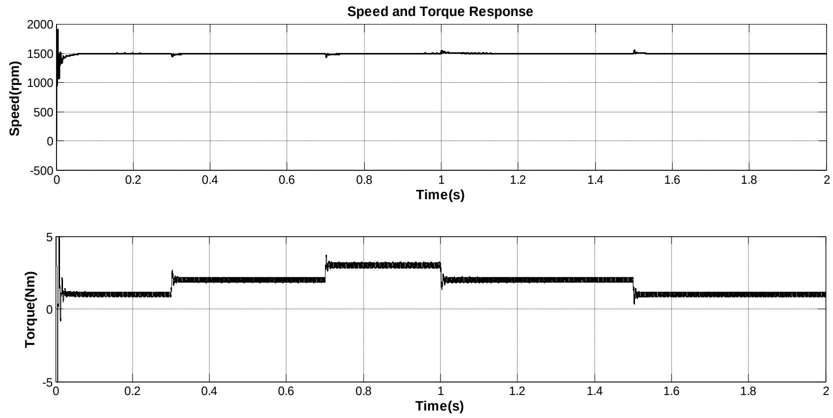

Figure 14 Speed and load torque responce

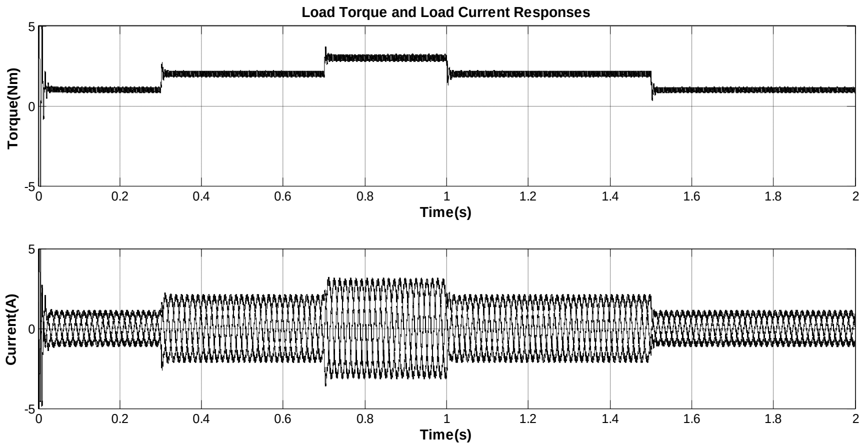

Figure 15 Load torque and load current responces

Figure above shows load torque response and load current waveform. It can be seen that the load currentvaries in accordance to the load torque response. The figure below shows the current waveform during the time interval 0 to 0.2s

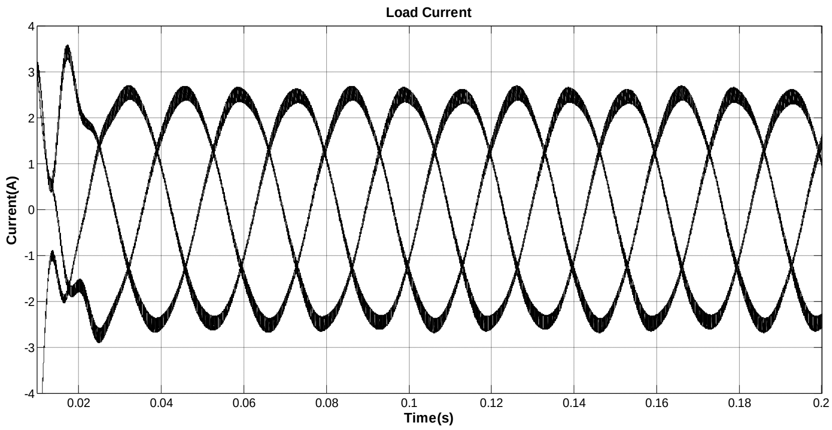

Figure 16 Load current waveform under constant load torque

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The figure below shows the torque and q-axis stator current in rotating reference frame. It is evident from the plot that the vector controlled PMSM drive acts like a torque amplifier that amplifies the stator q-axis current command.

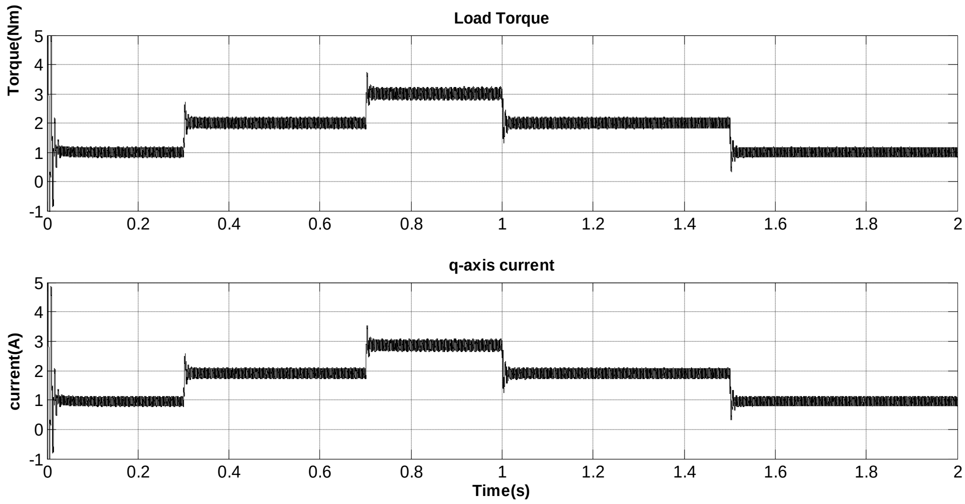

Figure 17 Load torque and q-axis current responses

VIII. EXPERIMENTAL RESULTS

The power factor correction is performed using PFC IC. The circuit diagram is given below. This circuit is implemented in a PCB and the circuit is operated under discontinuous conduction mode and the results were obtained.

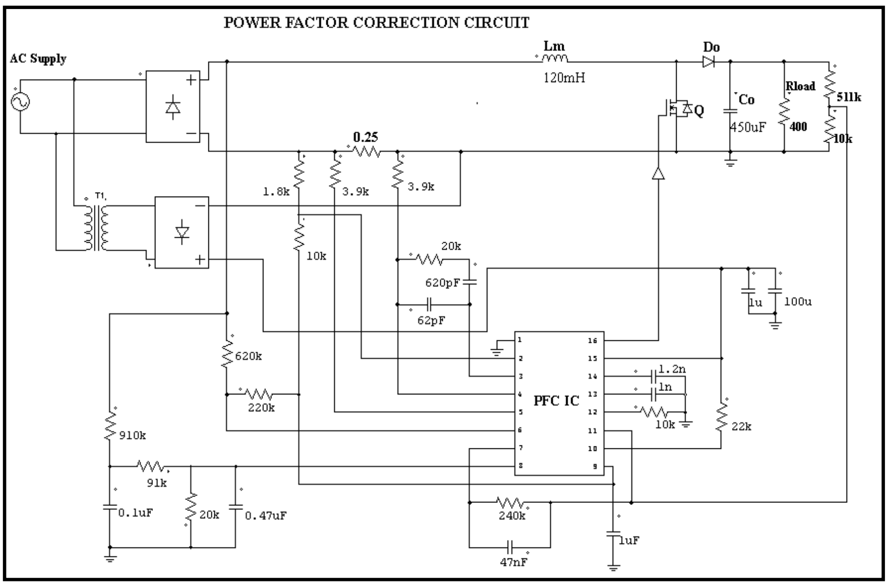

Figure 18 Power factor correction circuit

The overall experimental setup is shown in Figure:19. The initial testing was done with low voltage of 24V AC as input which is shown in figure given below. The input voltage is supplied thorugh an autotransformer.

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Figure 19 Experimental setup

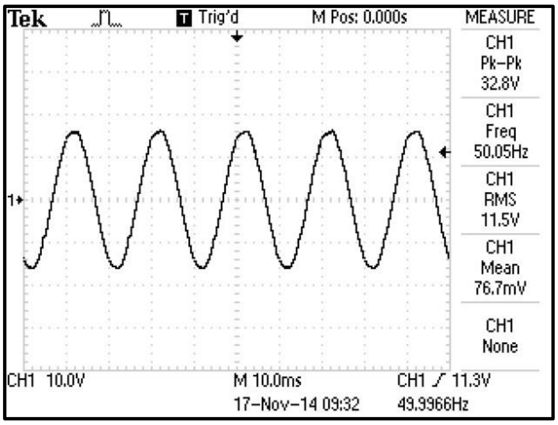

Figure 20 Input AC voltage waveform

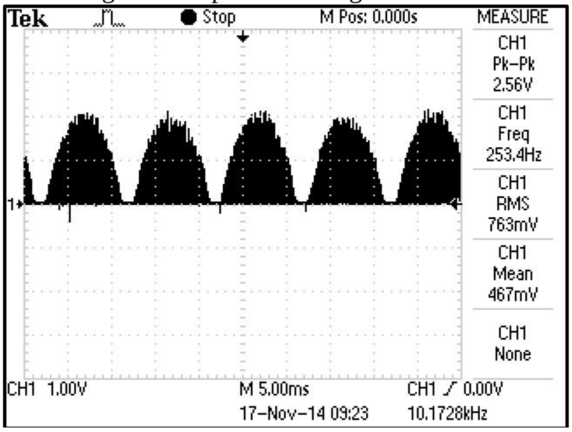

Figure 21 Inductor current waveform

Figure 20 shows the input AC voltage waveform from autotransformer. Figure 21 shows the inductor current waveform measured across the sense resistor. It can be oserved that the inductor current is discontinous. The converter operates in discontinous mode as the load current is set to a low value

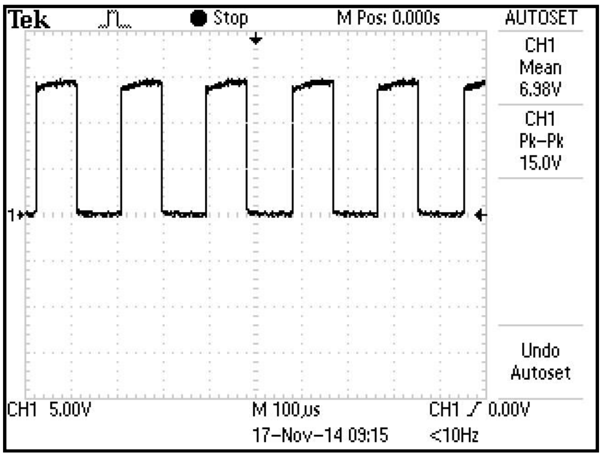

Figure 22 Gate pulse waveform

Figure 22 shows the gate pulse for the MOSFET, and it is captured from gate pulse pin of power factor correction IC.. The carrier ramp waveform is compared with the dc error value and hence the PWM signals are generated. The frequency of the ramp signal is decided by externally connected RC network.

IX. CONCLUSION

High efficiency, high performance drive can be realized with the help of a PMSM and sensored field oriented control technique. The field orientation conditions are attained by aligning the rotor flux vector along the direct axis. Dynamic torque control under different speeds is found to be the highlight of vector control. As all practical drive systems employ front end diode bridge rectifier to create the DC bus, all power quality issues associated with diode bridge rectifier are inherent in drive systems employing this scheme. But these issues were addressed by the use of a power factor correction unit based on a boost converter. The design and operation of the PFC unit were discussed in length. A prototype is attempted for PFC unit and it is tested in discontinuous mode of operation and the results are as predicted.

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