



GLOBAL JOURNAL OF RESEARCHES IN ENGINEERING
MECHANICAL AND MECHANICS ENGINEERING
Volume 13 Issue 9 Version 1.0 Year 2013
Type: Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals Inc. (USA)
Online ISSN: 2249-4596 Print ISSN:0975-5861

Modelling, Simulation of Permanent Magnet Synchronous Machine Drive using FOC Technique

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GJRE-A Classification : 040401



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Modelling, Simulation of Permanent Magnet Synchronous Machine Drive using FOC Technique

Rajendra Aparnathi ^α & Ved Vyas Dwivedi ^σ

Abstract- The research work deals with the detailed modeling of a permanent magnet synchronous motor drive system in Simulink. Field oriented control is used for the operation of the drive. The simulation includes all realistic components of the system. This enables the calculation of currents and voltages in different parts of the inverter and motor under transient and steady conditions. The losses in different parts are calculated, facilitating the design of the inverter. A closed loop control system with a Proportional Integral (PI) controller in the speed loop has been designed to operate in constant torque and flux weakening regions. Implementation has been done in Simulink.

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I. INTRODUCTION

An electrical drive, as shown in Fig. 1.1 can be defined in terms of its ability to efficiently convert energy from an electrical power source to a mechanical load. The main purpose of the drive is to control a mechanical load or process. The direction of energy flow is generally from electrical to mechanical i.e. motoring mode with power flow from the power source to the mechanical load via the converter and machine as shown in Fig. 1.1. However the energy flow can be reversed in some cases, in that case the drive often is configured bi-directional to allow energy flow from the mechanical load to the power source. Modern electrical drives as considered utilize power electronic devices to (digitally) control this power conversion process. A feature which is highlighted in Fig. 1.1 by the presence of the modulator and control unit. The controller module shown in Fig. 1.1 must be able to communicate with higher level computer systems because drives are progressively networked. Communication links to high level computer networks are required to support a range of functions, such as commissioning, initialization, diagnostics and higher level process control.

The embedded digital controller shown in Fig. 1.1 houses the high-speed logic devices, processors

and electronic circuitry needed to accommodate the sensor signals derived from mechanical and electrical sensors. Further the most suitable control algorithms must be developed to facilitate the power conversion processes within the drive. With the advent of new materials and new design tools, novel machine concepts such as linear machines, PM magnet, switched reluctance and transversal flux machines etc. have been developed over the past twenty years. Power electronic devices have on the other hand been around for about forty five years, while high-speed digital devices have only been available over the past twenty five years.

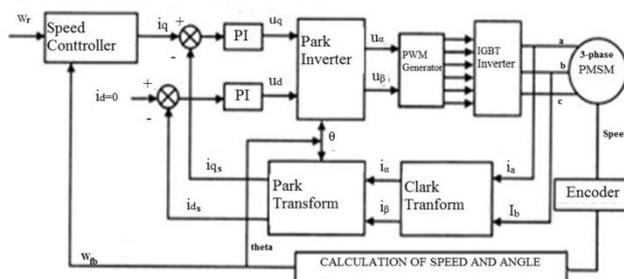


Figure 1 : Basic block diagram of drive system

The Suitable control algorithm named field-oriented control has been developed. Ongoing drive development is fuelled by the continuous emergence of new drive related drive product such as new processors, sensors and most importantly new control algorithms. Such developments enhance drive robustness, improve reliability, and expand the use of electrical drives to other industrial applications, hitherto considered to be unfeasible. The power range associated with these industrial applications is impressive and typically ranges from a few milliwatts to hundreds of megawatt, which underlines the flexibility and broad application base of modern drive technology. One of the recently used electrical machines is the Permanent Magnet Synchronous Machine (PMSM), because of its resemblance with the Direct Current machine in terms of controls.

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II. PMSM DRIVE SCHEME

Permanent Magnet Synchronous Machines are being increasingly used in industrial applications because of the many advantages they present over the other types of machines. These machines are compact and have very high efficiency, and the drives associated are well developed and reliable. However, the main drawback for these drives is the need for an accurate knowledge of the rotor position to achieve the most efficient drive.

An optical encoder usually ensures this accurate knowledge of the shaft position. This encoder introduces extra cost, extra wiring leading to a decrease in the overall reliability of the drive. One particular type of PMSM known as Brushless Direct Current (BLDC) machine uses three or fewer low-resolution sensors to operate, and has trapezoidal waveforms. Nevertheless these machines have a non-negligible torque ripple. In applications where a smooth torque profile is required or where vibrations have to be low these machines cannot replace the sinusoidal PMSM.

Numerous researches have been conducted to eliminate the encoder in PMSM drives and it is necessary to find among them a realistic sensorless method whose implementation is feasible for a defined set of industrial applications, taking into account its complexity and reliability.

One can find various names for the same motor based on different approaches or points of view. Brushless synchronous AC motors are one type of synchronous motor. Synchronous AC motors are sinusoidal current-driven machines that use a quasi-sinusoidal distributed AC stator winding and inverter. The three main types are shown in Figure 2. Figure 2. (a) Shows the cross-section of a surface-mounted PM-motor (SPM). Radial or straight-through magnetized permanent magnets are fixed to an iron rotor core. The magnets are normally glued to the rotor surface. Due to its isotropic rotor, the d- and q-axis inductances are identical.

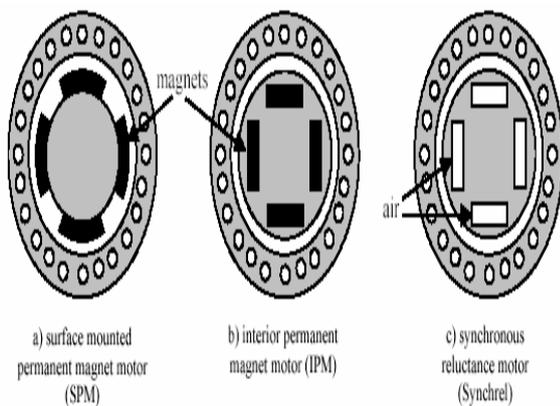


Figure 2 : Cross section of the three main types of PMSM

Therefore no reluctance torque occurs. In Figure 2.2b, a possible design of an interior permanent magnet motor (IPM) is presented in which the magnets are buried in the rotor core. Setting the magnets inside the rotor improves the mechanical strength and magnetic protection. An IPM motor exhibits both magnetic and reluctance torque. These features allow the PMSM drive to be operated in high-speed mode by incorporating the field –weakening technique. Figure 2.2c shows the cross-section of a synchronous reluctance motor. Without permanent magnets, the reluctance motor produces only reluctance torque.

III. DETAILED MODELLING OF PMSM

Detailed modeling of PM motor drive system is required for proper simulation of the system. The d-q model has been developed on rotor reference frame as shown in Fig. 3. At any time t, the rotating rotor d-axis makes an angle θ_r with the fixed stator phase axis and rotating stator mmf makes an angle α with the rotor d-axis. Stator mmf rotates at the same speed as that of the rotor.

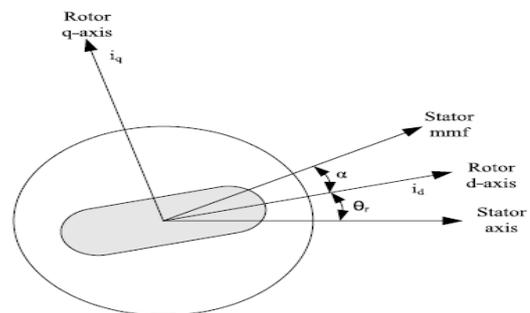


Figure 3 : Motor axes

The model of PMSM without damper winding has been developed on rotor reference frame using the following assumptions:

- ✓ Saturation is neglected.
- ✓ The induced EMF is sinusoidal.
- ✓ Eddy currents and hysteresis losses are negligible.
- ✓ There are no field current dynamics.

Voltage equations with respect to rotor axis are given by:

$$v_q = R_s i_q + w_r \lambda_d + \rho \lambda_q \quad (1)$$

$$v_d = R_s i_d - w_r \lambda_q + \rho \lambda_d \quad (2)$$

Flux Linkages are given by

$$\lambda_q = L_q i_q \quad (3) \quad \lambda_d = L_d i_d + \lambda_f \quad (4)$$

Substituting equations (3) and (4) into (1) and (2)

$$v_q = R_s i_q + w_r (L_d i_d + \lambda_f) + \rho \lambda_q \quad (5)$$

$$v_d = R_s i_d - w_r L_q i_q + \rho (L_d i_d + \lambda_f) \quad (6)$$

Arranging equations (5) and (6) in matrix form

$$\begin{pmatrix} v_q \\ v_d \end{pmatrix} = \begin{pmatrix} R_s + \rho L_d & \omega_r L_d \\ -\omega_r L_q & R_s + \rho L_d \end{pmatrix} \begin{pmatrix} i_q \\ i_d \end{pmatrix} + \begin{pmatrix} \omega_r \lambda_r \\ \rho \lambda_f \end{pmatrix} \quad (7)$$

The developed motor torque is being given by

$$T_e = \frac{3}{2} \left(\frac{P}{2} \right) (\lambda_d i_q - \lambda_q i_d) \quad (8)$$

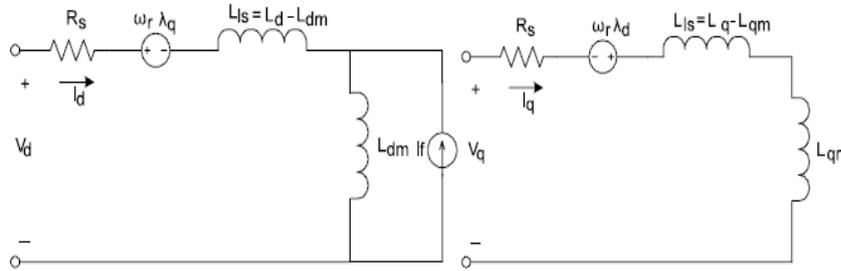


Figure 5 : Equivalent circuit of Permanent Magnet Synchronous Motor

V. CURRENT CONTROLLED VOLTAGE SOURCE INVERTER

The motor is fed from a voltage source inverter with current control. The control is performed by regulating the flow of current through the stator of the motor. Current controllers are used to generate gate signals for the inverter. Proper selection of the inverter devices and selection of the control technique will

IV. EQUIVALENT CIRCUIT OF PERMANENT MAGNET SYNCHRONOUS MOTOR

Equivalent circuit of the motor is used for study and simulation of motor. From the d-q modelling of the motor using the stator voltage equations the equivalent circuit of the motor can be derived. Assuming rotor d axis flux from the permanent magnets is represented by a constant current source.

guarantee the efficacy of the drive. Voltage Source Inverters are devices that convert a DC voltage to AC voltage of variable frequency and magnitude. They are very commonly used in adjustable speed drives and are characterized by a well defined switched voltage wave form in the terminals. Fig. 6 shows a voltage source inverter. The AC voltage frequency can be variable or constant depending on the application.

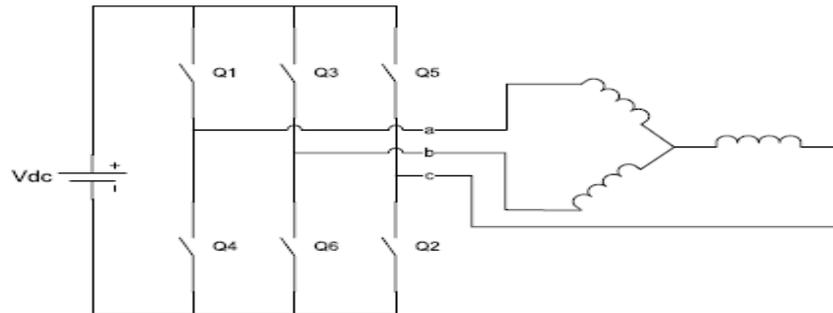


Figure 6 : Voltage Source Inverter Connected to a Motor

Three phase inverters consist of six power switches connected as shown in Fig. 6 to a DC voltage source. The inverter switches must be carefully selected based on the requirements of operation, ratings and the application. There are several devices available today and these are thyristors, bipolar junction transistors, MOS field effect transistors, insulated gate bipolar transistors and gate turn off thyristors.

VI. COORDINATE TRANSFORMS

Through a series of coordinate transforms determine and control the time invariant values of torque and flux with classic PI control loops. The process

begins by measuring the 3-phase motor currents. The instantaneous sum of the three current values is zero. Therefore by measuring only two of the three currents we can determine the third. Because of this fact hardware cost can be reduced by the expense of the third current sensor.

a) Clarke Transform

The first coordinate transform, called the Clarke Transform, moves a three-axis, two-dimensional coordinate system, referenced to the stator, onto a two-axis system, keeping the same reference.

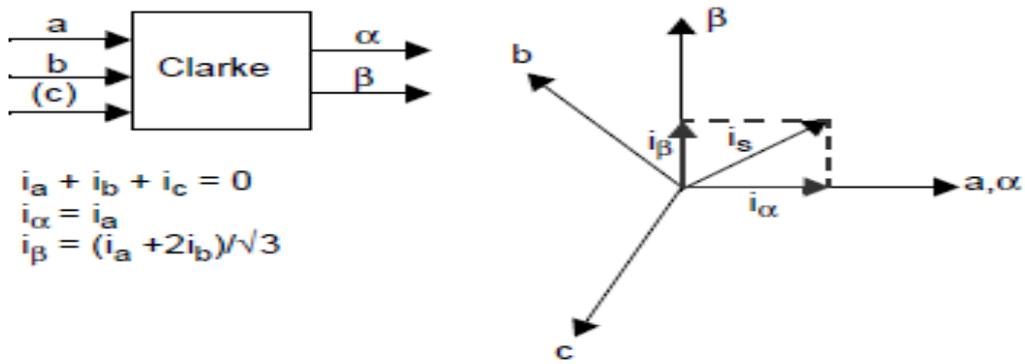


Figure 7 : Clarke Transform

b) Park Transform

At this point, you have the stator current represented on a two-axis orthogonal system with the axis called α - β . The next step is to transform into another

two-axis system that is rotating with the rotor flux. This transformation uses the Park Transform. This two-axis rotating coordinate system is called the d-q axis. θ represents the rotor angle.

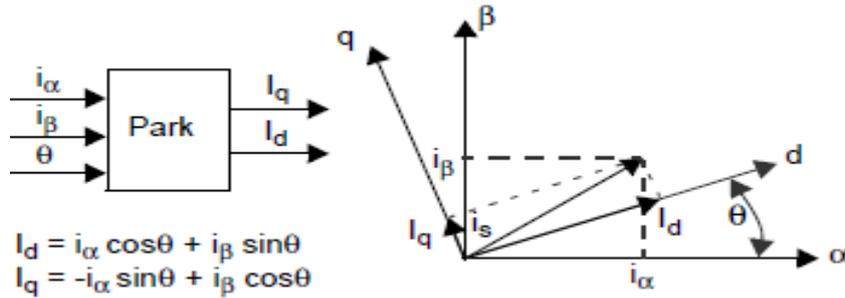


Figure 3.3 : Park Transform

c) PI Control

Three PI loops are used to control three interactive variables independently. The rotor speed, rotor flux and rotor torque are controlled by a separate PI module. There are three interdependent PI control loops in this application. The outer loop controls the motor speed. The two inner loops control the transformed motor currents, i_d and i_q . As mentioned previously, the i_d loop is responsible for controlling flux, and the i_q value is responsible for controlling the motor torque.

d) Inverse Park Transform

After the PI iteration, you have two voltage component vectors in the rotating d-q axis. You will need to go through complementary inverse transforms to get back the 3-phase motor voltage. First, you transform from the two-axis rotating d-q frame to the two-axis stationary frame α - β . This transformation uses the Inverse Park Transform.

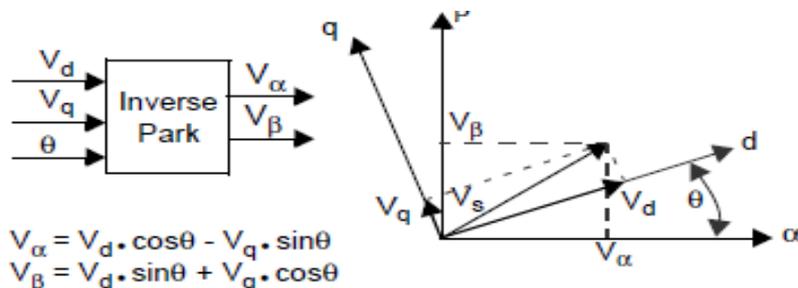


Figure 8 : Inverse Park transform

e) *Inverse Clarke Transform*

The next step is to transform from the stationary two-axis α - β frame to the stationary three-axis, 3-phase

reference frame of the stator. Mathematically, this transformation is accomplished with the Inverse Clark Transform.

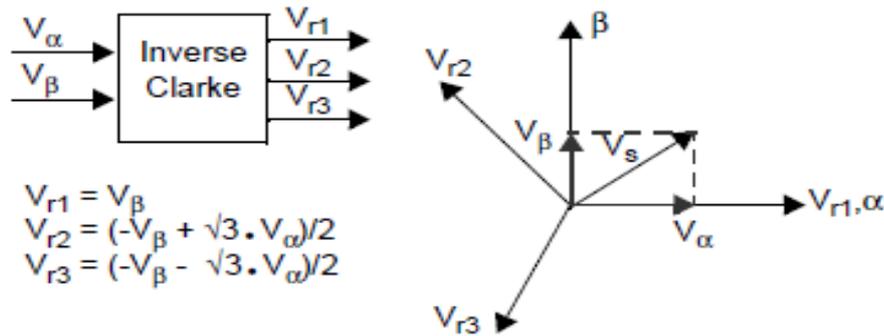


Figure 9 : Inverse Clarke Transform

VII. CURRENT CONTROL TECHNIQUE

The power converter in a high-performance motor drive used in motion control essentially functions as a power amplifier, reproducing the low power level control signals generated in the field orientation controller at power levels appropriate for driving the machine. High-performance drives utilize control strategies which develop command signals for the AC machine currents. The basic reason for the selection of current as the controlled variable is the same as for the DC machine; the stator dynamics (effects of stator resistance, stator inductance, and induced EMF) are eliminated. Thus, to the extent current regulatory functions as an ideal current supply, the order of the system under control is reduced and the complexity of the controller can be significantly simplified.

Current regulators for AC drives are complex because an AC current regulator must control both the amplitude and phase of the stator current. The AC drive current regulator forms the inner loop of the overall motion controller. As such it must have the widest bandwidth in the system and must by necessity have zero or nearly zero steady-state error.

Both current source inverters (CSI) and voltage source inverters (VSI) can be operated in controlled

current modes. The current source inverter is a "natural" current supply and can readily be adapted to controlled current operation. The voltage source inverter requires more complexity in the current regulator but offers much higher bandwidth and elimination of current harmonics as compared to the CSI and is almost exclusively used for motion control applications.

VIII. HYSTERESIS CURRENT CONTROLLER

Hysteresis current controller can also be implemented to control the inverter currents. The controller will generate the reference currents with the inverter within a range which is fixed by the width of the band gap. In this controller the desired current of a given phase is summed with the negative of the measured current. The error is fed to a comparator having a hysteresis band. When the error crosses the lower limit of the hysteresis band, the upper switch of the inverter leg is turned on. But when the current attempts to become less than the upper reference band, the bottom switch is turned on. Fig. 10 shows the hysteresis band with the actual current and the resulting gate signals. This controller does not have a specific switching frequency and changes continuously but it is related with the band width.

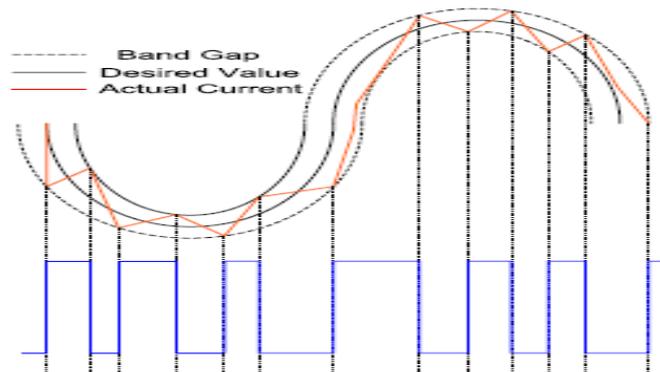


Figure 10 : PWM signal from Hysteresis controller

a) Modeling, Simulation

Study of electric motor drive needs the proper selection of a simulation tool. Their complex model needs computing tools capable of performing dynamic simulation. SIMULINK is a toolbox extension of the MATLAB program. It is a program for simulating dynamic systems.

Simulink has the advantages of being capable of complex dynamic system simulations, graphical environment with real time programming and broad selection of tool boxes. The simulation environment of Simulink has a high flexibility and expandability which allow the possibility of development of a set of functions for a detailed analysis of the electrical drive. Its graphical interface allows selection of functional blocks, their placement on a worksheet and description of signal flow by connecting their data lines using a mouse device.

System blocks are constructed of lower level blocks grouped into a single makeable block. Simulink simulates analogue systems and discrete digital systems. Fig.-11 shows complete simulation diagram of PMSM drive using FOC technique. Here first take speed feedback, rotor angle position and three phase current for different calculation. Three phase current are first converted into two phase component using Clarke transformation and that component are again converted in to d-q component using Park transformation which is compared with the reference d-q component generated by comparing two speeds i.e. reference speed and feedback speed using PI speed controller. After comparison of two current we can get three reference phase current using inverse Clarke and Park transformation and using Hysteresis current controller compare the actual current MATLAB modeling results.

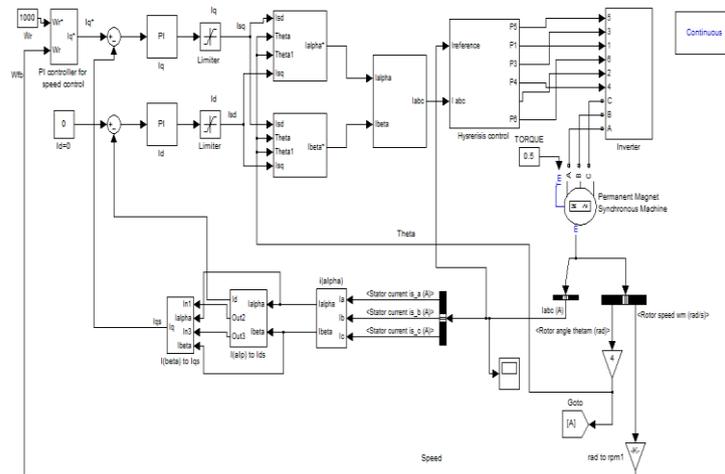


Figure 11 : Simulation circuit of PMSM Drive circuit

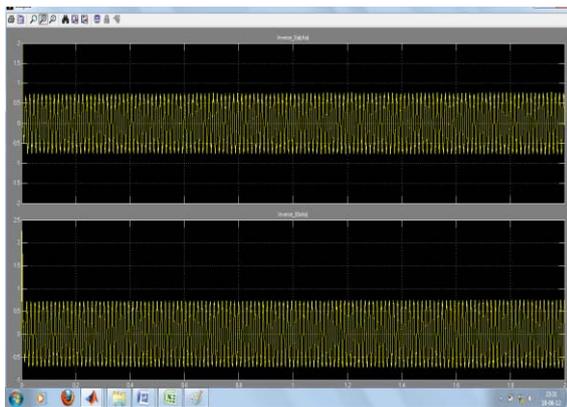


Figure 12 : Inverse Transformed current i_{α} and i_{β}

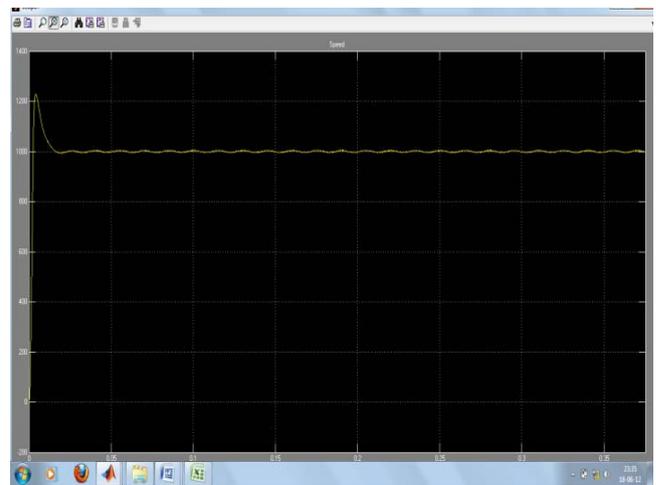


Figure 13 : Gating signal for upper switches of VSI

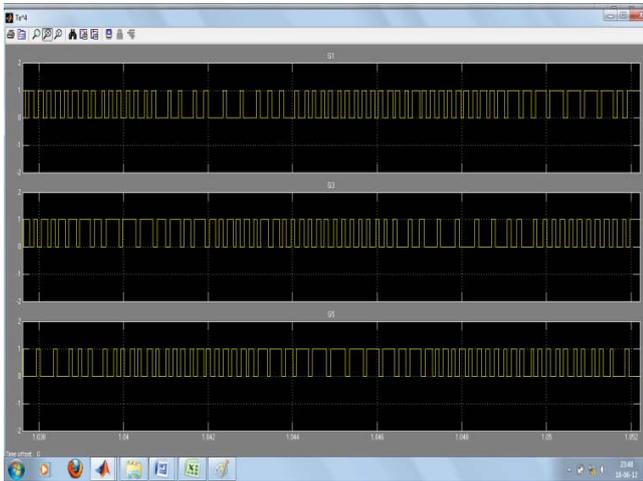


Figure 13 : Rotor speed



Figure 14 : Phase voltage

IX. TESTING AND EXPERIMENTAL RESULT

In college laboratory set up, we are using different controller and STM32F103 Processor is used for the control signal generation and these control signals are given to the 3-Phase IPM module. This chapter illustrates different experimental results Experimental Results:

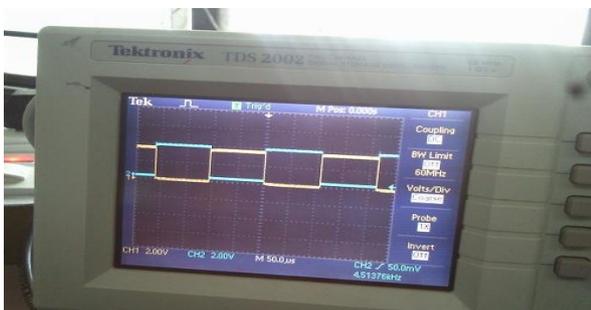


Figure 16 : gating signal showing delay

Table 1 : Speed v/s Voltage at constant torque

Speed (rpm)	Torque(N-m)	Voltage(Volt)
1700	1.6	244.2
1600	1.6	230.4
1600	1.6	210.2
1400	1.6	194.1
1300	1.6	180
1200	1.6	169.3
1100	1.6	166.4
1000	1.6	144.3
900	1.6	130
800	1.6	111.2
700	1.6	100.2
600	1.6	90.26

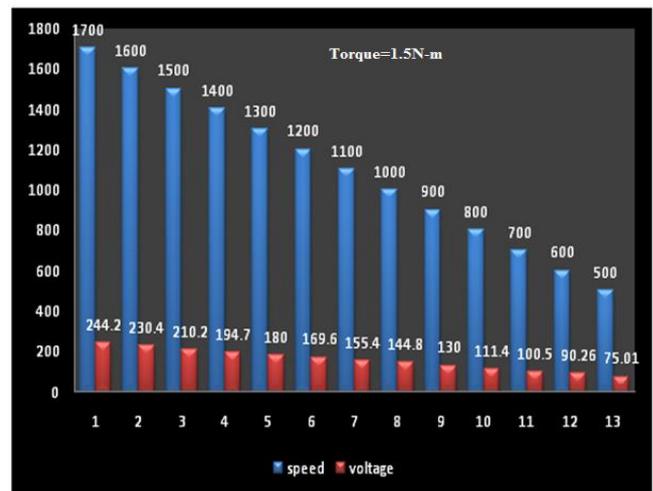


Figure 17 : Graph between speed and voltage

X. CONCLUSION

This paper covers major issues and solutions dealing with sensorless Field Orientation control of permanent magnet synchronous motor (PMSM) over wide speed range in constant torque region. A constant torque control technique has been implemented and the following conclusions can be drawn.

Moreover no saturation of current controller occurs under load conditions, resulting in control robustness in the constant torque region. A single shunt current sensing measurement has been developed for the estimation of rotor position angle in the sensorless Field Orientation Control of PMSM without saliency. Compared to conventional sliding mode observers, the proposed scheme has the feature which gives the flexibility to design parameters of single shunt current measurement with wide operating speed range.

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