A Novel Three Phase Voltage Source Converter Fed PMSM Drive

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Abstract— This paper presents a three Phase Voltage Source Converter (VSC) Fed Permanent Magnet Synchronous Motor drives for automotive application. In the proposed work the Voltage Source Converter (VSC) fed Permanent Magnet Synchronous Motor (PMSM) drive system is designed, simulated and implemented using Microcontroller. Simulation is carried out on MATLAB-Simulink software under various operating Conditions to show the effectiveness of proposed methodology. &a lab setup is designed and implemented based on a Four-pole, 373 W Permanent Magnet Synchronous Motor drive. The simulated performance along with test results of the Permanent Magnet Synchronous Motor drive is studied for starting, steady-state condition, and speed and load perturbation. It is found that, speed remains constant at constant frequency with varying load conditions. Experimental results show that the drive system has a good dynamic response in terms of speed and torque response. Hence Permanent Magnet Synchronous Motor drive is suitable for Automotive Application.

Keywords— **Permanent Magnet Synchronous Motor (PMSM), Main power circuit, Control circuit, Isolator and driver Circuit. Microcontroller.**

I. INTRODUCTION

In an ace drives, permanent magnet synchronous machine drives have been increasingly applied broadly in automotive industry. The main advantages of PMSM are high torque to inertia ratio, reliability, power density and efficiency. Continuous cost reduction of magnetic materials having large energy density with larger value of coercitivity makes the ac drives based on permanent magnet synchronous machine more attractive and competitive. In the automotive industry, the performance of permanent magnet synchronous machine drives are ready to meet least requirement such as high power factor, faster dynamic response, and wide operating speed range. Subsequently, a continuous use of permanent magnet synchronous motor drives will surely increase in the nearby future [1-3]. The work, allowing for the faster torque response with ac machines just like to that of dc machines, has became much advanced and also become popular in an automotive industry. To achieve the FOC of permanent magnet synchronous motor, knowledge of the rotor position is required. Usually the rotor position is measured by a shaft encoder & Hall sensors. [4-8]. the advantages of PM machines make them highly attractive for automotive industry, such as hybrid electrical vehicles [11- 16]. The permanent magnet synchronous machine drive in an Electrical power steering system can be considered as a torque amplifying and tracking system. In the column type Electrical power steering system, the permanent magnet synchronous motor is linked to the steering shaft via a reduction gear, so that the motor vibrations and torque fluctuation are transferred directly through the steering wheel to the hands of the driver. The direct drive systems normally require larger shaft torque at standstill along with lower speeds as well as constant output power over the wide speed range. For such requirements, the Permanent Magnet machines are designed to operate in the constant torque mode and their speed being below the rated speed and in the constant power mode when above the rated speed. The constant torque operation of Permanent Magnet motor can be achieved easily using the vector control. But, when the speed is greater than the base speed, the produced back-EMF of Permanent Magnet motor is greater than the line voltage and then the motor doesnot continuously produce torque due to voltage and current constraints. By applying negative magnetizing current component to weaken the air-gap flux, the operating speed range can be extended [9, 10].

II. PRINCIPLE OF OPERATION

The permanent magnet synchronous motor drive consists of Diode bridge rectifier with filter circuit, Main power circuit, Control circuit, Isolator and driver circuit, over current protection circuit, permanent magnet synchronous motor and Loading arrangement. In PMSM with three stator windings for the motor operation, supply voltages are obtained using three phase MOSFET bridge inverters. Shunt capacitor filter has been used for filtering purpose. MOSFET bridges are fed with dc voltage which is obtained by rectifying ac voltage.

The control circuit can controlled the Operation of the MOSFET Bridge circuit. The control circuit are for the switching operation of MOSFET circuit. Control circuit consists of clock generator counter and Erasable Programmable Read Only Memory. First data required to generate gating pulses is calculated and is stored in Erasable Programmable Read Only Memory. This data is outputted at the output of the Erasable Programmable Read Only Memory by generating the address of the memory location with the help of 4 bit binary ripple counter. Clock input required for the operation of the counter is generated using IC 555 in a stable mode. Frequency of the gating signals coming out of Erasable Programmable Read Only Memory is dependent on the frequency with which addressing is done which is turn dependent on the clock frequency. Thus by varying the clock frequency of gating signal is varied. Here we obtain variable frequency output gating signal outputted by Erasable Programmable Read Only Memory cannot be directly applied to MOSFET Bridge as they are very weak. So isolator and driver circuit is used. Necessary isolation of low power control circuit from high power bridge circuit is obtained by using optoisolator. The motor is connected on load and its speed depends on the stator supply frequency. The block schematic of proposed Three Phase Voltage Source Inverter Fed Variable Speed permanent magnet synchronous motor Drive System in fig.1. The output Voltage Waveforms for 120^0 mode six-step 3-Phase VSI is shown in fig.2.

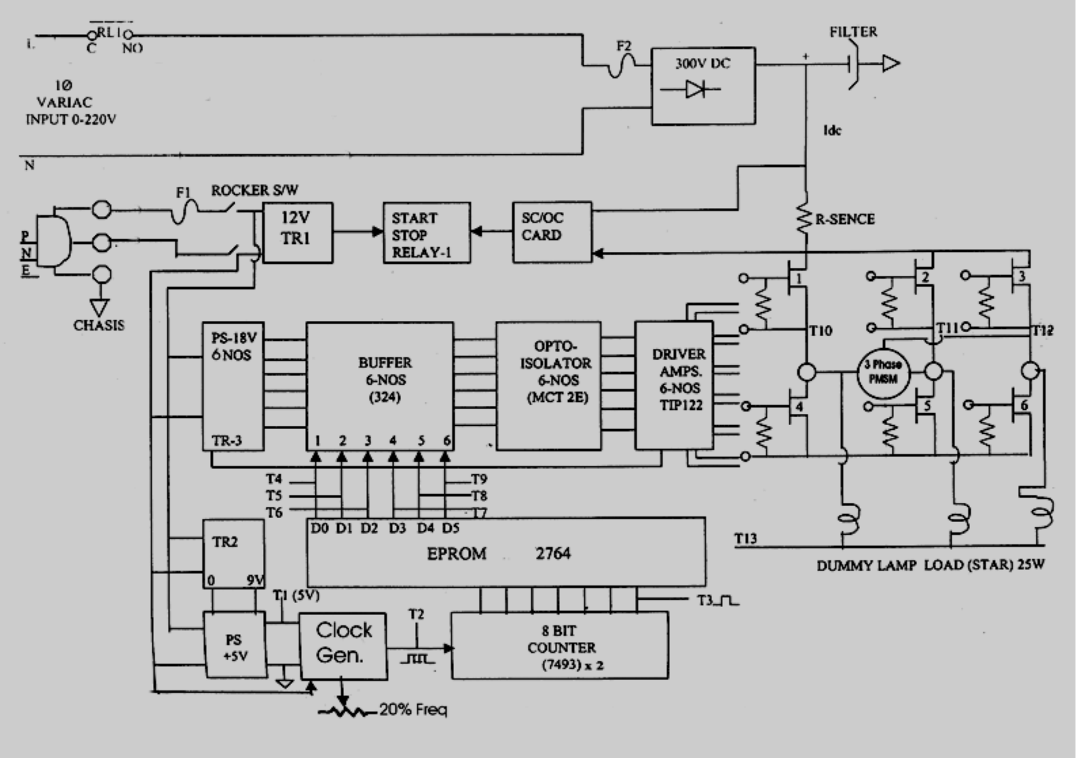

Fig.1 The block schematic of three Phase Voltage Source Converter (VSC) Fed PMSM Drive System.

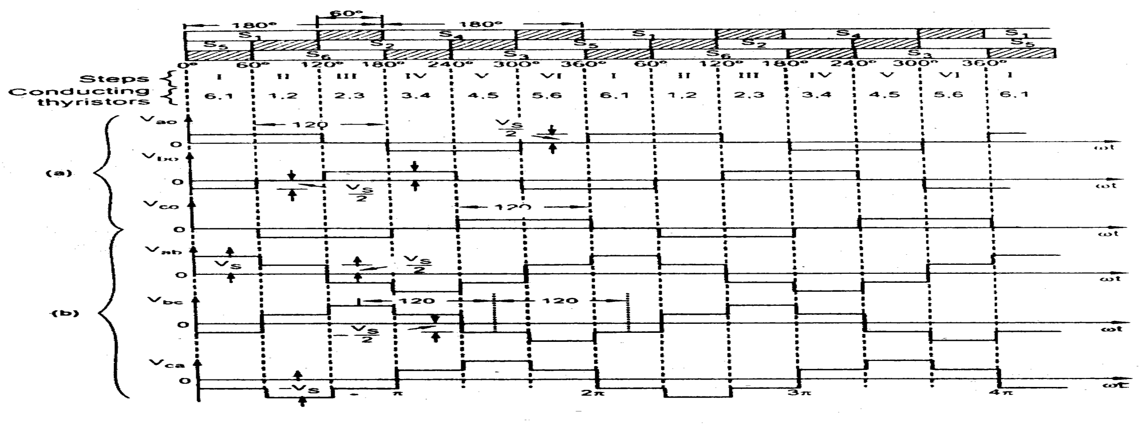

Fig.2.Voltage Waveforms for 120^0 mode six-step 3-Phase VSC

III. LOAD MODELING

The model equations of the PMSM are

$$V_d = RI_d + L_d(dI_d/dt) - P\omega L_q I_q \qquad (1)$$

$$V_q = RI_q + L_q(dI_q/dt) + P\omega L_d I_d + P\omega\lambda_f \qquad (2)$$

$$T_e = T_L + B\omega + J_m(d\omega/dt) \qquad (3)$$

$$T_e = K_t I_q + (3/2)P\,(L_d - L_q)I_d I_q \qquad (4)$$

The d, q variables are related with a, b, c variables through the Park's transformation defined as:

$$\begin{bmatrix} Vq \\ Vd \\ Vo \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ \sin\theta & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}$$

The inverse Parks transformation is defined below:

$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - 2\pi/3) & \sin(\theta - 2\pi/3) & 1 \\ \cos(\theta + 2\pi/3) & \sin(\theta + 2\pi/3) & 1 \end{bmatrix} . \begin{bmatrix} Vq \\ Vd \\ Vo \end{bmatrix}$$

where
V_d,V_q–stator voltage of d and q axis
R – Stator resistance of PMSM
I_d,I_q - stator current in d and q axis
L_d ,L_q - stator inductance of d and q axis
T_e – Electromechanical torque

T_L – Load torque
B – Viscous friction constant,Nm/rad/sec
ω- Speed of rotor
J- Moment of inertia,kg.m^2

IV. HARDWARE DESIGN

The Hardware consists of Diode bridge rectifier with filter circuit, power circuit, control circuit & Specification of PMSM.

A. Design of Diode bridge rectifier and filter circuit-

Input line voltage = 230 Vac
Output dc voltage =300 vdc
Load current =1.5 Amp.
$Vm=\sqrt{2} \times 230$
$=325.26$ v
$Vdc=2\,Vm/\pi=2 \times 325.26/\pi$
=207.07 (without filter)
But with Capacitor filter
V_{dc} required =300 v
$V_{dc}=V_m-(Vrpp/2)$
$300=325.26-(Vrpp/2)$
$\therefore V_{rpp}=50.52$ v
$V_{r\,rms}=Vrpp/2\sqrt{3}$
$=14.58$ v
$\therefore r=V_{rrms}/vdc$
$=14.58/300$
$c=\frac{1}{4}\sqrt{3}f.\,r.\,Rs$
$=\frac{1}{4}\sqrt{3} \times 50 \times 0.48 \times 200$
$=300\ \mu f$
Selected capacitors $C_1 = 150\ \mu f$, 400 v
$C_2 = 150\ \mu f$, 400 v
and
$V_{ac\,(max)} = V_m = 325.26$ v
$V_{o\,(min)} = V_m = V_m - V_{rpp}$
$= 325.36 - 50.52$
$= 274.74$ v

$\theta = \sin^{-1}\ V_0(min) / V_0\,(max)$
$= \sin^{-1} \times 274.74 / 325.26$
$= 57.63^0$
diode conduction angle $= 90 - \theta$
$= 90 - 57.63^0$
$= 32.36^0$
I_p (surge current) $= T/T_1 \times Idc$
$= 360^0 / 32.36^0 \times 1.5$
$= 16.68$ A

4.1.1 Diodes:-

V_R (max)> V_m
> 325 Volts
I_f (ave) > I_0
> 1.5 A
Isurge > I_p
> 17 A
selected diode are D_1 to D_8 = IN 5408

B. Design of main power circuit- MOSFET bridge

While selecting MOSFET

V_{dc} > 0.707 x m_a Vdc [let m_a = 1 (max)]
> 0.707 x 1 x 300
> 212.1 volts
V_{gs} > 12 volts
I_d > I_L max
> 2 Amps

Switching time should be as small as possible selected MOSFET is IRF 840.

4.2.1 Snubber Circuit:

From data sheet of MOSFET
Turn off delay = 90 ns, fall time = 30 ns
Let to be design for maximum current capacity of MOSFET i.e. 8 Amps
C = I_0 T off / 2 V_d
= 8 x 120 ns / 2 x 212.5
= 0.0014 μF
Freewheeling Diode
I_f (avg) = 8 A
V_K = 600 V
Selected diodes D_{17} to D_{24} = IN5408
The reverse recovery current. I_n of the freewheeling diodes
V_d / R_s = I_n
But generally
I_n is limited 0.4 I_0
R = V_d /0.4 I_0 = 500 / 0.4 x 8
= 156.75 Ω
Selected resister R_7 to R_{14} = 150Ω 2 w each.

B. *Design of control circuit*-

Conduction mode	120 degree
Output Frequency	10 to 60 Hz
Pulse Generation	Using EPROM 256 location data

D. Three phase Permanent Magnet Synchronous Motor with Mechanical loading arrangement-

0.5 H.P (373 watt), 3 phase Delta connected, 1.4 amp, 270V, 1500rpm&25 W (3 lamps) dummy load for observation of Waveforms.

V. SIMULATION RESULTS

Voltage Source Converter-Fed PMSM Drive is simulated using MATLAB/Simulink.The model can determine the stator current, speed and electromagnetic torque. The Steady state & transient responses of the Voltage Source Inverter-Fed PMSM Drive are evaluated by simulating step changes in the torque responses at different speed. The variation in the motor speed as a function of inverter frequency & load at different frequency are shown in table1 to table3. The torque responses obtained at 1000rpm, 1200rpm, 1400rpm &1600rpm are shown in Fig.4 to Fig.11The Frequency, load & speed characteristics are shown in Fig.12 to Fig.20.

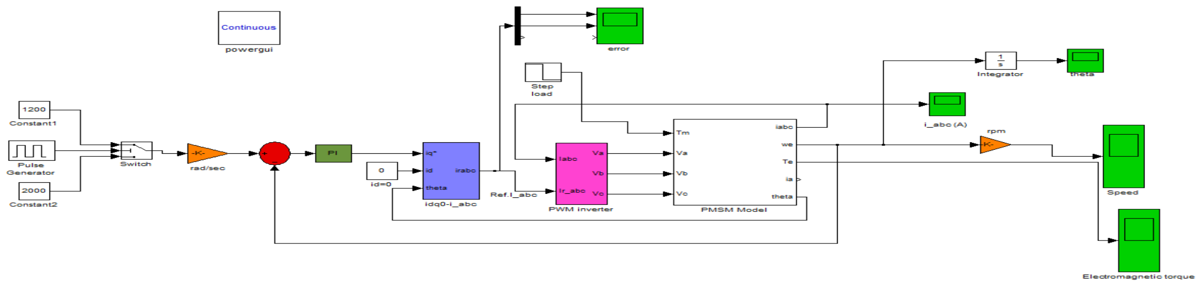

Fig.3. Simulink model of PMSM Drive

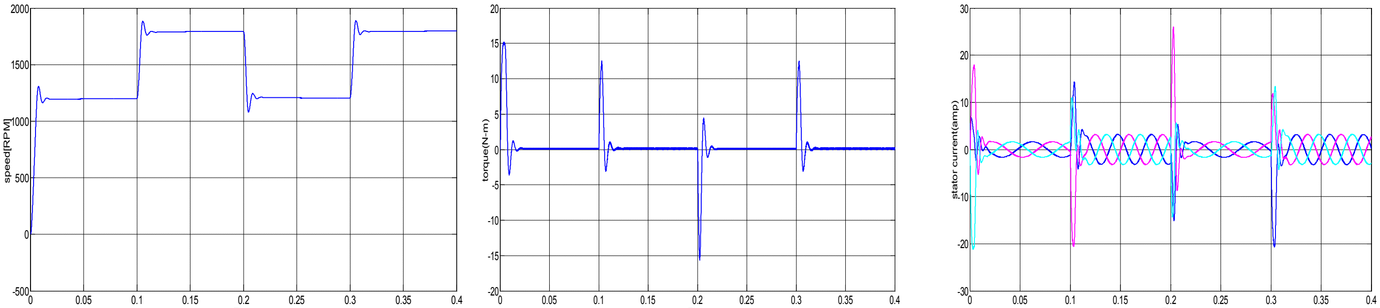

Fig. 4. Steady state response of speed, torque and current at 1000 to 1800 rpm

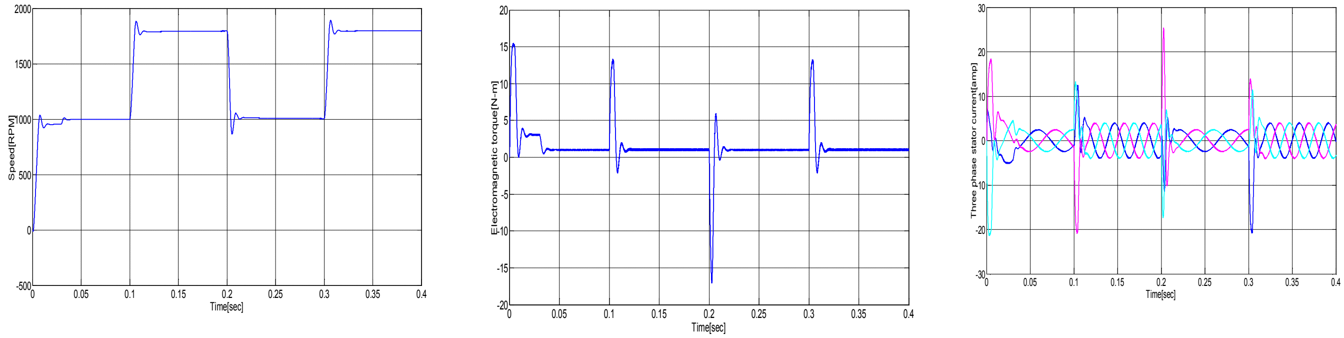

Fig.5. Transient response of speed, torque and current at 1000to 1800 rpm

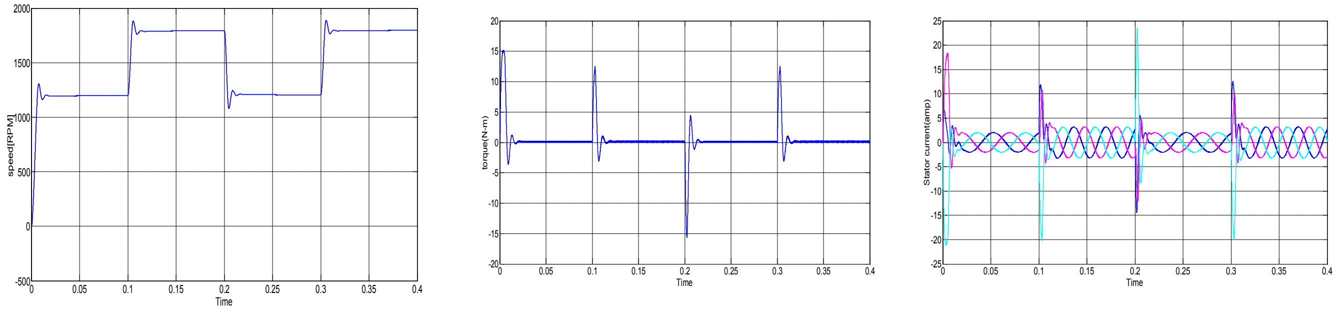

Fig.6. Steady state response of speed, torque and current at 1200 to 1800 rpm

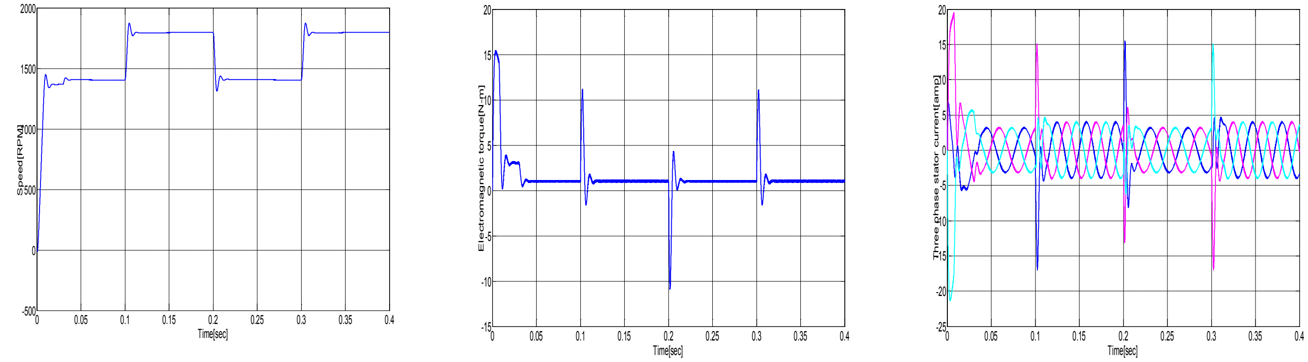

Fig.7. Transient response of speed, torque and current at 1200 to 1800 rpm

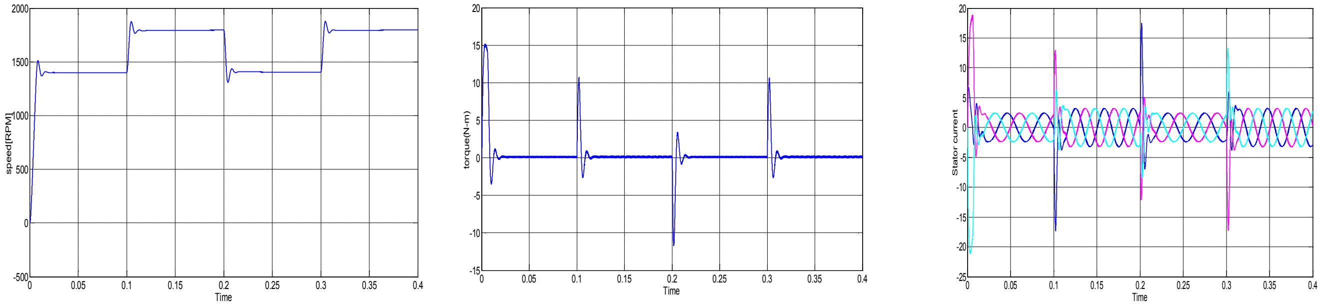

Fig.8. Steady state response of speed, torque and current at 1400 to 1800 rpm

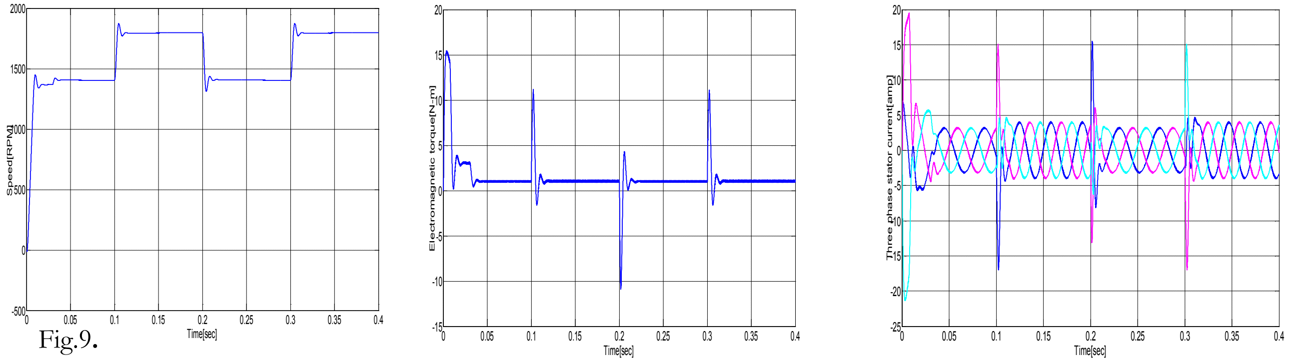

Fig.9.

Transient response of speed, torque and current at 1400 to 1800 rpm

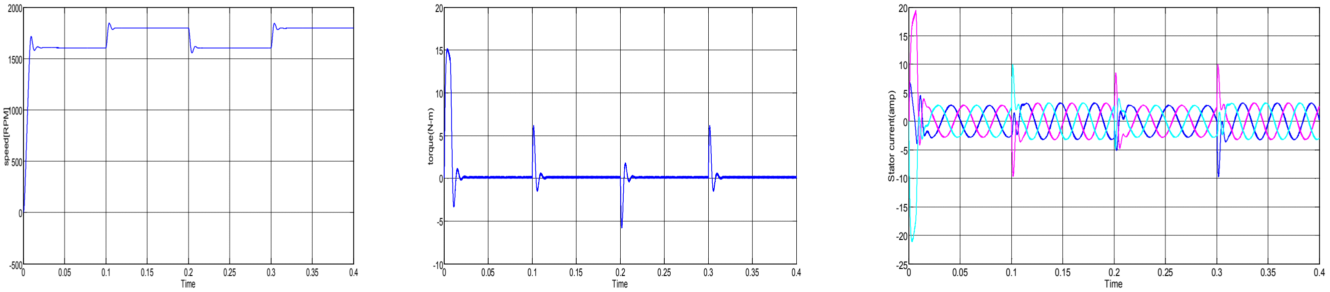

Fig.10. Steady state response of speed, torque and current at 1600 to 1800 rpm

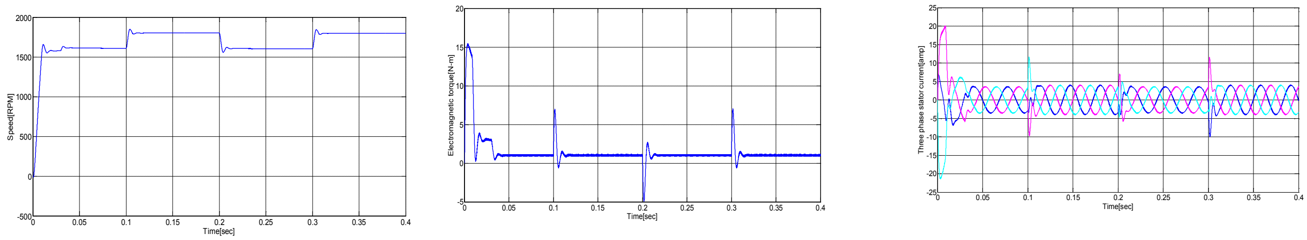

Fig.11. Transient response of speed, torque and current at 1600 to 1800 rpm

VI. TESTING & EXPERIMENT RESULTS

Following procedure was carried out for the testing of variable frequency mode of operation of the motor. Before connecting the motor to the drive, the drive operation was worked on dummy load. The dummy load used here is a 3 phase star connected lamps either 40W or 60W rating. Firstly the frequency knob on the drive was kept at its minimum position. The converter card was then switched on. The power supply status was indicated by all the LEDs inside the unit. The frequency knob position was slowly changed along with the set speed pot. Slowly the lamps were turned on as the soft start in the result table. After observing the satisfactory performance of the control card then the motor was connected to the drive. The dummy lamp load was now removed and the motor was connected in the output connector. The set up was again switched on and the drive was started. The set speed pot was slowly moved to its maximum position so that maximum voltage was applied to the motor. Now the frequency knob was changed and moved at various positions. This changes frequency of input supply voltage to motor and hence changes the synchronous speed of the motor. Thus the motor runs at variable speed depending on the frequency. After testing the various test points the dummy star connected load is removed and across the output of the bridge inverter PMSM is connected. Then gradually increasing the load on the shaft of the motor for different values of frequency speed of the motor is measured.

Table No.1 Variation in the motor speed as a function of inverter frequency

Sr.No.	Time (m.s.)	Frequency (Hz)	Expected Speed (rpm)	Measured Speed (rpm)	Voltage (Volts)
1	30	33.3	999	1010	265
2	25	40	1200	1226	270
3	22	45.4	1362	1380	270
4	20	50	1500	1520	270
5	18	55.5	1665	1682	270
6	17	59	1770	1790	270

Table No.2 Variation in the motor speed as a function of load at constant frequency of 33.3 & 40Hz

Sr. No.	Load (gm)	Expected Speed (rpm)	Measured Speed (rpm)	Voltage (volts)
1	500	999	1010	270
2	1000	999	1010	270
3	1500	999	1010	270
4	2000	999	1010	270
5	2500	999	1010	270
6	3000	999	1010	270

Sr. No.	Load (gm)	Expected Speed (rpm)	Measured Speed (rpm)	Voltage (Volts)
1	500	1200	1226	270
2	1000	1200	1226	270
3	1500	1200	1226	270
4	2000	1200	1226	270
5	2500	1200	1226	270
6	3000	1200	1226	270

Table No.3: Variation in the motor speed as a function of load at constant frequency of 45.4. & 50Hz

Sr .No.	Load (gm)	Expected Speed (rpm)	Measured Speed (rpm)	Voltage (Volt)
1	500	1500	1520	270
2	1000	1500	1520	270
3	1500	1500	1520	270
4	2000	1500	1520	270
5	2500	1500	1520	270
6	3000	1500	1520	270

Sr. No.	Load (gm)	Expected Speed (rpm)	Measured Speed (rpm)	Voltage (Volt)
1	500	1362	1380	270
2	1000	1362	1380	270
3	1500	1362	1380	270
4	2000	1362	1380	270
5	2500	1362	1380	270
6	3000	1362	1380	270

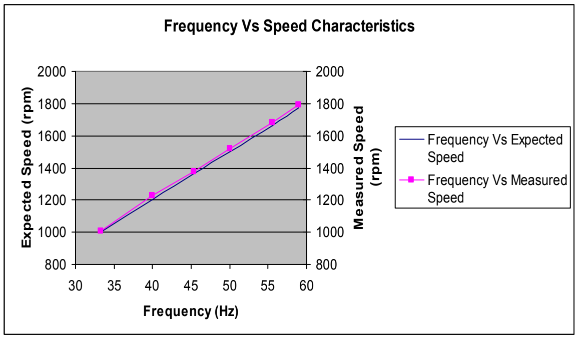

Fig 12. Frequency Vs Speed characteristics

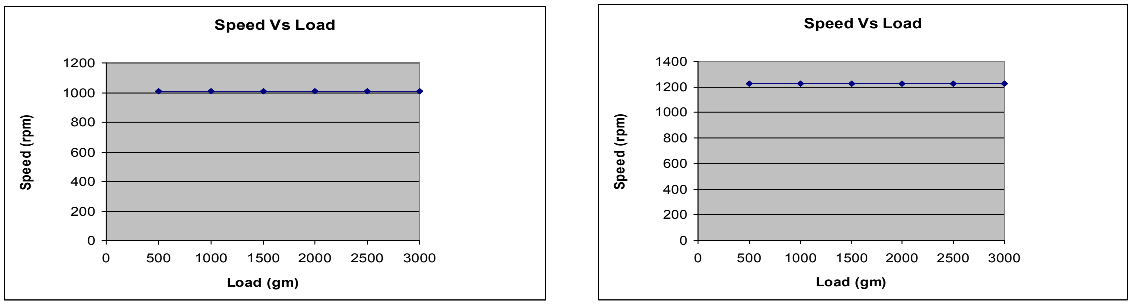

Fig. 13 Speed Vs Load Characteristics at 33.3 Hz & 40 Hz

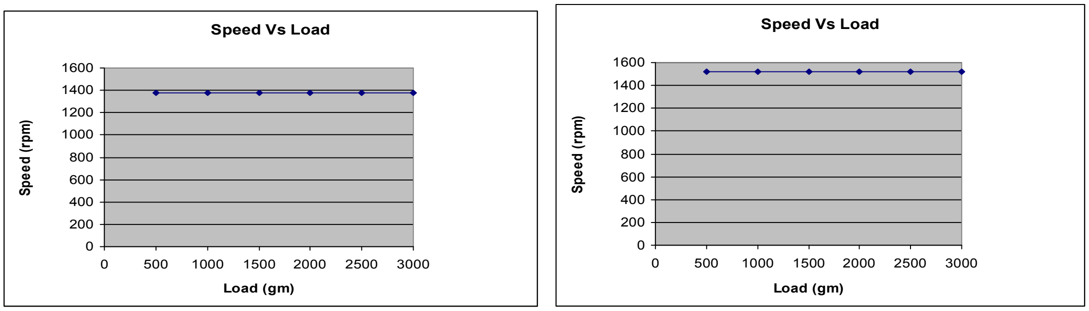

Fig14. Speed Vs Load Characteristics at 45.4 Hz & at 50 Hz

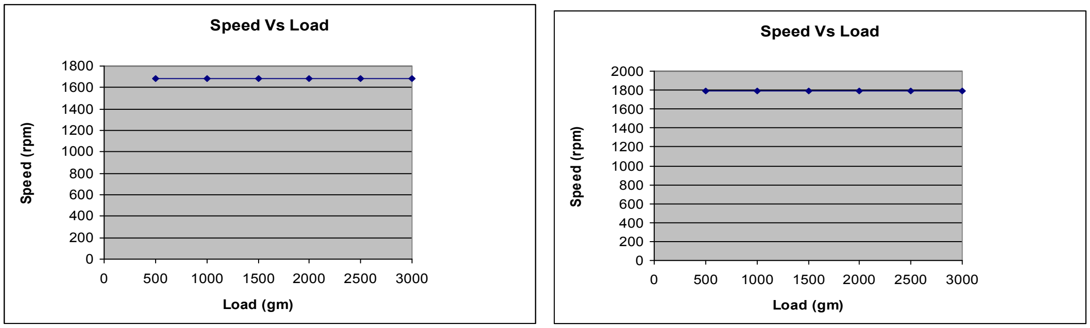

Fig. 15. Speed Vs Load Characteristics 55.5 Hz & at 59 Hz

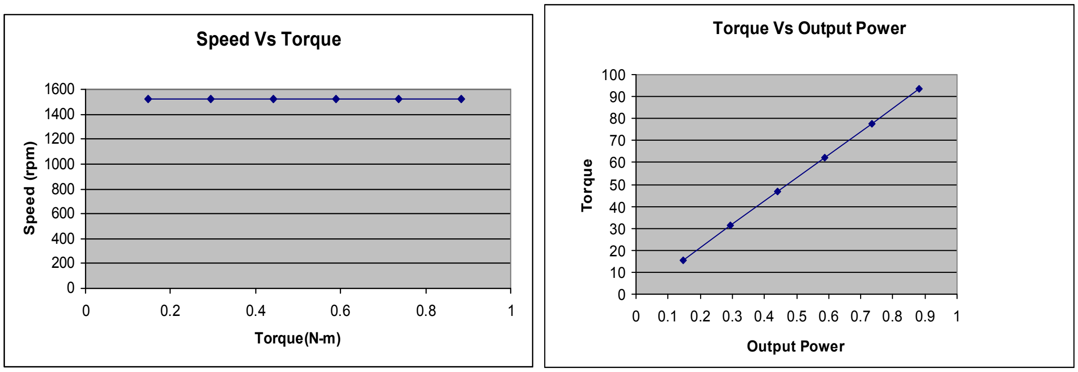

Fig. 16. Torque Vs Output Power at 33.3 Hz & at 50 Hz

VII. CONCLUSION

The performance of the permanent magnet synchronous motor is experimentally verified by varying frequency of an inverter. It is observed that, at constant frequency, speed remains constant irrespective of load. The motor runs at synchronous speed. But varying the inverter frequency, speed also gets changed accordingly .The overall performance of the motor can be very well judged from the performance characteristic shown. At the end we conclude that simulation results and performance parameters shall be considered in choosing the suitable model as well as a hardware implementation shall give better view with respect to performance analysis. Hence it is used in automotive application.

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