MODELING AND SIMULATION OF DISCONTINUOUS CURRENT MODE INVERTER FED PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVE

[1]M. RAJASHEKAR [2] I.V.VENU GOPALA SWAMY [3]T.ANIL KUMAR

[1]Assistant Professor, Department of Electrical & Electronics Engineering, St. Martin's Engineering College, Dullapally, Hyderbad-059

[2]Senior Assistant Professor, Department of Electrical & Electronics Engineering, ACE Engineering College

[3]Associate Professor, Department of Electrical & Electronics Engineering, ACE Engineering College, Ghatkesar, Ranga Reddy Dist.

E-mail rajashekar_eee@yahoo.co.in, venugopalace@gmail.com, nil_ttt555@yahoo.co.in

ABSTRACT

The aim of this project is to model a six step discontinuous current mode inverter fed to a Permanent Magnet Synchronous Motor (PMSM) drive using MATLAB/SIMULINK. The dq-axis Voltage-Current and Torque relation in terms of machine parameters are used along with a six step 120 degree mode inverter and gate drive using MATLAB/SIMULINK. There is also a provision for easy changes to the machine parameters and gate drive inverter parameters at appropriate places. The various subsystems allow us to change the parameters like power supply data, phase angle advance, PMSM parameters such as stator resistance, inductance, number of poles, rotor magnet constant, Moment of Inertia of motor and damping constant etc.
The above model finds its application in power electronics and drives laboratories. Simulation will be done for a phase angle advance of 30° and 45° for a six step discontinuous current mode inverter fed PMSM drive at no load.

Keywords- *Permanent Magnet Synchronous motor (PMSM), Brushe Less Direct Current Motor(BLDC), Current Source Inverter (CSI), Voltage Source Inverter (VSI)*

I. INTRODUCTION

THE Permanent Magnet Synchronous motor (PMSM) is a rotating electric machine where the stator is a classic three phase stator like that of an induction motor and the rotor has surface-mounted permanent magnets. In this respect, the Permanent Magnet Synchronous motor is equivalent to an induction motor where the air gap magnetic field is produced by a permanent magnet. The use of a permanent magnet to generate a substantial air gap magnetic flux makes it possible to design highly efficient PM motors.

A PM Synchronous motor is driven by sine wave voltage coupled with the given rotor position. The generated stator flux together with the rotor flux, which is generated by a rotor magnet, defines the torque, and thus speed, of the motor. The sine wave voltage output have to be applied to the 3-phase winding system in a way that angle between the stator flux and the rotor flux is kept close to 90° to get the maximum generated torque. To meet this criterion, the motor requires electronic control for proper operation.

For a common 3-phase Permanent Magnet Synchronous motor, a standard 3-phase power stage is used. The same power stage is used for AC induction and BLDC motors. The power stage utilizes six power transistors with independent switching. The power transistors are switched in the complementary mode. The sine wave output is generated using a PWM technique.

II. BASIC THEORY OF A PMSM

A. Construction of a PMSM

a) In principle, the construction of a permanent magnet synchronous machine does not differ from that of the BLDC, although distributed windings are more often used. However, while the excitation current waveform was rectangular with a BLDC, sinusoidal excitation is used with PMSMs, which eliminates the torque ripple caused by the commutation. PMSMs are typically fed by voltage source inverters, which cause time-dependent harmonics on the air gap flux. Permanent magnet synchronous machines can be realized with either embedded or surface magnets on the rotor, and the location of the magnets can have a significant effect on the motor's mechanical and electrical characteristics, especially on the inductances of the machine.

As the relative permeability of the modern rare-earth magnets, such as the NdFeB is only slightly above unity, the effective air gap becomes long with a surface magnet construction. This makes the direct-axis inductance very low, which has a substantial effect on the machine's overloading capability, and also on the field weakening characteristics. As the pull-out torque is inversely proportional to the d-axis inductance, the pull-out torque becomes very high.

The drawback of a low L_d –value is the very short field weakening range, as the armature reaction with a surface magnet construction is very weak. This means that a high demagnetizing stator current component would be required to decrease the air gap flux, and consequently, there would be very little current left on the q-axis to produce the torque. Direct-axis inductance of a machine having embedded magnets becomes high, as the rotor magnets per pole form a parallel connection for the flux, while with a surface magnet construction they are connected in series. With equivalent magnets, the rotor reluctance of the surface-magnet construction is therefore double compared to an embedded-magnet construction, and the inductance is inversely proportional to the reluctance. With embedded-magnets, the direct-axis inductance is further increased because of the higher rotor leakage flux. Three basic configurations of PMSMs are shown in Fig. 1(a),1(b) and1(c)

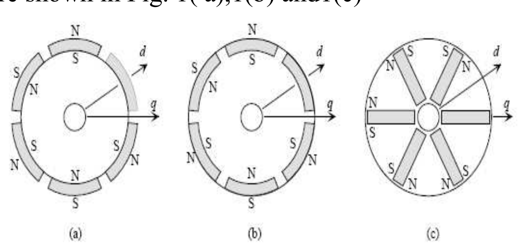

Fig. 1. The most common PM rotor constructions.

Fig1(a) Non-salient surface magnet rotor. Due to high d axis reluctance, Ld is low and consequently the pull-out torque high. Fig1(b) Salient pole surface magnet rotor with inset magnets, which is basically the same as Fig1(a), but this type produces also some reluctance torque. Fig1(c) Embedded magnets in the rotor, which has a high Ld value, and consequently a poor overloading capability, but a lot better field weakening characteristics than with the surface magnet constructions. Typically the construction of the PMSM servomotor is somewhere between Fig1(a) andFig1(b), and the q-axis inductance is larger. Industrial PMSMs often represent the type Fig1(c).

The rotor in Fig. 1 b) with inset surface magnets has better mechanical characteristics, but on the other hand, it has higher leakages between two adjacent magnets. In addition to the higher leakage, the torque production decreases more as the motor must operate at higher pole angle due to increased q-axis inductance compared to a non-salient rotor. Typically, the construction of commercial servomotors is somewhere between Fig. 1(a) and Fig1(b), that is, the magnets are slightly embedded in the rotor. This improves the mechanical strength of the rotor and introduces a reluctance difference based term in the torque.

With buried magnets and flux concentration, a sinusoidal air gap flux density distribution is possible with simple rectangular magnets. A sinusoidal air gap flux distribution significantly decreases the cogging torque especially with low-speed multi-pole machines that have a low number of slots per poles per phase number q. Also, it is possible to increase the air gap flux density beyond the reminisce flux density of the magnets with a flux concentration arrangement, and the machine can produce more torque at a given volume. This is especially desirable in low speed applications, such as in wind generators and in propulsion motors where the space is limited. As the direct-axis inductance is typically high with a buried magnet construction, the overloading capability will be poor, which makes this motor type incompetent in motion control applications.

B. Model of a PMSM

A dynamic model of the PMSM is required to derive the vector control algorithm to decouple the air gap-flux and torque channels in the drive system. The derivation of the dynamic model is easily made from the dynamic model of the induction machine in flux linkages.

The two-axes PMSM stator windings can be considered to have equal turns per phase. The rotor flux can be assumed to be concentrated along the *d* axis while there is zero flux along the *q* axis. Further it is assumed that the machine core losses are considered to be negligible. Also, rotor flux is assumed to be constant at a given operating point. Variations in rotor temperature alter the magnet flux, but its variation with time is considered to be negligible. There is no need to include the rotor voltage equations as in the case of a induction motor, since there is no external source connected to the rotor magnets, and variation in the rotor flux with respect to time is negligible.

The stator equations of the induction machine in the rotor reference frames using flux linkages are taken to derive the model of the PMSM. The rotor frame of reference is chosen because the position of the rotor magnets determines, independently of the stator voltages and currents, the instantaneous induced emf's and subsequently the stator currents and torque of the machine. Again, this is not the case in the induction machine; there, the rotor fluxes are not independent variables, they are influenced by the stator voltages and currents, and that is why any frame of reference is suitable for the dynamic modeling of the induction machine. When rotor reference frames are considered, it means the equivalent *q* and *d* axis stator windings are transformed to the reference frames that are revolving at rotor speed. The consequence is that there is zero speed differential between the rotor and stator magnetic fields and the stator *q* and *d* axis windings have a fixed phase relationship with the rotor magnet axis, which is the *d* axis in the modeling.
The stator flux-linkage equations are :

$$v_{qs} = R_s i_{qs} + s\lambda_{qs} + \omega_{re}\lambda_{ds} \quad \text{………. ……….(2.1)}$$

$$v_{ds} = R_s i_{ds} + s\lambda_{ds} - \omega_{re}\lambda_{qs} \quad \text{…………………...……(2.2)}$$

Where Vds and Vqs are the dq axis stator voltages and ω re is the angular speed of the rotor in electrical radians per second. And the *q* and *d* axes stator flux linkages in the rotor reference frames are :

$$\lambda_{qs} = L_q . i_{qs} \quad \text{……………...………………… ……(2.3)}$$

$$\lambda_{ds} = L_d . i_{ds} + \lambda_m \quad \text{……………………… ……..(2.4)}$$

where λ m is the amplitude of the stator flux linkages established by the permanent magnet, which is a constant.

Now, using equations (2.3) and (2.4) in equations (2.1) and (2.2) equation (2.5) is obtained:

$$\begin{bmatrix} v_{qs} \\ v_{ds} \end{bmatrix} = \begin{bmatrix} R_s + sL_q & -\omega_{re}L_d \\ -\omega_{re}L_q & R_s + sL_d \end{bmatrix} * \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} + \begin{bmatrix} \omega_{re}\lambda_m \\ 0 \end{bmatrix} \quad \text{……….(2.5)}$$

In equation (2.5), Rs, L_d, L_q are the resistance and inductance of the stator in dq axis respectively.

The electromagnetic torque is given by equation (2.6) below:

$$T_{em} = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\lambda_{ds} . i_{qs} - \lambda_{qs} . i_{ds}\right) \quad \text{......................(2.6)}$$

Where P is the number of poles. Using equation (2.3) and (2.4) in equation (2.6) equation (2.7) follows:

$$T_{em} = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\lambda_{ds} . i_{qs} + \left(L_d - L_q\right) i_{qs} . i_{ds}\right) \quad \text{..(2.7)}$$

The rotor electromagnetic torque and speed are related as follows

$$T_{em} = J\left(\frac{\partial \omega_{rm}}{\partial t}\right) + D\omega_{rm} + T_{mech} \quad \text{…… ……(2.8)}$$

Where ω_{rm} is the rotor speed in mechanical radians per second, J is rotor inertia, D is damping constant and Tmech is the mechanical load torque.

C. Park's Transformation

Parks Transformation is used to get from the stationary reference plane to the rotating reference plane. First, two of the three phase currents are measured. Note that you do not even need to know (or measure) the value of the third phase current. This is because the sum of the 3-phase currents should sum to zero. The measured currents represent the vector components of the current in a 3-axis coordinate system with each axis separated by 120 ° It is easier to represent the rotating current vector in a 2-axis orthogonal coordinate system, so the Park's Transform just converts the measured currents so that the current vector is represented with two vector components instead of three. The two vector components calculated using the Park Transform still vary with time.

Next, it is used to rotate the 2-axis coordinate system so that is aligned with the rotating motor. The rotation angle is represented by θ. Now, it may wonder, where the value of θ comes from. When using Field Oriented Control for a synchronous 3-phase motor, the rotating reference plane would always be aligned with the rotor and θ could be obtained directly from the rotor position using a sensor.

The key to Park transformations provide DC representations of the stator phase currents under steady state conditions. But, we know that the motor current is really an AC signal represented as a rotating current vector. It is only because the coordinate system is synchronously rotating with the current vector that the transformed current components appear as DC values. If the value of either current component changes over time, this means that the amplitude and phase of the motor current vector has changed.

Considering the currents as inputs, the three phase currents are :

$$i_{as} = i_s \sin(\theta_{re} + \delta) \quad \text{......(2.9)}$$

$$i_{bs} = i_s \sin\left(\theta_{re} + \delta - \frac{2\Pi}{3}\right) \quad \text{......(2.10)}$$

$$i_{cs} = i_s \sin\left(\theta_{re} + \delta + \frac{2\Pi}{3}\right) \quad \text{......(2.11)}$$

Where θ_{re} is the product of electrical rotor speed and time and δ is the angle between the rotor field and stator current phasor, known as the torque angle.

The rotor field is traveling at a speed of ω_r rad/sec, hence q and d axes stator voltages in the rotor reference frame for a balanced three phase operation are given by :

$$\begin{bmatrix} v_{qs} \\ v_{ds} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta_{re} & \cos\left(\theta_{re} - \frac{2\Pi}{3}\right) & \cos\left(\theta_{re} + \frac{2\Pi}{3}\right) \\ \sin\theta_{re} & \sin\left(\theta_{re} - \frac{2\Pi}{3}\right) & \sin\left(\theta_{re} + \frac{2\Pi}{3}\right) \end{bmatrix} * \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix}$$

…(2.12)

Where, θ_{re} is the angular position of the rotor in electrical radians.

Similarly the stator currents in the three phases a, b and c are given by:

$$\begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} = \begin{bmatrix} \cos\theta_{re} & \sin\theta_{re} \\ \cos\left(\theta_{re} - \frac{2\Pi}{3}\right) & \sin\left(\theta_{re} - \frac{2\Pi}{3}\right) \\ \cos\left(\theta_{re} + \frac{2\Pi}{3}\right) & \sin\left(\theta_{re} + \frac{2\Pi}{3}\right) \end{bmatrix} * \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix}$$

….(2.13)

Where, θ_{re} is the angular position of the rotor in electrical radians.

III. INVERTERS

A device that converts dc power to ac power at desired output voltage and frequency is called an inverter. Inverters can broadly classified into two types : VSI and CSI .A VSI, is one in which the dc source has small or negligible impedance. In other words a voltage source inverter has stiff dc voltage source at its input terminals. A CSI is fed with an adjustable current from a dc source of high impedance, i.e from a stiff dc current source. In a CSI fed with stiff current source, output current waves are not affected by the load.

In VSIs using thyristors, some type of forced commutation is usually required. In case VSIs are made up of using GTOs, power transistors, power MOSFETs or IGBTs, self commutation with base or gate drive signals is employed for their turn-on and turn-off.

A. Six Step Three Phase Voltage Source Inverter

The power circuit diagram of this inverter is shown in the Fig.3.1

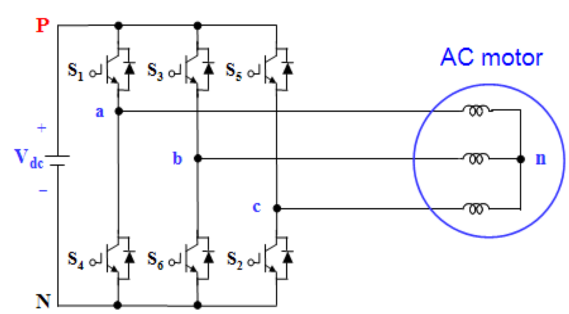

Fig. 2. Three-phase voltage source inverter.

For the 180° mode VSI, each IGBT conducts for 180° of a cycle. Like a 180° mode , 120° mode inverter also requires six steps, each of 60° duration, for completing one cycle of the output ac voltage.

Where, S1 to S6 are the IGBTs and the three phase load is assumed to be star connected. The IGBTs are numbered in the sequence in which they are triggered to obtain voltages v_{ab}, v_{bc}, v_{ca} at the output terminals a, b and c of the inverter.

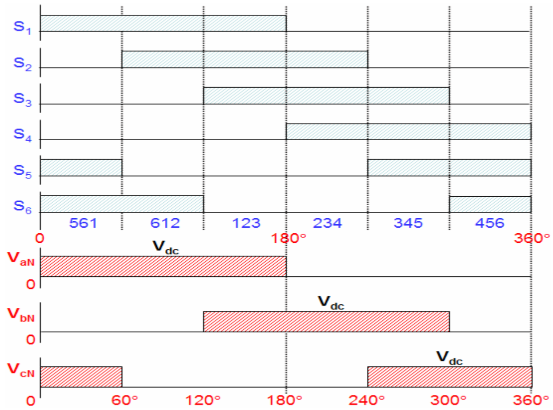

Fig. 3. Waveforms of gating signals, switching sequence, line to negative voltages for six-step voltage source inverter.

As seen in the Fig (3) the IGBTs S1,S4 ; S3,S6 and S5,S2 are turned on with a time interval of 180 degrees. It means that S1 conducts for 180° of a cycle. IGBTs in the upper group, i.e. S1, S3, S5 conduct at an interval of 120° . It implies that if S1 is fired at 0°then S3 must be fired at 120° and S5 at 240° . Same is true for lower group of IGBTs. Thus as seen from the Fig.3only three IGBTs are conducting one from upper group and two from lower group or two from upper group and one from lower group.

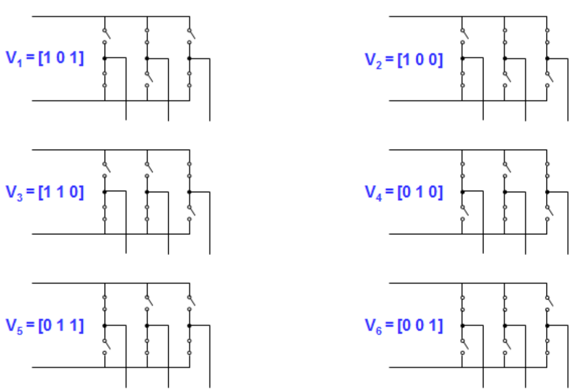

Fig. 4. Six inverter voltage vectors for six-step voltage source inverter.

As shown in the Fig.4the switching sequence for the six step voltage source inverter is shown and the sequence is :561 (V1) → 612 (V2) → 123 (V3) → 234 (V4) → 345 (V5) → 456 (V6) → 561 (V1), Where, 561 means that S5, S6 and S1 are switched on similarly the other sequences. The line to line voltages are given as :

Vab = VaN-VbN……………………………………(3.1)

Vbc = VbN - VcN……………………………………..(3.2)

Vca = VcN-VaN……………………………………..(3.3)

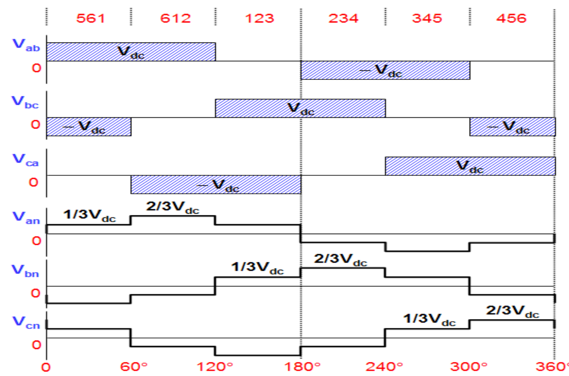

Fig. 5. Waveforms of line to neutral (phase) voltages and line to line voltages for six-step voltage source inverter.

As seen in the Fig 5 the phase voltages have six steps per cycle and line voltages have one positive pulse and one negative pulse (each of 120 ° duration) per cycle. The phase as well as line voltages are out of phase by 120 ° so, the function of the diodes is to allow the flow of currents through them when the load is reactive in nature.

TABLE I.

Parameters	Value
Number of poles	4
Stator Resistance (R_s)	9.3041 Ohms/Ph
Stator Inductance (L_s)	0.0596 H/Ph
Rotor Magnet Constant λm	0.1354 V.Sec/elec.rad
Damping Constant (D)	0.00044066 Nw.M.sec/mech.rad
Rotor Inertia (J)	0.0035 Kg.m^2
DC Link Voltage	40 Volts

The line voltage waveforms as shown in the Fig 5 represent a balanced set of three phase alternating voltages. During six intervals, these voltages are well defined. Therefore these voltages are independent of the nature of the load circuit which may consist of any combination of resistance, inductance and capacitance and the load may be balanced or unbalanced, linear or non-linear.

The phase voltages are given as:

Van = 2/3VaN - 1/3VbN - 1/3VcN………(3.4)

Vbn = -1/3VaN + 2/3VbN - 1/3VcN…….(3.5)

Vcn = -1/3VaN - 1/3VbN + 2/3VcN…….(3.6)

Coming to the operation of a 120° mode inverter the power circuit diagram is similar to that of a 180° mode inverter as shown in the Fig 3.1. In the 120 °mode inverter each IGBT conducts for 120° of a cycle. Similar to a 180° mode inverter this also requires six steps, each of 60° duration, for completing one cycle of the output ac voltage.

As seen in the Fig.2 the IGBTs S1,S4 ; S3,S6 and S5,S2 are turned on with a time interval of 180° degrees. It means that S1 conducts for 120° of a cycle and after that S1 remains turned off for the next 60° and only after that *i.e* at 180° S4 begins to conduct this process continues for the pairs S3,S6 and S5,S2. Thus as seen from the Fig.2 only two IGBTs are conducting one from upper group and one from lower group.

Similarly the switching sequence for 120° mode is : 61 (V1) → 12 (V2) → 23 (V3) → 34 (V4) → 45 (V5) → 56 (V6) → 61 (V1), Where, 61 means that S6 and S1 are switched on similarly the other sequences.

Its also seen that the phase voltages have one positive pulse and one negative pulse for one cycle of output alternating voltage. The line voltages, however, have six steps per cycle of output alternating voltage.

B. Merits and Demerits of 120 ° mode inverter over 180 ° mode inverter

1. In the 180° mode inverter, when the gate signal is turned off to turn off S1 at 180°, gating signal to S4 is simultaneously applied to turn on S4 in the same leg. In practice interval must exist between the removal of gating signal to S1 and application of gating signal to S4, because otherwise source would experience a direct short circuit through S1 and S4 in the same leg.

This difficulty is overcome considerably in 120° mode inverter. In this inverter there is a 60° interval between the turning off of S1 and turning on of S4. During this 60° interval, S1 is commutated safely. In general, this angular interval of 60° exists between the turning off of one device and turning on of the complementary device in the same leg.

2. In the 120° mode inverter, the potentials of only two output terminals connected to the dc source are defined at any time of the cycle. The potential of the third terminal, pertaining to a particular leg in which neither device is conducting, is not well defined; its potential therefore depends on the nature of the load circuit. Thus, the analysis of the performance of this inverter is complicated for a general load circuit. For a balanced resistive load, the potential of all the three terminals is, however, well defined.

For the simulation of the permanent magnet synchronous motor in this project we use a six step inverter in 120° mode because of its advantages over 180° mode.

IV. SIMULINK IMPLEMENTATION

A. Simulation Blocks

The SIMULINK implementation of the six step discontinuous current mode inverter fed PMSM with its subsystems which include a Three Phase 120 ° Mode Gate Drive Cum Inverter Block, Permanent Magnet Synchronous Motor Block, ABC to DQ Block, Torque Calculator Block, DQ to ABC block, Rotor Speed Calculator Block, VLL to VLN Transform Block and Phase to Neutral Value Calculator Block for Current and Voltage.

B. Simulink Model of the PMSM Drive

The combination of the above blocks is shown in the Fig. 6

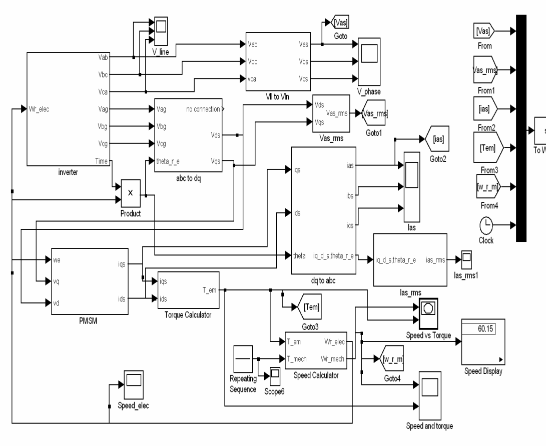

Fig.6 Simulink mode of a six step discontinuous mode inverter

Fig. 6 shows the Simulink mode of a six step discontinuous mode inverter fed PMSM drive where by changing the phase advance angle by π/6 and π/4 we can obtain different outputs of the PMS Motor like R.M.S Voltage, R.M.S Current, Torque, Speed and Speed vs Torque. The outputs of all the scope blocks are shown in the figures of the next section along with certain additional graphs for different phase advance angles i.e. π /6 and π/4 in the present case.

V. SIMULATION RESULTS

Current mode inverter fed PMSM simulation was carried out using Simulink 6, using ode15s (stiff/NDF) solver and the simulation time is taken as 6 seconds.

A. Simulation Results for switching advance of π/6

The simulation outputs for the V LN and RMS V LN of the PMSM for a switching advance of π/6 are plotted as:

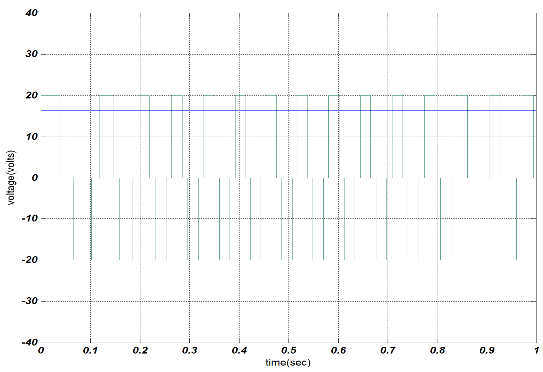

Fig 7 V LN and RMS V LN vs TIME

The simulation output for the Line Current of PMSM for a switching advance of π/6 is plotted as:

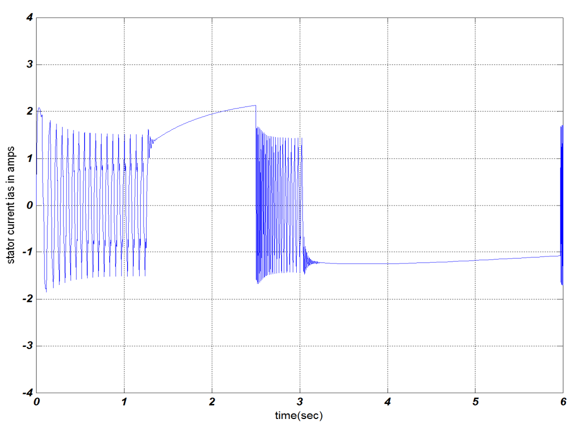

Fig9Stator Current Ias vs Time

The simulation output for the Electromagnetic Torque of PMSM for a switching advance of π/6 is plotted as :

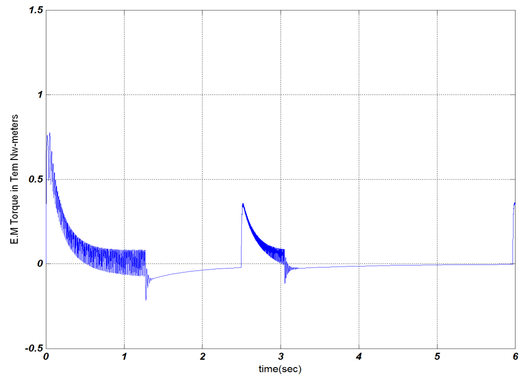

Fig8 E.M.Torque vs Time

The simulation output for the Rotor Speed in Mech.rad per second of a PMSM for a switching advance of π/6 is plotted as :

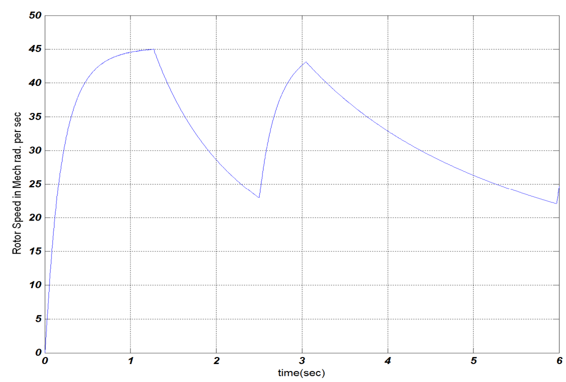

Fig10Rotor Speed vs Time

The simulation output for the E.M.Torque vs the Rotor Speed of a PMSM for a switching advance of π/6 is given as :

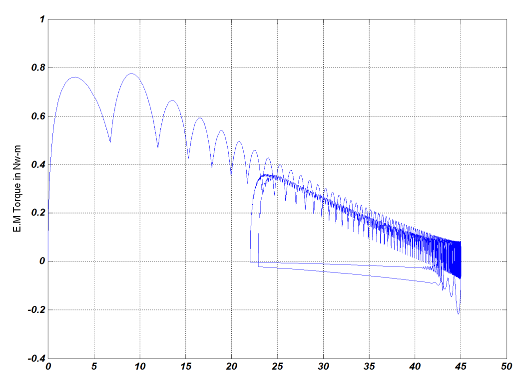

Fig11 E.M.Torque vs Rotor Speed

B. Simulation Results for switching advance of π/4

Current mode inverter fed PMSM simulation was carried out using Simulink 6, using ode15s (stiff/NDF) solver and the simulation time is taken as 6 seconds.

The simulation outputs for the V LN and RMS V LN of the PMSM for a switching advance of π/4 are plotted as :

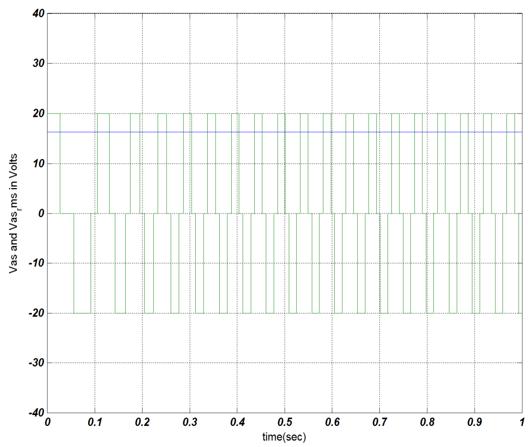

Fig12V LN and RMS V LN vs TIME

The simulation output for the Line Current of PMSM for a switching advance of π/4 is plotted as :

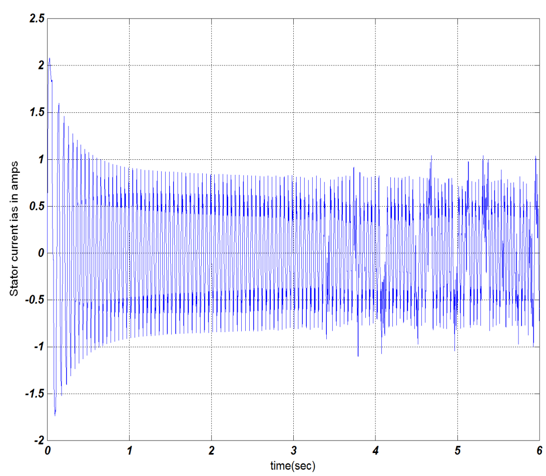

Fig13Stator Current Ias vs Time

The simulation output for the Electromagnetic Torque of PMSM for a switching advance of π/4 is plotted as :

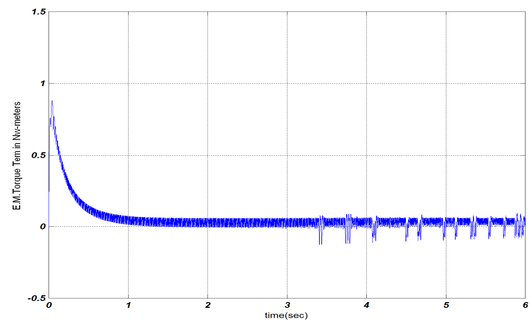

Fig14E.M.Torque vs Time

The simulation output for the Rotor Speed in Mech.rad per second of a PMSM for a switching advance of π/4 is plotted as:

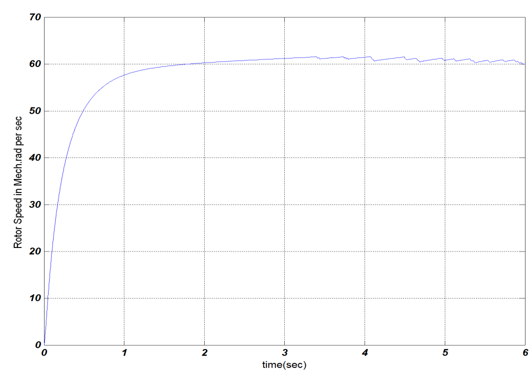

Fig15 Rotor Speed vs Time

The simulation output for the E.M.Torque vs the Rotor Speed of a PMSM for a switching advance of π/4 is given as :

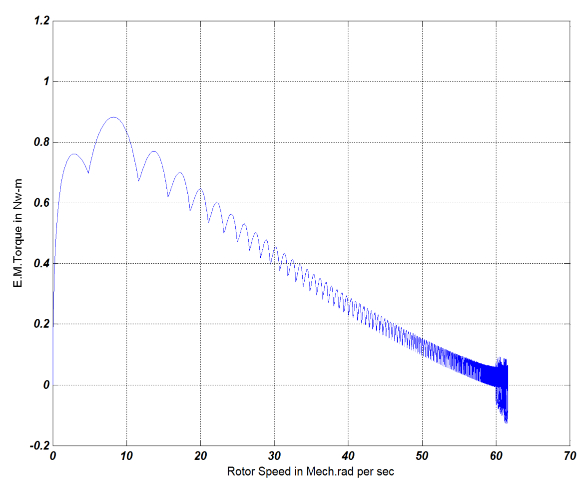

Fig16 E.M.Torque vs Rotor Speed

VI. CONCLUSIONS

The above model is thus considered to be a novel feature when it is used in power electronics laboratories for virtual simulation where the motor parameters can be changed at any instant for better results and performance.

Also, for simulation purposes when designing a PMSM for heavy loads the transient period of operation is very small and any disturbances can cause a severe damage to the system so we can also simulate the transient conditions and we can know the effects in advance and hence the conditions can be changed to minimize the damage and if possible we can also avoid it.

REFERENCES:

[1] R.Krishnan, Electric Motor Drives *Modeling, Analysis, and Control,* Pearson Education.Edition, 2004

[2] Dr.P.S.Bimbhra, Power Electronics, Khanna Publishers.Edition 2005

[3] P.C.Krause, Generalized Machine Theory, Mc.Graw Hill. Edition 2006

[4] B.K.Bose, Modern Power Electronics & AC Drives.Edition 2005

[5] www.ieee.org on Energy conversion

[6] www.ocw.mit.edu on Synchronous motors

[7] P.C.Krause, "Analysis of a permanenet magnet synchronous machine suppled from a 180^0 inverter with phase control"IEEE on Energy Conversion Transactions,Sept1987

[8] R.Sankaran "Adaptive neuro-fuzzy controller for improved performance of a permanent magnet brushless DC Motor" IEEE on International Fuzzy System Conference,2001

[9] S.D.Sudhoff " Operating modes of the brushless DC Motor with a 120^0 inverter" IEEE on Energy Conversion Transactions,Sept1990

[10] M.Kadjoudj, " A Robust Hybrid Current Control for Permanent magnet synchronous motor drive",27th Annual Conference of the IEEE Industrial Electronics Society in 2001

[11] Ying Yan, "A direct torque controlled surface mounted PMSM Drive with initial rotor position estimation based on structural and saturation saliencies"IEEE 2007