Vector Control of Permanent Magnet Synchronous Motor using high performance Hexagram Inverter

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Abstract — **This The Permanent Magnet Synchronous Motors (PMSM) are used for medium power applications and preferred over conventional motors like Induction and Synchronous motors due its superior performance, efficiency and controllability. Normal voltage source inverters are suitable only for three phase drives. Cascaded multi-level inverters are used to improve the power quality. The Hexagram inverter has the advantages of both these inverters, while, it also drives six-phase motors which are more popularly used now. This paper deals with Hexagram inverter fed PMSM drive. Vector control scheme has been employed due to its benefits like better dynamic response. The PMSM has been modeled in dq frame and the drive system is simulated using MATLAB / Simulink. The results of the hexagram inverter and the drive structure are presented for various operating conditions. The model delivers promising results due to the multilevel property of the hexagram inverter and the vector control method.**

Index Terms— **PMSM, Hexagram Inverter, Vector Control, MATLAB / Simulink.**

I. INTRODUCTION

Permanent Magnet Synchronous Motors (PMSM) have been employed in various applications due to its high power density, low inertia, high reliability, fast response, and no maintenance requirements. Permanent Magnet Synchronous motor's construction, principles of operation are well described in the text [1-2]. It has windings only in the stator and requires no field excitation. It has permanent magnets of high B-H product like Neodymium Iron Boron in the rotor. PMSM motor is controlled electronically using the rotor position to energize the windings appropriately. Rotor position is sensed using Hall Effect sensors embedded into the stator. PMSM motors require less maintenance, so they have a longer life and produce more output power per frame size.

PMSM is an improved machine without the disadvantages of the synchronous motor by replacing its field coil, dc power supply, and slip rings with a permanent magnet. The PMSM, therefore, has a sinusoidal induced EMF and requires sinusoidal currents to produce constant torque just like the synchronous motor. Current research in the design of the PMSM indicates that it has a higher-torque-to-inertia ratio and power density when compared to the induction motor or the wound-rotor synchronous motor, which makes it preferable for certain high-performance applications like robotics and aerospace actuators.

The d, q model of the wound rotor synchronous machine is used to study the performance of a permanent-magnet synchronous motor [3-4]. Using the rotor position feedback, the motor can be held in synchronism with the inverter at all times. Vector control is normally used in ac machines to convert them, performance wise, into equivalent separately excited dc machines which have highly desirable control characteristics.

Normally PMSM requires Voltage source inverter (VSI) which gives three phase voltages based on the gate pulses produced by the rotor position sensor and decoder logic. This is called electronic commutation. VSI has the disadvantage of producing harmonics and has poor power factor. Hence various types of converters for PMSM are tried to improve the performances [5-7]. Various circuitries are employed for improving the power factor and quality of power fed to the motor [8]. A flux-weakening control scheme of PMSM-incorporating and adaptive to wide-range speed regulation is discussed [9]. Multilevel inverters provide near sinusoidal voltages and hence better quality which is acceptable. Various multilevel inverter configurations are available with complicated topologies and control techniques [10-11]. Multilevel converters are extensively used in electric drives [12]. Multilevel selective harmonics elimination is employed with PWM technique in series connected voltage inverters for improving the power factor [13].

Microprocessors and Digital controllers are employed to generate the gate pulses of these multilevel inverters and to generate pulse width modulation of the gate signals [14]. Space Vector Pulse Width modulation is very widely employed and controllers with built-in SVPWM generation circuits are available [15]. Optimum fuel cell utilization is achieved with multilevel converters [16]. Some multilevel converters are also developed for high power AC drives [17]. Hexagram inverters are used in medium voltage six phase variable speed drives [18]. Control structures for the multilevel inverters are complicated and a simple solution is desired which gives ease of generation of gate pulses from rotor position information and based on the speed reference and feedback. Hexagram inverters provide high power for both three phase and six phase PMSM drives.

In this work hexagram inverter is used which require only simple gate pulses similar to normal VSI but mitigates the harmonics and switching stresses found in them. Hexagram inverter fed PMSM drive is presented with dynamic performance simulated using MATLAB / Simulink.

II. DYNAMIC MODEL OF PMSM MOTOR

The model developed for the sinusoidal PMSM drive is using the assumptions that all a balanced three-phase voltage source inverter is used, the electric quantities are referred to direct and quadrature reference frames mounted on the rotor, the fundamental frequency has a dominant effect on system dynamics and the air gap is uniform[18].

$$\frac{di_d}{dt} = \omega i_q - \frac{Ri_d}{L} + \frac{V_d}{L} \tag{1}$$

$$\frac{di_q}{dt} = -\omega i_d - \frac{Ri_q}{L} + \frac{V_q}{L} - \frac{\lambda\omega}{L} \tag{2}$$

$$\frac{d\omega}{dt} = \frac{3P\lambda i_q}{4J} - F\frac{\omega}{J} - \frac{T_L}{J} \tag{3}$$

$$\frac{d\theta}{dt} = \frac{P\omega}{2} \tag{4}$$

$$V_d = -\left(\sqrt{2}\right)V_s \sin\phi \tag{5}$$

$$V_q = \left(\sqrt{2}\right)V_s \cos\phi \tag{6}$$

The angle ϕ is defined by $\phi = \phi v(0) + \phi r(0)$ where $\phi v(0)$ is the initial phase angle of the stator voltage and $\phi r(0)$ is the initial rotor position with respect to the stator axis. $\phi v(0)$ can be adjusted to advance or delay the switching of the inverter related to the rotor position. The motor inertia J, damping F and mechanical load T_L are modelled as explained in equation (3). The equations (1) to equation (6) are used for the simulation of PMSM model using MATLAB / Simulink.

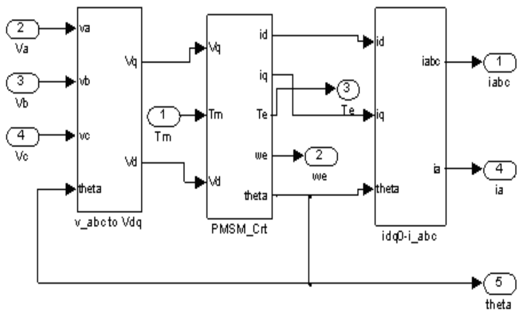

Fig. 1. Block diagram of sinusoidal PMSM drive

Fig. 1 shows the block diagram of PMSM motor drive system. The inverter used is a multilevel hexagram inverter. The three phase output phase voltages of the inverter are converted to V_d and V_q using the abc to dq transformation block.

III. HEXAGRAM INVERTER

Recently multilevel converters have gained momentum in high power applications. In this series the new arrival is the hexagram inverter [4, 5]. This combines the advantage of widely used H-bridge multilevel inverter and the well known traditional phase Voltage Source Inverter (VSI).

This has been used to drive the PMSM which is designed with vector control scheme. The hexagram inverter includes six 3 phase VSI modules. The VSI modules are interconnected through the inductors to build the required hexagram inverter in such a way as shown in Fig. 2. The hexagram inverter has six output terminals;

hence it has an added advantage that it can be employed to control either a three phase or six phase drive system. The inductors serve for the purpose of limiting the circulating current. Also their values are kept as low as possible in order to reduce the voltage drop. At the same time these inductor values must be sufficiently large enough to limit the circulating currents. Since the control signals are well synchronized a small value of inductor will be able to limit the circulating current. The output voltage of the hexagram inverter is six times that of traditional VSI. The six VSI modules carry equal currents.

Fig. 3 reveals simulation results of the Hexagram inverter. From the results it is found that the proposed hexagram inverter is performing satisfactorily. The THD is reduced and the switching stresses are also found to be reduced. Fig 3a gives the hexagram inverter three phase output voltages before filtering. It has to be filtered for driving a PMSM. For this reason the output is passed through an analog filter. A third order low pass Butterworth filter has been designed with a cut off frequency of 12.6 K rad / sec. Fig. 3b represents the output of the hexagram inverter with Butterworth filter. The near sinusoidal output voltage illustrate the filter significance. This can be employed to drive a 3-phase or 6-phase drive system. The switching methodology is same as for traditional VSI. The modular structure of the hexagram inverter makes it more feasible for implementation. The hexagram inverter with 6 traditional VSI is designed in MATLAB / Simulink and the results are presented. Each VSI module is fed with a DC input of 60V. To realize the superiority of hexagram inverter, the THD of the traditional VSI and the hexagram inverter is also studied.

In the same way as the hexagram inverter traditional VSI is also fed with a DC input of 60V and Butterworth filter has been used. Figure 4a provides the output voltage THD for traditional VSI. Figure 4b reveals the hexagram inverter output voltage THD which seems to be 57% lesser than the normal three phase VSI. From this it is apparent that the proposed hexagram inverter is suitable for high power applications.

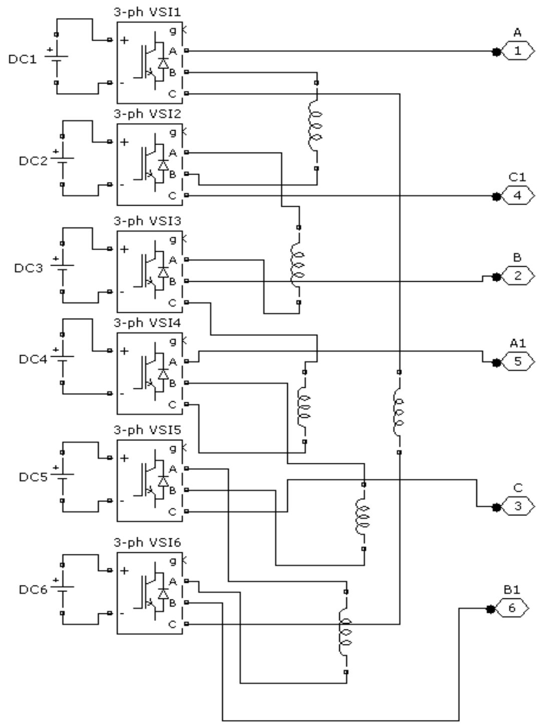

Fig. 2. Circuit diagram of hexagram inverter

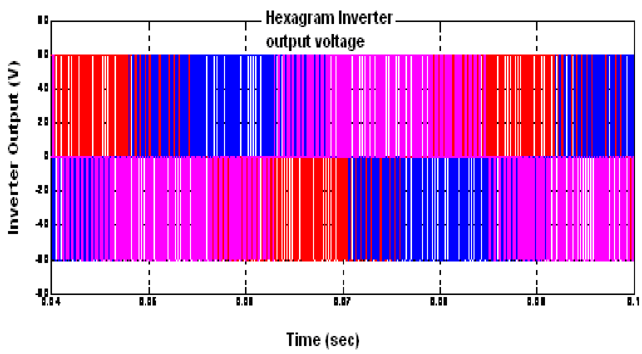

Fig. 3a. Hexagram inverter output voltage before filtering

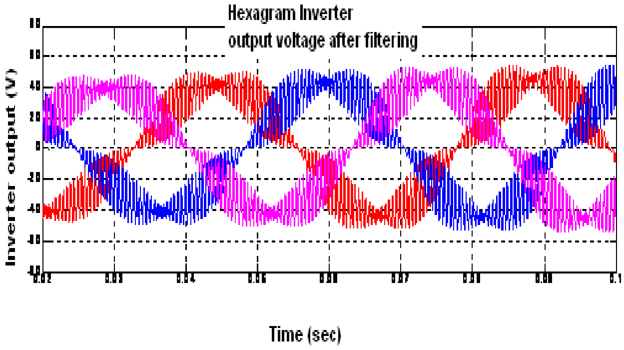

Fig. 3b. Hexagram inverter output voltage of after filtering

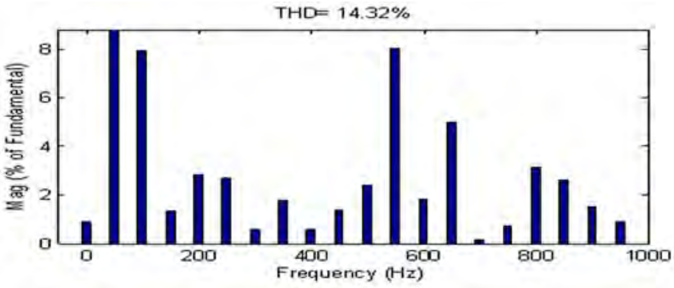

Fig. 4a. Output voltage THD result of 3 phase VSI

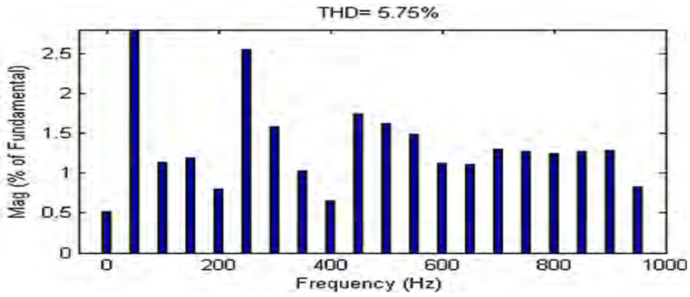

Fig. 4b. Output voltage and THD of hexagram inverter

IV. CONTROL TECHNIQUE

A. Vector Controlled PMSM drive scheme

Vector control is also known as the “field oriented control”, “flux oriented control” or “indirect torque control”. Using field orientation (Clarke-Park transformation), three-phase current vectors are converted to a two-dimensional rotating reference frame (d-q) from a three-dimensional stationary reference frame. The “d” component represents the flux producing component of the stator current and the “q” component represents the torque producing component. These two decoupled components can be independently controlled by means of vector control. The outputs of the PI controller are transformed back to the three-dimensional stationary reference plane using the inverse vector transformation. The corresponding switching pattern is pulse width modulated to drive a Voltage source Inverter. This control simulates a separately exited DC motor model, which provides an excellent torque-speed curve. This performance can be extended to PMSM by using vector control.

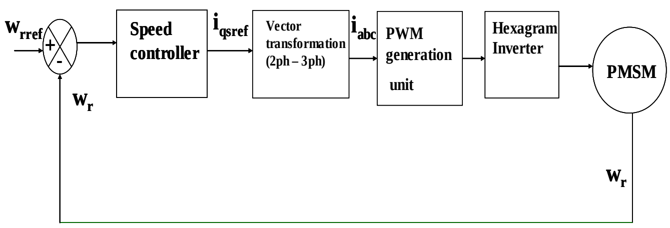

Fig. 5. Hexagram inverter fed vector controlled PMSM

This requires the measurement of the rotor position. With position sensors, this method performs reasonably well over the entire speed range. The complete drive scheme of hexagram fed vector controlled PMSM has been modeled using SIMULINK as shown in Fig. 5. The speed controller generates the q-axis reference current. The torque command is generated as a function of the speed error signal, generally processed through a PI controller. The torque command is processed in the calculation block. The three phase reference current generated is compared with the actual current in the hysteresis band current controller and the controller takes the necessary action to produce PWM pulses.

In this work the hexagram inverter is used to feed the PMSM and hence the pulses are to be fed to the hexagram inverter. This includes six three phase VSI modules as seen in the earlier section. Since the performance of the hexagram inverter is superior compared to that of the conventional VSI, the vector controlled PMSM drive also provides a better response. The main advantage is that the torque ripple is reduced to an appreciable value. This in turns reduces the losses and improves the system efficiency. Though the system cost is increased due to more number of switches but it is compensated in the energy saved.

B. *Design of PI controller*

The rotor speed is controlled by independent PI controller. The speed controller generates the torque reference. The design is conventional. The controller is designed with the two constraints that the peak overshoot must be less than 15% and the settling time has to be less than 1sec. The P gain of a PI controller decides the overall response of the system. At first the open loop response of the system is observed. Then the integral gain is set as zero and the response with proportional gain alone is studied. The proportional gain is increased till the system response tracks the reference with limited oscillations. At this point, the system will converge to the reference point with a constant steady state error. After the proportional gain value is fixed at a point, the integral gain is gradually increased to force the steady state error to zero.

Through the above said process of tuning the PI controller, the final proportional and integral gains arrived are 0.85 and 70 respectively. To exhibit the robustness of the designed controller the drive system has been analyzed with normal and worst operating states. Also it is evident from the results that under normal conditions the controller is performing excellently meeting the design constraints.

V. SIMULATION RESULTS AND DISCUSSIONS

The simulation results are taken under steady state with a reference speed of 1000rpm and reference flux of 0.9wb. The drive system is operated with a constant load torque of 4Nm. The simulation results are observed for speed, torque and motor currents. Simulation studies show the satisfactory performance of the drive where the reference speed is tracked under steady state and dynamic load conditions.

The drive scheme performance is studied under various operating conditions. As a first step the steady state performance is examined. Then the drive is analyzed with a disturbance in the speed command and the results are shown. The drive is operated with constant load torque through out and there is step change in speed reference. At 6sec the speed changes from 800rpm to 1000 rpm. Fig. 6 shows the actual and command speed for this 20% step change in the speed command. It can be seen that the reference speed is tracked with a peak overshoot of 3.5% and settling time of 0.04sec. As a worst case condition of the command signal, speed reversal is simulated. Fig. 7 displays the drive response with speed reversal. The speed command is given a step change of 160% at 6 Sec. The response is quiet satisfactory as the reference is trailed with 30% peak overshoot and with a settling time of 0.045 Sec. This validates the robustness of the designed controller. The Fig. 8 and 9 expresses the result of the vector controlled PMSM drive fed through hexagram inverter under dynamic conditions in load side.

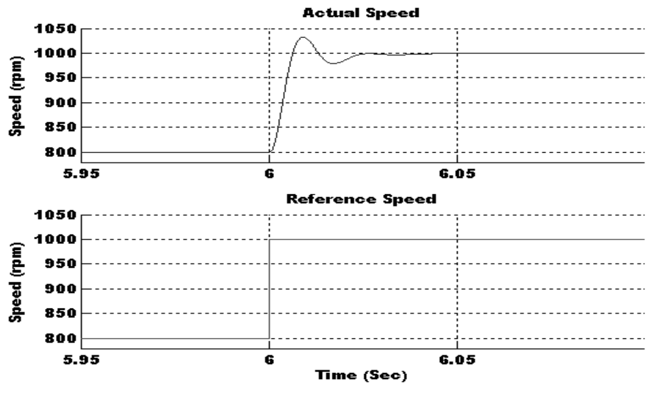

Fig. 6. Speed response for step change in reference

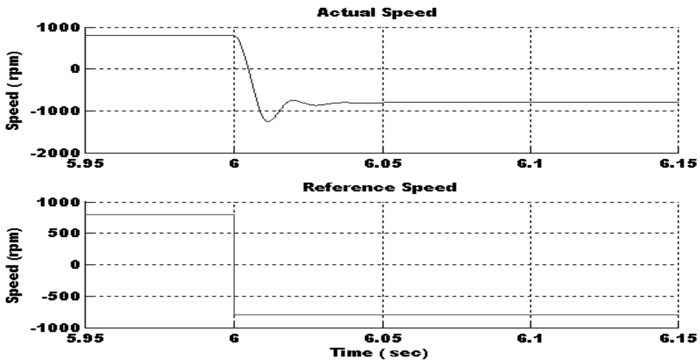

Fig. 7. Speed response for reference speed reversal

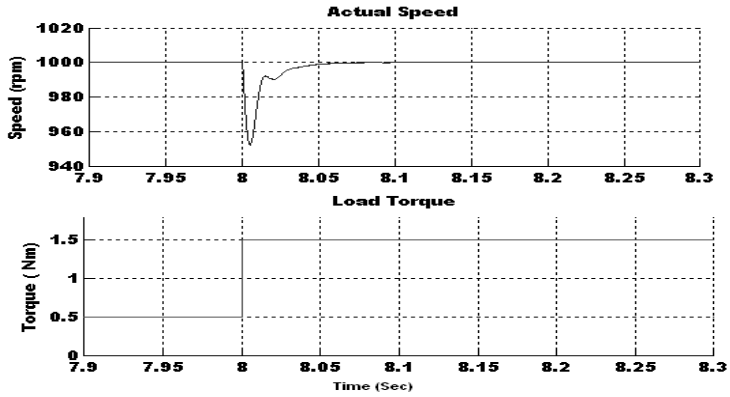

Fig. 8. Speed response for load torque step change

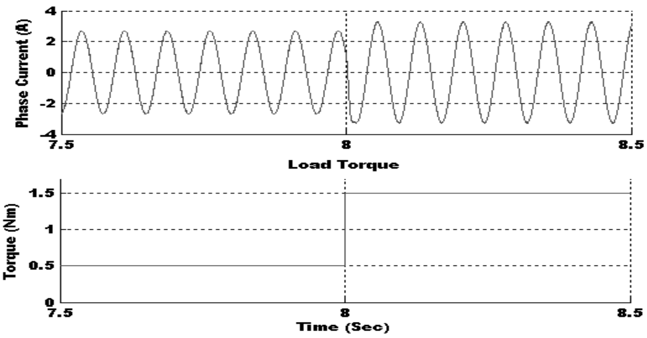

Fig. 9. Current variation for load torque step change

The drive is operated with constant speed through out and there is step change in load. At 8 sec the load torque increases from 0.5Nm to 1.5Nm which correspond to 25% variation as the rated torque is 4Nm. Figure 8 reveal the drive speed response for this step change in load. Speed curve exhibits a 4% peak overshoot and it takes 0.05 Sec to settle at the set point. Fig. 9 depicts the motor current for the same step variation in load torque. This also illustrates the mitigated performance of the drive system. Hence the vector controlled PMSM fed through hexagram inverter has been studied for various operating conditions. The drive performance is found to be excellent in all the cases. Thus the design of the hexagram inverter and the vector controlled PMSM drive has been validated through the simulation results.

To alleviate the complexity the results obtained through simulation in the MATLAB / Simulink environment have been summarized in a tabular format. Table I consolidates the performance of the vector controlled hexagram inverter fed PMSM drive under various operating conditions.

Table I Performance of the vector controlled drive

Nature of disturbance	Variation	Peak over shoot / under shoot (%)	Settling time (Sec)
20% change in reference speed	800rpm to 1000rpm	3.5	0.04
160% change in reference speed	800rpm To -800rpm	30	0.04
25% change load torque	0.5 Nm to 1.5 Nm	4.5	0.05
50% change load torque	0.5Nm to 2.5Nm	10	0.06

Both the variations either in the command side or in the load side are given as step change which is the worst case or it is of abnormal conditions. Normally the load variation in real time system is not of sudden change instead it will be of gradual variation. Since the drive functioning is superior under these conditions the design is validated. The above table establishes the eminence of the hexagram inverter fed vector controlled PMSM drive system developed in MATLAB. Using this analysis the real time implementation can be exploited out in an enhanced manner. The motor ratings used for simulation studies are given as Table II in the appendix.

VI. CONCLUSION

The hexagram inverter with 6 traditional VSI is designed in MATLAB / Simulink and the results are presented. The THD and the switching stresses are found to be reduced when compared with the traditional three phase VSI. The main advantage also includes that the hexagram inverter is suitable to drive a 3-phase or 6-phase drive system. Hence the proposed hexagram inverter seems to be suitable for high power applications. The hexagram inverter is used to drive the PMSM. The complete drive scheme has been modeled using Simulink.

The drive scheme performance is studied under various operating conditions. As a first step the steady state performance is examined. Then the drive is analyzed for its dynamic response, with a disturbance in the input side and the output side. Also the results are tabulated which depicts the efficient performance of the drive scheme. It is apparent from the response obtained as the peak overshoot / undershoot and the settling times are reasonably with the set limits. Thus the design of the hexagram inverter and the vector controlled PMSM drive has been validated through the simulation results. The tabulated results confirm the efficacy of the drive scheme.

Appendix

Table II. Parameters of the PMSM

Parameters	Values
Rated Power	1. 5 KW
Rated voltage	120 V
Rated current	7.4A
Type	3 Phase
Frequency	50Hz
Number of poles	6
Rated Torque	4Nm

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