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Multilevel Inverter Fed Permanent Magnet Synchronous Motor Drive with Constant Torque Angle Control

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Abstract

This paper presents a strategy for vector control of Permanent Magnet Synchronous Motor (PMSM) drive fed with a diode clamped multilevel inverter. In the proposed work the conventional 2-level inverter is replaced with three and five level inverters in PMSM drive system. The implementation of multilevel inverters improved the torque and speed response under various operating conditions. PI controller is employed as speed controller and PWM technique is used to trigger switches of multilevel inverter. Simulations are carried out using MATLAB/Simulink environment under various operating conditions to show the effectiveness of proposed methodology. Simulation results reflect the effectiveness of proposed scheme in steady state and dynamic conditions. Particular attention is paid to the motor torque pulsations and speed response.

Keywords: Permanent magnet synchronous motor (PMSM), multilevel inverter (MLI), Vector control, PI.

1. Introduction

Two types of permanent-magnet ac motor drives are available in the drives industry. These are PMSM drive with a sinusoidal flux distribution, and the brushless dc motor (BDCM) drive with a trapezoidal flux distribution [1]. PMSM has numerous advantages over other machines that are conventionally used for ac servo drives. The use of the permanent magnet in the rotor of the PMSM makes it unnecessary to supply magnetizing current through the stator for constant air gap flux; the stator current need only be torque-producing. Hence for the same output, the PMSM will operate at a higher power factor (because of the absence of magnetizing current) and will be more efficient than the IM. PMSM drives are widely used for high- performance servo applications like robotics and aerospace actuators since no external excitation is given to rotor losses are reduced and make PMSM highly efficient. Also absence of rotor winding renders slip rings and brushes obsolete and thus reduces maintenance cost. PMSM drives are preferred because of less complexity in control as compared with field oriented control of induction motor drives. These drives have high torque inertia ratio thus implies rapid dynamic response. 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. Multilevel inverter technology has emerged recently as a very important alternative in the area of high-power-medium voltage energy control [2]. Advantages of multilevel inverters over conventional two-level inverter are less switching losses, reduced harmonics. The multilevel voltage source inverters unique structure allows them to reach high voltage and power levels without the use of transformers. Benefits of reactive power compensation on power systems, on both, transmission and distribution level are well known. There are three types of multilevel topologies, flying capacitor multilevel inverter, diode clamped and cascaded multilevel inverters. Diode clamped multilevel inverter is chosen for feeding PMSM drive over all configurations of multilevel inverter.

2. Proposed Scheme

The machine, speed and position feedback, speed and current controllers, and inverter constitute the PMSM drive system as shown in Fig 1. The torque reference is a function of speed error, and the speed controller is usually of PI type. For fast response speed controller is replaced by PID controller. The product of torque response and air gap flux linkage generates the torque producing component of the stator current .the reason for this block is to adjust the torque producing component of the stator current both in constant torque and in the constant power.

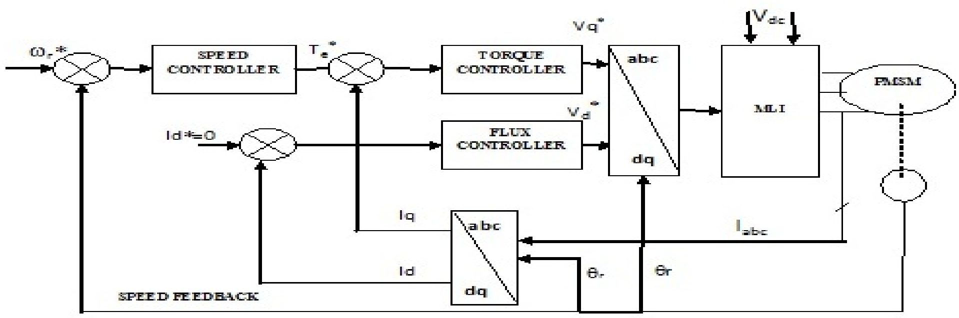


Figure 1: Multilevel inverter fed PMSM drive system.

Regions of operation. The stator phase current commands are amplified by the inverter and its logic and are fed to PMSM. The rotor position is obtained with a position encoder or synchronous resolver. The velocity signal is extracted from the rotor position by using signal processors available commercially at present. In the derivation of stator current commands, it was assumed that the zero sequence current is zero. The error between the reference and actual speeds is operated upon by the speed controller to generate the PWM pulse. In the constant air-gap flux mode of operation where id=0 rotor position feedback is needed to generate these currents. The PWM current controller attempts to force the actual motor currents to equal the commanded values at all times. Current feedback is required for the PWM current controllers to achieve this. Current control is implemented by the appropriate firing of power devices. Two three and five level multilevel inverter is used here in place of conventional inverters to improve the speed and torque performances.

3. Multilevel Inverters

Multilevel inverters have drawn tremendous interest in the power industry. They present a new set of features that are well suited for use in reactive power compensation. Multilevel inverters will significantly reduce the magnitude of harmonics and increases the output voltage and power without the use of step-up transformer. Multilevel inverters are preferred over traditional inverters as single devices can’t handle the V and I because for that the device voltage rating required 8-10kV is generally not available so voltage handling capability problem arises also poor power quality due to harmonic distortions and high switching losses.

3.1 Inverter Topologies

There are 3 basic types of multi-level inverter
Isolated H-bridge
Diode clamped inverter
Flying capacitor inverter
Combinational Multilevel Topologies
Cascading Fundamental Topologies [3]

With the use of multilevel inverters device voltage sharing is automatic because of the independent DC supplies also there is no restriction on switching pattern. With N devices (each capable of operating at voltage V_{dc}) per-phase, the circuit can produce an output varying between ± $(N/2)*(V_{dc}/2)$. By using a lot of H-bridges, very high voltage converters can be made this way. The circuit is modular this is an advantage for manufacture and maintenance also the voltage stress on each of the switch gets reduced with the advent of multilevel inverters

3.2 Phase Disposition PWM(PDPWM)

The carriers are in phase across all the bands. For this technique, significant harmonic energy is concentrated at the carrier frequency, but since it is a co-phase component, it doesn't appear in the line-to-line voltage. There are several pulse width modulations based on sine-triangular comparisons with voltage-shifted or time-shifted carrier for multilevel converter.

4. PMSM Drive

PMSM, it is a synchronous motor which the rotor windings are replaced by high resistivity permanent magnet material so no induced current in the rotor i.e. the rotor is lossless. In these motors (PMSM) the permanent magnet material is placed on the rotor by many methods. Among these methods, surface mounted magnets, inset magnets and buried magnet. Depending on these configurations, different properties of the machine are obtained. In case of surface mounted magnets, the rotor iron is approximately round and the stator inductance is low, as well as independent of the rotor position. The control of the machine becomes simple and the reluctance effect can be neglected [8].

The operation of that motor in field weakening is difficult due to generate higher d-axis current this is because the low value of stator inductance. The method of motor control is very important in the drive system. This is because the operation of the PMSM under some methods of control is suffered from complicated coupling and nonlinear dynamic performance. This problem can be solved by field oriented control (FOC). To achieve the field-oriented control of PMSM, knowledge of the rotor position is required. Usually the rotor position is measured by a shaft encoder, resolver, or Hall sensors. PMSM with FOC emulates the separately excited DC motor. In this method of control, the stator current can be decupled into flux and torque current components.

3.3 Mathematical model of PMSM drive

The model of PMSM without damper winding has been developed on rotor reference frame using the following assumptions[9,10]:

1) Saturation is neglected
2) The induced EMF is sinusoidal
3) Eddy currents & hysteresis losses are negligible
4) There are no field current dynamic

Voltage equations are given by:

$$V_q = R_s i_q + \omega_r \lambda_d + \rho\lambda_q \quad (1)$$

$$V_d = R_s i_d - \omega_r \lambda_q + \rho\lambda_d \quad (2)$$

Flux Linkages are given by

$$\lambda_q = L_q i_q \quad (3)$$

$$\lambda_d = L_d i_d + \lambda_f \quad (4)$$

Substituting above equations

$$V_q = R_s i_q + \omega_r (L_d i_d + \lambda_f)+ \rho L_q i_q \quad (5)$$

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

The developed torque motor is being given by

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\lambda_d i_q - \lambda_q i_d) \quad (7)$$

The mechanical torque equation is

$$T_e = T_L + B\omega_m + J\frac{d\omega m}{dt} \quad (8)$$

Solving for the rotor mechanical speed

$$\omega_m = \int \left(\frac{Te - TL - B\omega m}{J}\right) dt \quad (9)$$

$$\omega_m = \omega_r \left(\frac{2}{P}\right) \quad (10)$$

In the above equation ω_r is the rotor electrical speed where as ω_m is the rotor mechanical speed.

$$v_d = R_s i_d + L_d \frac{d}{dt} i_d - \omega_r L_q i_q \quad (11)$$

$$v_q = R_s i_q + Lq \frac{d}{dt} i_q + \omega_r (L_d i_d + \Phi_f) \quad (12)$$

$$\Phi_d = L_d i_d + \Phi_f \quad (13)$$

$$\Phi_q = L_q i_q \quad (14)$$

3.4 Vector control of PMSM drive

Objective of vector control of PMSM is simply to control the motor just like a separately excited DC motor. Direct current 'i_d' is forced to be zero and d-axis is aligned with permanent magnet flux linkage phase. The basic principle of controlling a PMSM is based on field orientation is that of a DC motor by a decoupling control which separates the current and flux channels. Equation can be written as follows

$$\Phi_d = \Phi_f \quad (15)$$

$$\Phi_q = L_q i_q \quad (16)$$

Expression for electromagnetic torque is given by

$$C_e = k_t i_q \tag{17}$$

$$K_t = \frac{3}{2} p \Phi_f \tag{18}$$

Constant torque operation that is $i_d=0$ is used .This control strategy is derived from field oriented control where maximum possible torque is desired at all times like DC motor. This is performed by making the torque producing current i_q equal to supply current that results in making angle α to be 90 degrees

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\lambda_f i_q) \tag{19}$$

Thus the torque is given by

$$T_e = k_t i_q \tag{20}$$

3.5 PWM current controlled inverter

A method used to generate the require currents is to use a PWM stator current controller. The actual values of the three stator currents are measured and compared to the reference currents. Thus error currents are generated. These error currents are compared to a saw tooth-shaped triangular wave. If the current error signal is positive and larger than the saw tooth, the voltage is switched positively, while if the current error signal is positive and smaller than the saw tooth, the voltage is switched negatively. Note that it is unnecessary to use complementary switching to achieve this voltage profile.

3.6 Speed control loop

For a motor drive system with full speed range will consist of a motor, an inverter, a controller, speed controller calculates the difference between the reference speed and actual speed producing an error, which is fed to PI controller. PI controllers are widely used for motion control systems. They consist of a proportional gain that produces an output proportional to the input error and an integration to make the steady state error zero for a step change in input.

3.7 Constant Torque Angle Control

Constant torque control strategy is derived from field oriented control, where the maximum possible torque is desired at all times like the dc motor. By making the I_d equal to zero the torque equation can be written as:

$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\lambda_f i_q)$. Assuming that $k_t == \frac{3}{2}\left(\frac{P}{2}\right)(\lambda_f)$. The torque is given by $T_e = k_t i_q$. Like the dc motor, the torque is dependent of the motor current. The dynamic modelling is used for study of motor during transient and steady state which is done by converting the three phase voltages and currents todq0 variables by using Park's transformation. On converting the phase voltages variables abc to dq0 variables in rotor reference frames

$$I_{abc} = T^{-1} I_{abc} \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & -\sin\theta & \frac{\sqrt{2}}{2} \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & \frac{\sqrt{2}}{2} \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix} \quad (21)$$

$$I_{dq0} = T I_{abc} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (22)$$

5. Simulation Results

Simulations of PMSM drive using a three level and five level multilevel converters were carried out in MATLAB/Simulink. The results of these simulations are depicted in figure 6. In fig. 6(a) simulation results of speed response for two and three- level is compared and it is seen that with the increase in level of inverter the torque ripples are reducing. The overshoot with three-level inverter is less as compared with two-level inverter with same rating of motor.

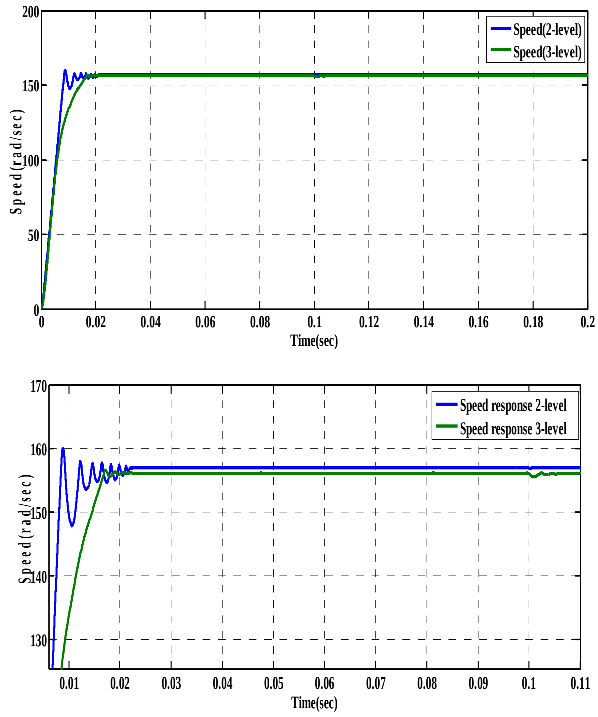


Figure 6: (a): Simulation results of speed (2- level and 3- level)

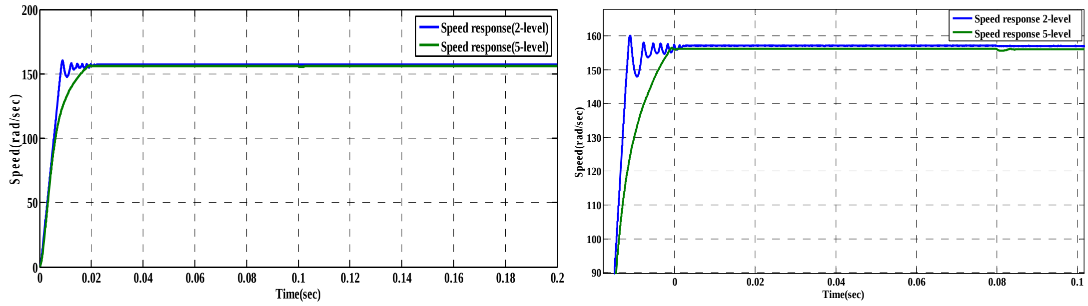
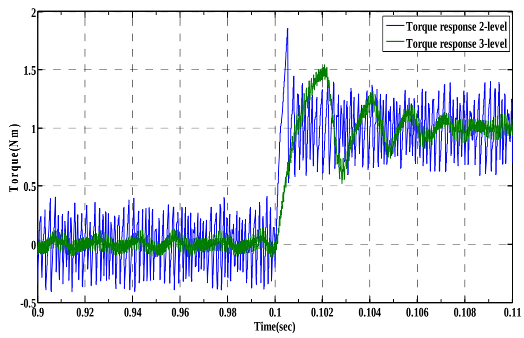


Figure 6: (b): Simulation results of speed (2- level and 5- level).

In fig. 6(b) the speed response of 2 and 5-level inverter is compared and it is observed that the ripples in speed response are even less as compared with three-level inverter fed PMSM. Figure 6(b) also shows speed response of two and five-level inverters at load of 1 Nm at 0.2 seconds with X-axis zoomed.



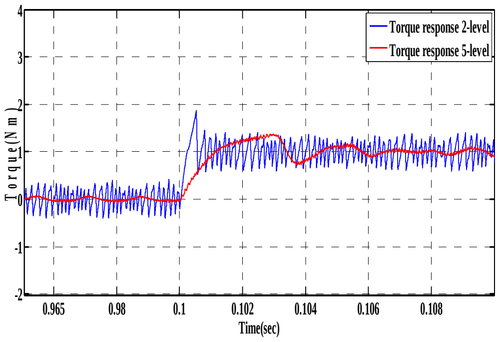
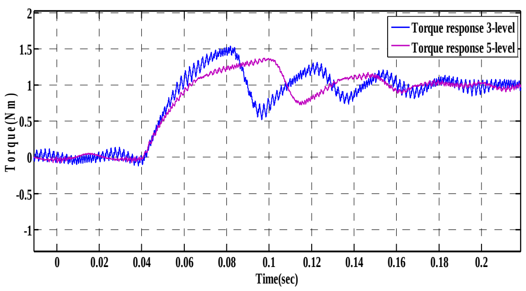


Figure 6(c): Simulation results for torque (2- level and 3-level) Figure 6(d): Simulation results for torque (2- level and 5-level)



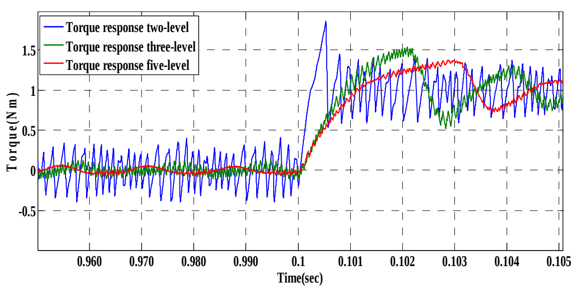


Figure 6(e): Simulation results of torque (3- level and 5- level) Figure 6(f): Simulation results for torque (2, 3 and 5-level)

Fig. 6(f) show the comparative torque response of two, three and five-level inverter fed PMSM drive. Load torque of 1N.m is given at 0.2 sec. Depicted results show that as the level increases the torque ripples are reducing. In fig. 6(c) torque response of two and three-level inverter fed PMSM drive is shown and it can be seen that the ripples for three-level inverter fed PMSM is less as compared with two level. Fig. 6(e) torque response of three and five level inverter fed PMSM is depicted and ripples in fivel level inverter fed PMSM are less than three level invertere fed PMSM drive and even less than two level inverter fed drive. Figure 6(h),6(i) and 6(h) shows the voltage waveform of two, three and five level inverter fed PMSM input voltage given is 280V for all three levels of inverter fed PMSM drive.

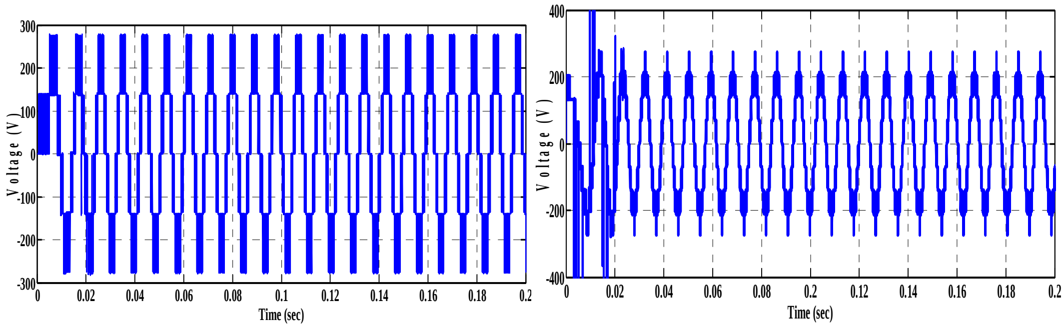


Figure 6(g): Simulation results of voltage for 2- level.

6. Conclusion

In this paper vector control has been described in adequate detail and has been implemented on PMSM in combination with multilevel inverter with two, three and five levels. This method enables the operation of the drive at zero direct axis stator current. Therefore, it permits the operation at minimum armature current. In this situation, we obtain maximum torque per ampere as well as maximum efficiency. Transient results when a PMSM is started up from standstill to a speed of 157 rad/sec. The linear manner in which the speed increases is possible because of vector control. During the start-up period, the commanded torque equals the maximum capability of the motor. This ensures that the machine runs up in the shortest time possible. The motor needs much smaller voltage compared to the conventional synchronous motor. The performance of vector control is quite satisfactory for achieving fast reversal of PMSM even at very high speed ranges. These drives can be used for RADAR tracking systems.

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