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Speed Control Schemes of Four Quadrant Operating PMSM Drive For Electric Vehicles Applications

Ritu Tak[1], Sudhir Y Kumar[2] and B.S.Rajpurohit[3]

[1,2] *Electrical Engineering, Mody University of Science & Technology, Lakshmangarh, India.*
Electrical Engineering, School of Computing and Electrical Engineering, IIT, Mandi, India.

[1]*Orcid: 0000-0002-7072-7956*

Abstract

Electric vehicles (EVs) become popular in an accelerated pace in the world due to the energy crises and environmental pollution. The higher fuel prices forced the automobile company to develop EVs having high fuel economy and low emission; however the technology is still in early development stage. The smooth and accurate speed control of PMSM emphasis is on electric vehicles, in this paper a Surface Mounted PMSM drive is developed for the four quadrant operation the PWM or Hysteresis techniques are used for controlling the torque as in the inner loop and the PI controller is used in the outer loop as a speed controller. The speed of the motor depends on the driving cycle as the motor is coupled by mechanical connection to transmission. In EVs the driver's torque demand is computed the motor torque, the ripples in the torque increase the losses and produce the noise. The performance of the electric drive is improved by reducing the ripples in torque and current waveform. The simulation results of speed control of PMSM are realized in MATLAB. A comparative analysis of speed control scheme with PWM and hysteresis controller has been presented in this paper.

Keywords: Surface Mounted Permanent magnet synchronous motor (SM-PMSM), four quadrant operation, Electric vehicles (EVs), pulse width modulation (PWM), Hysteresis current controller.

INTRODUCTION

The interest of researcher in development of high efficient electric vehicles increases due to the oil prices increases and natural environment concerns. For build a high efficient EVs PMSM drives preferred in place of IM drives. PMSM drives provide a high torque, high power at low weight, robustness against the uncertainty and high efficiency these distinct properties of PMSM make it the first choice for the EVs.

In paper [1,2] for electric vehicles Induction motor, surface-mounted permanent-magnet motor, and interior PMSM drives compared in terms of output power and efficiency with reference to a common vehicle specification. The merits and limitations of these three motor drives are quantified comprehensively and summarized. The induction motor has less expensive but high losses where as SM-PMSM has simple construction but at high speed eddy current loss is more so it limit the use of SM-PMSM for the low or light electric vehicles. The interior permanent magnet synchronous motor shows better performance but it might be complicated.

A permanent magnet synchronous machine operated with field oriented control is used in electric vehicles, field oriented control allows for a machine operation at a low voltage level. To ensure a stable performance, and to design the controller without oscillation, an accurate knowledge of the machine in the d-q rotor reference frame is required [3]. The specified torque-speed characteristic required for the electric vehicles mainly influence by the stator winding turn and the permanent magnet width. In the paper [4] the torque ripple and the harmonic contents are decreased by optimizing the rotor shape by the offset arc method and improve the supply quality and traction performance. The electromagnetic and structural analysis of surface-mounted permanent-magnet synchronous machine (SM-PMSM) for light-electric vehicles are evaluated numerically as well as experimentally through test in the paper [5] and conclude that the SM-PMSM has the best power density but a high torque ripples is the drawback of this, these ripples introduces vibration and noise. The EV motor work on a low-torque region due to this a high percentage of PWM carrier harmonic iron loss accounts. In paper [6] a novel technique is proposed for carrier harmonic loss reduction and also compared with the conventional motor. A PMSM drive train system with various inverter modulation schemes are discussed in the paper [7] and indicated that the use of hysteresis controller reduces the pulsing frequency. Generally hysteresis current controllers are used in the Electric vehicles due to the lower cost but the simulation results shows in this paper that PWM current controllers are the best choice for the electric vehicles they reduce the ripples and losses in the drive likewise improve the performance of the electric vehicles.

The paper is organized as section I is the introduction. Section II explains the basic mathematical model of PMSM and in section III describe the four modes of operation of the PMSM this is the basic requirement of the electric vehicles applications. The speed control scheme with PWM and hysteresis current control technique is discussed in section IV.

The simulation results are presented in the section V and at last paper is concluded in section VI followed by the references.

MATHEMATICAL MODELING OF PMSM

The dynamic model of the PMSM is derived using a two-phase motor in direct and quadrature (dq) axes [8,9]. The model of PMSM has been developed on rotor reference frame assume that induced EMF is sinusoidal, and losses are negligible.

The d-and q-axes stator voltages are for surface mounted PMSM is:

$$\begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix} = R_s \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} + \begin{bmatrix} \frac{1}{2}\left(L_q + L_d\right) & 0 \\ 0 & \frac{1}{2}\left(L_q + L_d\right) \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} + \lambda_{af}\omega_r \begin{bmatrix} \cos\theta_r \\ -\sin\theta_r \end{bmatrix} \qquad (1)$$

V_{ds} and $V_{qs}$are the d- and q-axes windings voltages

i_{ds} and $i_{qs}$are the q- and d-axes windings currents

R_s the stator winding resistance

λ_{af} the mutual flux linkages

θ_r is the instantaneous rotor position

ω_r is the rotor speed in electrical radians per second

The system equation become simple and compact at the rotating reference frame. The relationship between the stationary reference frames and the rotor reference frames is written as:

$$i_q d_s = [T^r] i_q^r d_s \qquad (2)$$

$$v_q d_s = [T^r] v_q^r d_s \qquad (3)$$

$$T^r = \begin{bmatrix} \cos\theta_r & \sin\theta_r \\ -\sin\theta_r & \cos\theta_r \end{bmatrix} \qquad (4)$$

$$\begin{bmatrix} v_{qs}^r \\ v_{ds}^r \end{bmatrix} = \begin{bmatrix} R_s + L_q p & \omega_r L_d \\ -\omega_r L_q & R_s + L_d p \end{bmatrix} \begin{bmatrix} i_{qs}^r \\ i_{ds}^r \end{bmatrix} + \begin{bmatrix} \omega_r \lambda_{af} \\ 0 \end{bmatrix} \qquad (5)$$

$$\begin{bmatrix} i_{qs}^r \\ i_{ds}^r \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta_r & \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos\left(\theta_r + \frac{2\pi}{3}\right) \\ \sin\theta_r & \sin\left(\theta_r - \frac{2\pi}{3}\right) & \sin\left(\theta_r + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} \qquad (6)$$

The expression for the electromagnetic torque

$$T_e = \frac{3}{2}\frac{P}{2}\left[\lambda_{af} + \left(L_d - L_q\right) I_{ds}^r\right] I_{qs}^r \qquad (7)$$

The overall dynamic model of PMSM in rotor reference frame is

$$\begin{bmatrix} \frac{dI_{qs}^r}{dt} \\ \frac{dI_{ds}^r}{dt} \\ \frac{d\omega_r}{dt} \\ \frac{d\theta_r}{dt} \end{bmatrix} = \begin{bmatrix} \frac{R_s}{L_q} & -\left(\frac{L_q}{L_d}\omega_r\right) & \frac{\lambda_{af}}{2H} & 0 \\ \left(\frac{L_q}{L_d}\omega_r\right) & -\frac{R_s}{L_q} & 0 & 0 \\ \frac{\lambda_{af}}{2H} & -\frac{\left(L_d - L_q\right) I_{qs}^r}{2H} & -\frac{B}{2H} & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} I_{qs}^r \\ I_{ds}^r \\ \omega_r \\ \theta_r \end{bmatrix} + \begin{bmatrix} \frac{1}{L_q} & 0 & 0 \\ 0 & \frac{1}{L_q} & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} V_{qs}^r \\ V_{ds}^r \\ T_l \end{bmatrix} \qquad (8)$$

FOUR-QUADRANT OPERATION OF PMSM

In application of EVs PMSM drives operate to rotate in both directions, it must be capable of motoring and regeneration in both directions of rotation. The drives used in EVs are operating in the entire four quadrants with the variable speed [10,11]. Figure 1 shows the speed and torque variation of the PMSM machine in a different mode of operation namely forward motoring (FM), forward regeneration (FR), reverse motoring (RM) and the reverse regeneration (RR) mode. The fist quadrant is the FM mode in this motor rotates in forward direction as the speed and torque is positive, the third quadrant is the mirror reflection of the first quadrant here speed and torque both are in negative direction. The negative torque opposes the positive motoring torque, due to this power flow from the machine to the power supply source this mode is called as the reverse braking mode.

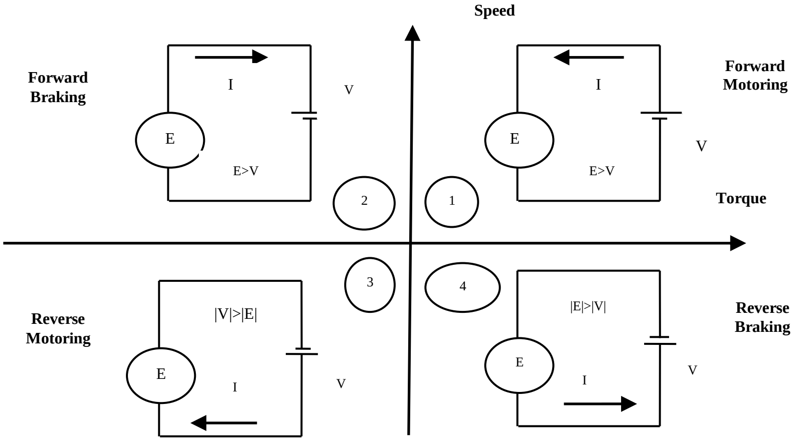


Figure 1: Four Quadrant operation of PMSM

Similarly the quadrant III and II, the difference between the I and IV quadrant is the direction of rotation, hence the phase sequence is changed. The four quadrant operation of the PMSM drive and its relationship between torque, speed, power output and the phase sequence of the motor supply are summarized in table- I

Table I: Four-Quadrant Operation of PMSM

Quadrant	Mode of Operation	Speed	Torque	Power Output	Phase Sequence
I	Forward motoring mode (FM)	Positive	Positive	Positive	abc
II	Reverse regeneration mode (RR)	Negative	Positive	Negative	acb
III	Reverse motoring mode (RM)	Negative	Negative	Positive	acb
IV	Forward regeneration mode (RR)	Positive	Negative	Negative	abc

SPEED-CONTROL SCHEME OF PMSM DRIVE FOR EVs

A speed-controlled PMSM drive system having a two loop, the inner loop is for the torque controlled that is the basic core of the drive system and an outer loop is the speed control loop for controlling the rotor speed of the drive. The figure 2 shows the schematic block diagram of the speed controlled system of the EVs. A proportional integral controller is used in outer loop for speed regulation [12]. For increasing the efficiency of the EVs PID controller is appropriate in place of PI it gives a fast response of the speed. As shown in figure 2, the speed error is the input of the speed controller block, that generate the electromagnetic torque, the speed error can be minimized by increasing or decreasing the electromagnetic torque in the machine. The speed controller block also generates the mutual flux linkages reference according the demand of the rotor speed. The electromagnetic torque reference and the mutual flux linkage reference synthesis the reference stator current, that can be used in a inner loop that is torque controlled of the drive system.

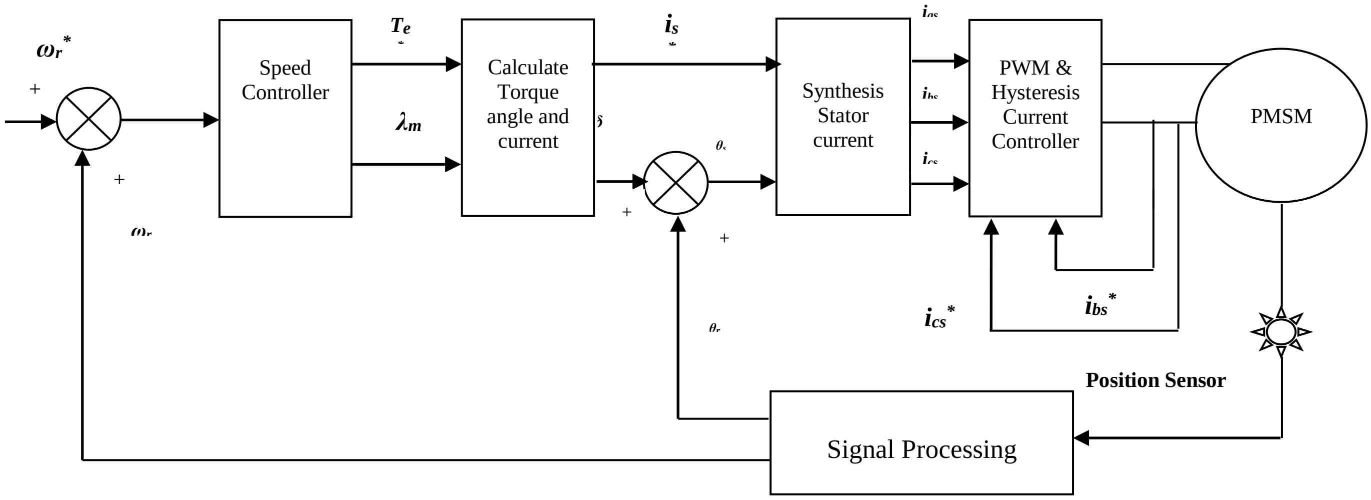


Figure 2: Speed Controlled PMSM Drive

There are two schemes for the torque controlled one is the hysteresis current control and other is the PMSM current control. In the hysteresis controller, the actual current and the desired value to control is compare and generate the bounded envelope or a narrow band within the stator phase current has to be maintained [13,14].

The switching logic for the hysteresis phase 'a' current controller is given below all other can be similarly made.

$$i_{as} - i_{as}^{*} \geq \Delta i \qquad set \quad v_{ao} = \frac{V_{dc}}{2} \tag{9}$$

$$i_{as} - i_{as}^{*} \leq -\Delta i \qquad set \quad v_{ao} = \frac{-V_{dc}}{2}$$

The d-and q-axes voltages and stator current can be derived from the line and phase voltages. The stator phase currents came by the inverse transformation of d-and q axes stator currents and from the rotor reference frames the torque and mutual flux linkages can be computed.

The hysteresis controller is simple in this the hysteresis current window is set according to the preset deviation of current.

In PWM scheme the pulse width to gate signals of the inverter changes by this the input voltage applied to the machine changes. There are a number of PWM schemes that can be realized in PMSM drives [15]. The PWM schemes eliminate the harmonics and maximize the fundamental component.

The switching logic for one phase is summarized as

$$v_{am} = \frac{V_{dc}}{2}\frac{v_{pref}}{v_{pc}} \tag{10}$$

Where,

v_{pref} is the peak value of the command signal or phase 'a' voltage and v_{pc} is the peak value of the carrier signal

The modulation index or ratio is defined by

$$m = \frac{v_{pref}}{v_{pc}} \tag{11}$$

Varying modulation index changes the fundamental amplitude.

SIMULATION RESULTS OF THE PMSM CONTROLLED DRIVE SYSTEM

The PMSM drive system, whose rating and parameters are given in Table-II, is subjected to test

Table II: Machine Parameters

Parameter	**Notation**	**Value**
Stator Resistance	R_s	2.4 Ω
d axis inductance	L_d	0.0035 H
q axis inductance	L_q	0.0075 H
Rated speed	ω_r	314.3 rpm
Friction Coefficient	B	0.02 Nms
Rotor Flux linkage	λ_{af}	0.1845 Wb
Moment of Inertia	J	0.006 kg/m2
Number of Poles	p	6

The simulation done in MATLAB, for making the PMSM drive high efficient for the EVs the two speed controlled schemes are tested and compare. In one of the scheme used the hysteresis current controller in a torque controlled loop and in the other scheme use the PWM current controller. The simulation results of these two schemes shown in figure (3) and (4) respectively.

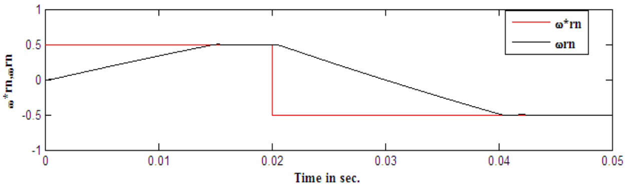


Figure 3(a)

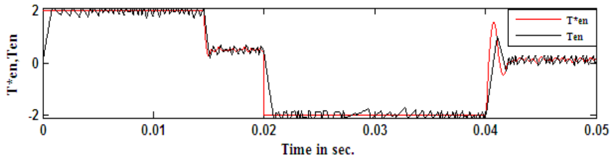


Figure 3(b)

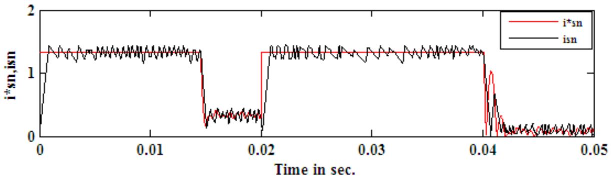


Figure 3(c)

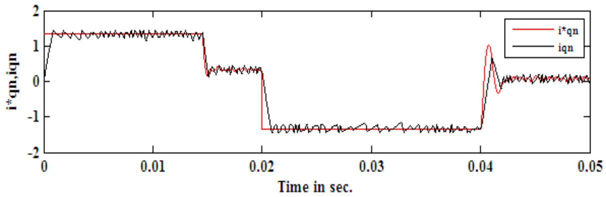


Figure 3(d)

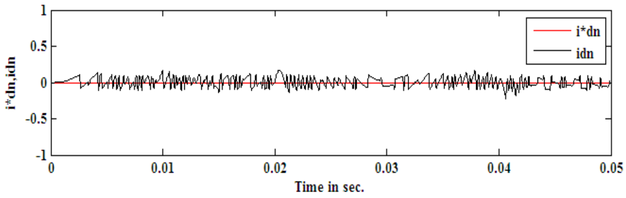


Figure 3(e)

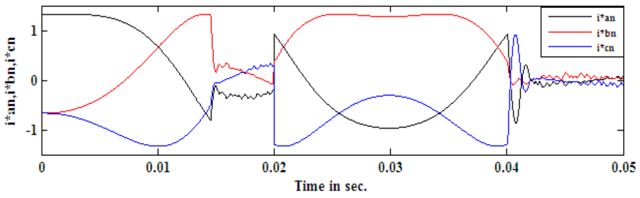


Figure 3(f)

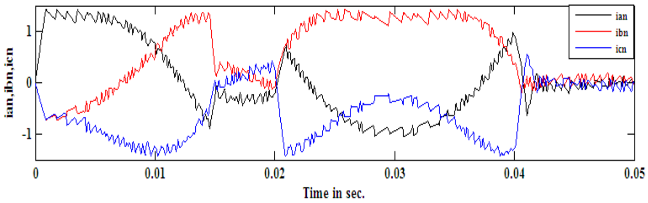


Figure 3(g)

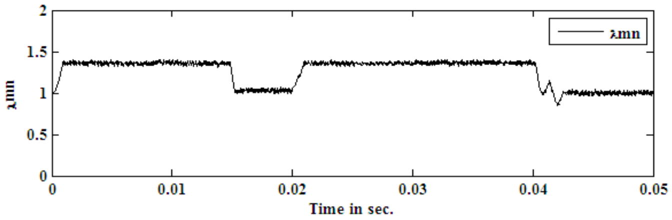


Figure 3(h)

Figure 3: Hysteresis current controlled PMSM drive

The machine is start at standstill, when a speed command comes in positive direction, the torque is also driven in positive direction up to maximum and maintained there until the speed matches the speed command. As the rotor speed reaches to the command speed, the reference torque also comes down to match the load torque when the speed reference changes from positive to negative the torque reference is driven to negative as shown in figure 3(a) and 3(b) with hysteresis current controller and in figure 4(a) and 4(b) with PWM current controller.

During speed reversal the need for a sudden phase inversions in the phase current here the performance of the current loop is important and there performance reflects and make the EVs high efficient.

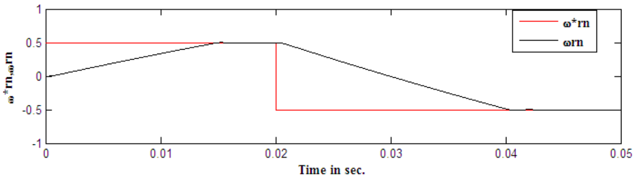


Figure 4(a)

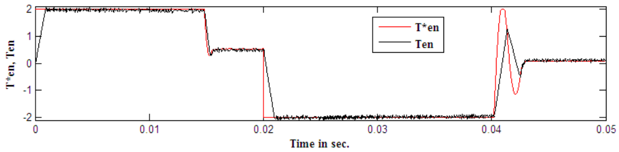


Figure 4(b)

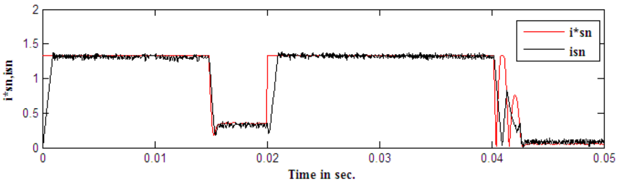
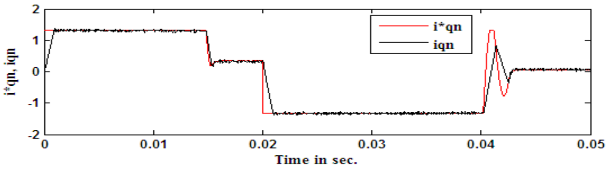


Figure 4(c)



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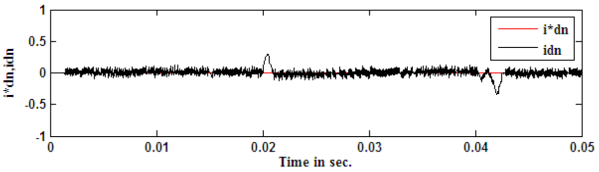

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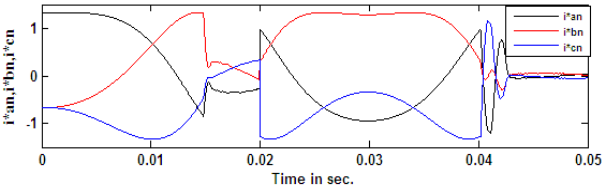

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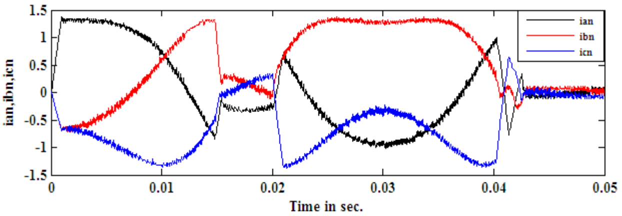

Figure 4(g)

Figure 4: PWM current controlled PMSM drive

The MATLAB/Simulation results are shown in figure 3 and figure 4 with the speed control technique with Hysteresis current controller and PWM current controller respectively. As compare the electromagnetic torque produce by the electric drive in the prescribed two schemes by the simulation results shown in figure 3 (b) and 4(b), found that the ripples in the torque with the hysteresis current controller are high. The ripples in the current waveform with the hysteresis current controller are also reported high as compare the simulation results of different currents waveform for the two speed control scheme as shown in figure 3(c),3(d),3(e),3(f),3(g) with 4(c),4(d),4(e),4(f) and 4(g). Even the flux produces by the armature is sluggish by the hysteresis current control is shown in figure 3(h) it will effect on time response as well as producing oscillations in speed loop. The ripples in torque and currents are less in the PWM current controller.

CONCLUSION

This paper presented simulation and analysis of a speed control technique with PWM or hysteresis current controller for a PMSM drive under different operating condition. Hysteresis current controller reduces pulsating frequency but at the same time it increases the ripples that may produces noises and vibration in the electric vehicles and these are reduces by using the PWM current controller in the speed control technique in place of hysteresis current controller that improve the performance of the vehicles. The control mechanism eliminates the noise and vibration in the system, make the fast dynamic response of the electric vehicles. The speed control system for PMSM is designed and simulated using MATLAB/Simulink platform The simulation results have demonstrated the feasibility of the speed control with the PWM current controller the fast dynamic torque response, low torque ripple.

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