International Journal of Mechanical Engineering and Technology (IJMET)
Volume 8, Issue 5, May 2017, pp. 1137–1146 Article ID: IJMET_08_05_119
Available online at http:// http://www.iaeme.com/ijmet/issues.asp?JType=IJMET&VType=8&IType=5
ISSN Print: 0976-6340 and ISSN Online: 0976-6359

 Scopus Indexed

MODELING THE TORQUE CONTROL SCHEME OF SURFACE MOUNTED PERMANENT MAGNET SYNCHRONOUS MOTOR

Ritu Tak, Sudhir Y Kumar
Mody University of Science & Technology, Lakshmangarh, India

B. S. Rajpurohit
School of Computing and Electrical Engineering, IIT, Mandi, India

ABSTRACT

In this paper a torque control scheme of surface mounted permanent magnet synchronous motor (PMSM) drive system is modeled and analyzed. The PMSM replaced the induction motor in many applications due to their low inertia, high torque and high efficiency. The dynamic per unit model of the PMSM is used to model the hysteresis current controller and PWM current controller under the torque control scheme. In this paper a comparative study between these two current controllers for a torque driven PMSM has been presented.

Key words: Permanent Magnet Synchronous Machine, Hyteriseis Current Controller, PWM Current Controller.

Cite this Article: Ritu Tak, Sudhir Y Kumar and B. S. Rajpurohit, Modeling The Torque Control Scheme of Surface Mounted Permanent Magnet Synchronous Motor, *International Journal of Mechanical Engineering and Technology*, 8(5), 2017, pp. 1137-1146.
http:// http://www.iaeme.com/ijmet/issues.asp?JType=IJMET&VType=8&IType=5

1. INTRODUCTION

In the recent years, the ac drives based on PMSM becomes more competitive and more attractive due to the availability of the high energy density magnetic material in lower cost. The PMSM drives replace the induction motors due to their numerous advantages say high torque, high efficiency and high reliability. The PMSM drives also removes the disadvantages of the synchronous motor by replacing the dc power supply, field coils and slip rings with a permanent magnet [1]. For achieve the fast torque response in PMSM drives such as the dc machines a vector control method is used, that make the PMSM popular in many applications like robotics, adjustable speed drives and electric vehicles[2,3]. The performance of the vector control PMSM drive depends on the applied torque control scheme; in the torque control scheme there is current controllers which force the load current to follow the reference current trajectory [4, 5]. In this paper two current control schemes hysteresis and PWM current controller is model and compare under the torque control scheme of the PMSM drive.

The organization of the paper as the I section is the introduction in this the importance of torque control in PMSM drive system is explained in II section the dynamic per unit model of PMSM drives is presented. The basic of the torque control scheme and the two current controllers are explained in the III, IV and V section respectively. The MATLAB simulation results are shown in section VI and comparison analysis of these two controllers is presented in the section VII and at last in section VIII the paper was conclude with the references.

2. MATHEMATICAL MODELING OF SURFACE MOUNTED PMSM

The dynamic model of the PMSM is derived using a two-phase motor in direct and quadrature (dq) axes [6,7]. The model of PMSM has been developed on rotor reference frame assume that induced EMF is sinusoidal, eddy current, saturation and hysteresis losses are negligible. The windings are displaced in space by 90^0 electrical degrees and the rotor windings at an angle θ_r from the stator d-axis winding. It is assumed that the q-axis lead the d-axis to a counter clockwise direction of rotation of the rotor.

The d-and q-axes stator voltages are

$$V_{qs} = R_q i_{qs} + p\lambda_{qs} \quad (1)$$

$$V_{ds} = R_d i_{ds} + p\lambda_{ds} \quad (2)$$

where-p is the differential operator, d/dt

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

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

R_q and R_d are the resistances in the q- and d-axes windings

λ_{qs} and λ_{ds} are the flux linkages in the q- and d-axes windings

The stator winding flux linkages can be written as the sum of the flux linkages due to their own excitation and mutual flux linkages resulting from other winding current and magnet sources. The q and d stator flux linkages are written as

$$\lambda_{qs} = L_{qq} i_{qs} + L_{qd} i_{ds} + \lambda_{af} \sin\theta_r \quad (3)$$

$$\lambda_{ds} = L_{dq} i_{qs} + L_{qd} i_{ds} + \lambda_{af} \cos\theta_r \quad (4)$$

where θr is the instantaneous rotor position. The windings are balanced and therefore their resistances are equal and denoted as $R_s = R_q = R_d$. The d and q stator voltages can then be written in terms of the flux linkages and resistive voltage drops as

$$V_{qs} = R_s i_{qs} + i_{qs} pL_{qq} + L_{qq} pi_{qs} + L_{qd} pi_{ds} + i_{ds} pL_{qd} + \lambda_{af} p \sin\theta_r \quad (5)$$

$$V_{ds} = R_s i_{ds} + i_{qs} pL_{qd} + L_{qd} pi_{qs} + L_{dd} pi_{ds} + i_{ds} pL_{dd} + \lambda_{af} p \cos\theta_r \quad (6)$$

L_{qq}& L_{dd}= self inductances of the q and d axes windings, respectively

$$L_{qq} = \frac{1}{2}\left[\left(L_q + L_d\right) + \left(L_q - L_d\right)\cos 2\theta_r\right] \quad (7)$$

$$L_{dd} = \frac{1}{2}\left[\left(L_q + L_d\right) - \left(L_q - L_d\right)\cos 2\theta_r\right] \tag{8}$$

Compactly represented as

$$L_{qq} = L_1 + L_2 \cos 2\theta_r \tag{9}$$

$$L_{dd} = L_1 - L_2 \cos 2\theta_r \tag{10}$$

where, L_1 & L_2

$$L_1 = \frac{1}{2}\left(L_q + L_d\right) \tag{11}$$

$$L_2 = \frac{1}{2}\left(L_q - L_d\right) \tag{12}$$

$L_{qd} = L_{dq}$= mutual inductances between two windings

$$L_{qd} = -L_2 \sin 2\theta_r \tag{13}$$

Substituting the self and mutual inductances in terms of the rotor position into the stator voltage equations will result in a large number of terms that are rotor position dependent, then the equation becomes:

$$\begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix} = R_s \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} + \begin{bmatrix} L_1 + L_2 \cos 2\theta_r & -L_2 \sin 2\theta_r \\ -L_2 \sin 2\theta_r & L_1 - L_2 \cos 2\theta_r \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} + 2\omega_r L_2 \begin{bmatrix} -\sin\theta_r & -\cos 2\theta_r \\ -\cos 2\theta_r & \sin 2\theta_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} + \lambda_{af}\omega_r \begin{bmatrix} \cos\theta_r \\ -\sin\theta_r \end{bmatrix} \tag{14}$$

In surface mount magnet machines, the inductances are equal and therefore L_2 is zero and the above equation becomes for surface mounted PMSM is:

$$\begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix} = R_s \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} + \begin{bmatrix} L_1 & 0 \\ 0 & L_1 \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} + \lambda_{af}\omega_r \begin{bmatrix} \cos\theta_r \\ -\sin\theta_r \end{bmatrix} \tag{15}$$

At rotating reference frames, the system inductance matrix becomes independent of the rotor position, thus leading to the simplification and compactness of the system equations. The relationship between the stationary reference frames and the rotor reference frames is written as:

$$i_{qds} = [T^r] i^r_{qds} \tag{16}$$

$$v_{qds} = [T^r] v^r_{qds} \tag{17}$$

$$T^r = \begin{bmatrix} \cos\theta_r & \sin\theta_r \\ -\sin\theta_r & \cos\theta_r \end{bmatrix} \tag{18}$$

$$\begin{bmatrix} v^r_{qs} \\ v^r_{ds} \end{bmatrix} = \begin{bmatrix} R_s + L_q p & \omega_r L_d \\ -\omega_r L_q & R_s + L_d p \end{bmatrix} \begin{bmatrix} i^r_{qs} \\ i^r_{ds} \end{bmatrix} + \begin{bmatrix} \omega_r \lambda_{af} \\ 0 \end{bmatrix} \tag{19}$$

where ω_r is the rotor speed in electrical radians per second.

$$\begin{bmatrix} i^r_{qs} \\ i^r_{ds} \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta_r & \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos\left(\theta_r + \frac{2\pi}{3}\right) \\ \sin\theta_r & \sin\left(\theta_r - \frac{2\pi}{3}\right) & \sin\left(\theta_r + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} \tag{20}$$

The relationship between the stator currents in the rotor reference frames and the actual stator dq currents is given by

$$i_{abc} = [T_{abc}]^{-1} i_{qdo}^{r} \tag{21}$$

$$[T_{abc}]^{-1} = \begin{bmatrix} \cos\theta_r & \sin\theta_r & 1 \\ \cos\left(\theta_r - \frac{2\pi}{3}\right) & \sin\left(\theta_r - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta_r + \frac{2\pi}{3}\right) & \sin\left(\theta_r + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \tag{22}$$

3. TORQUE-CONTROLLED PMSM DRIVE SYSTEM

The PMSM drives control through the stator currents, because the torque is directly proportional to currents either in stator frames or in rotor frames and control of torque gives the control in speed and position [8, 9,10]. A torque-controlled motor drive system has independent inputs of external torque and mutual flux linkages as reference single these are obtained from the known equations of torque and mutual flux linkages except that, reference variables are introduced instead of the real variables, and they are

$$T_{ref} = \frac{3}{2}\frac{P}{2}\left[\lambda_{af} i_{sref} \sin\delta_{ref} + \frac{1}{2}\left(L_d - L_q\right)(i_{sref})^2 \sin 2\delta_{ref}\right] \quad \text{(N.m)} \tag{23}$$

$$\lambda_{afref} = \sqrt{(\lambda_{af} + L_d i_{sref}\cos\delta_{ref})^2 + \left(L_q i_{sref}\sin\delta_{ref}\right)^2} \quad \text{(Wb-Turn)} \tag{24}$$

For a surface-mounted PMSM, where the direct and quadrature inductances are equal, then the references for torque and mutual flux linkages are reduced to

$$T_{ref} = \frac{3}{2}\frac{P}{2}[\lambda_{af} i_{sref}\sin\delta_{ref}] \quad \text{(N.m)} \tag{25}$$

$$\lambda_{mref} = \sqrt{(\lambda_{af} + L_d i_{sref}\cos\delta_{ref})^2 + \left(L_q i_{sref}\sin\delta_{ref}\right)^2} \tag{26}$$

$$= \sqrt{(\lambda_{af} + L_d i_{sref}\cos\delta_{ref})^2 + (L_d i_{sref}\sin\delta_{ref})^2}$$

$$\lambda_{mref} = \sqrt{\lambda_{af}^2 + (L_d i_{sref})^2 + 2(\lambda_{af} L_d i_{sref}\cos\delta_{ref})} \quad \text{(Wb-Turn)} \tag{27}$$

For obtaining the torque angle references, the flux producing component of the stator current $i_{sref}\cos\delta_{ref}$ is solved from equation (26) by substituting $i_{sref}\sin\delta_{ref}$ from equation (24) that comes out to be

$$i_{sref}\cos\delta_{ref} = \frac{\left[\sqrt{\left((\lambda_{mref})^2 - L_d^2 \frac{(T_{ref})^2}{\left(\frac{3P}{22}\lambda_{af}\right)^2}\right)} - \lambda_{af}\right]}{L_d} \tag{28}$$

The stator current reference is obtained by substituting $i_{sref}\cos\delta_{ref}$ from equation (28) in equation (27) as

$$i_{sref} = \frac{\sqrt{(\lambda_{mref})^2 - (\lambda_{af})^2 - 2\lambda_{af}(i_{sref}\cos\delta_{ref})}}{L_d} \tag{29}$$

The reference of torque angle obtained from equation (7) and (8). From the torque angle and current references, the torque and flux producing stator currents can be evaluated and adjusted for reference variables in place of real variables as

$$\begin{bmatrix} i_T^* \\ i_f^* \end{bmatrix} = i_{sref} \begin{bmatrix} \sin\delta \\ \cos\delta \end{bmatrix} \tag{30}$$

Now the phase current references are obtained by applying the transformation from rotor frame references currents to abc currents as

$$\begin{bmatrix} i_{as}^* \\ i_{bs}^* \\ i_{cs}^* \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r \\ \cos\left(\theta_r - \frac{2\pi}{3}\right) & \sin\left(\theta_r - \frac{2\pi}{3}\right) \\ \cos\left(\theta_r + \frac{2\pi}{3}\right) & \sin\left(\theta_r + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} i_T^* \\ i_f^* \end{bmatrix} = i_{sref} \begin{bmatrix} \sin(\theta_r + \delta_{ref}) \\ \sin\left(\theta_r + \delta_{ref} - \frac{2\pi}{3}\right) \\ \sin\left(\theta_r + \delta_{ref} + \frac{2\pi}{3}\right) \end{bmatrix} \tag{31}$$

The basic schematic implementation of torque scheme is shown in figure 1, the error between the phases currents are forced to zero through proportional integral controllers to yield phase voltage references. They can be enforced in the inverter through the current controllers. The nature of the controller is not matter the outcome of the current controller is a signal that will demand the phase voltage to follow in such a way that the current error in that phase is reduced to zero. The hysteresis and PWM current controllers are uses.

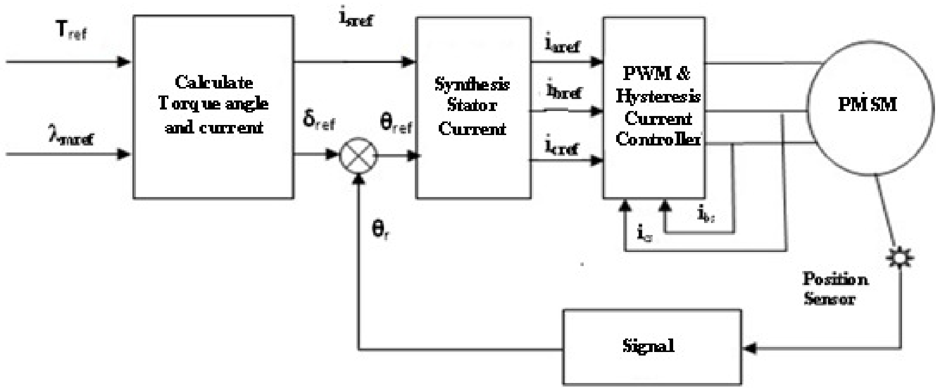

Figure 1. Block diagram of Torque scheme

4. HYSTERESIS CURRENT CONTROL

The hysteresis controller uses a fast-acting current source that is form by converting a voltage source. In the hysteresis controller a narrow band of excursion is form from its desired value to control the actual current. The hysteresis window determine the preset deviation of current Δi, by summing and subtracting it from the stator phase current reference to generate the bounded envelope within which the stator phase current has to be maintained [11,12,13] .

Based on that, the switching logic for the hysteresis phase current controller is given as

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

$$i_{as} - i_{as}^* \leq -\Delta i \qquad \text{set} \quad v_{ao} = \frac{-V_{dc}}{2} \tag{32}$$

The implementation for other phases can be similarly made. 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 and it is dependent only on the magnitude of the instantaneous peak current and the set current window. Hysteresis current controller performance with varying current windows as the analysis shows that switching frequency increases as the current window decreases.

5. PWM CURRENT CONTROLLER

The control of harmonics and variation of the fundamental component can be achieved by varying the duration of applied input voltage to the machine. It is realized by changing the pulse width to gate signals of the inverter and it is known as PWM. A number of PWM schemes have been in use in motor drives [14,15]. All the PWM schemes, in general, aim to maximize the fundamental harmonics and selectively eliminate a few lower harmonics. The reference signal for the PWM controller that interact with the carrier signal to generate gate pulse is the voltage signal output of the current controller

The switching logic for one phase is summarized as

$$v_{am} = \frac{V_{dc}}{2}\frac{v_{pref}}{v_{pc}} \quad (33)$$

Where,

v_{pref} is the peak value of the a phase reference or command signal

v_{pc} is the peak value of the triangular carrier signal

The modulation index or ratio is defined by

$$m = \frac{v_{pref}}{v_{pc}} \quad (34)$$

Varying modulation index changes the fundamental amplitude.

The schematic of the motor drive with inner current feedback loops and controllers is shown in Figure 2 Only two-phase currents are sensed and in a three-phase three-wire system; the sum of the phase currents being zero, the third phase current is constructed using this fact. The processing circuit provides this option and is intended to include the filters for all individual phase currents too.

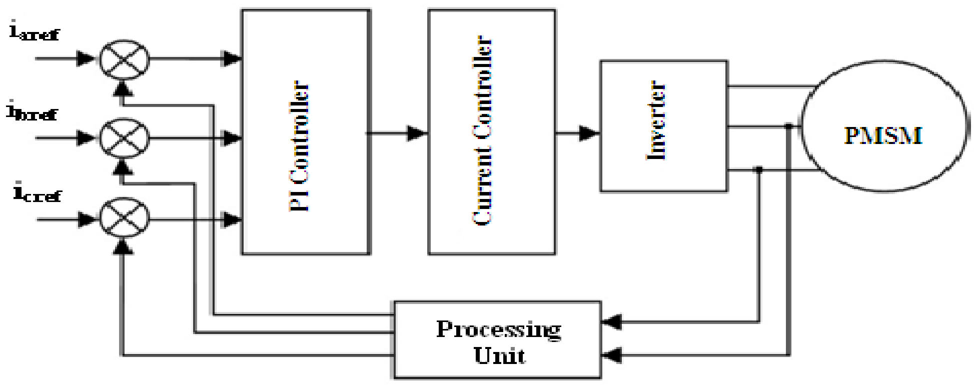

Figure 2 Block diagram of Current controller

6. MODELING OF A TORQUE-CONTROLLED DRIVE SYSTEM

The parameter of the surface mounted PMSM shown in Table 1 have been simulated in MATLBA environment. The speed of the machine is maintained constant at a speed of 0.5 p.u. and the current window for hysteresis current controller is set at 0.1 p.u. very low value because the torque ripple is increases as the ripple in q-axis current increases. It is seen that the hysteresis current controller force the current to follow the reference current with very small delay and the air gap flux increase with the stator current. The torque angle is controlled on an average to the desired value but their excursions from the reference value is primarily due to the deviation in the current from its reference determined by the current control quality in the inverter and machine parameters.

Table1 Machine Parameters

Parameter	**Value**
Number of Poles (P)	6
Stator Resistance (R_s)	1.4 Ω
d axis inductance (L_d)	0.0056 H
q axis inductance (L_q)	0.009 H
Rotor Flux linkage (λ_{af})	0.1546 Wb
Friction Coefficient(B)	0.01 Nms
Moment of Inertia (J)	0.006 kgm^2
Rated speed (ω_r)	314.3 rpm

The variables are plotted in normalized units of p.u. except torque angle, is it in electrical degrees and time. The MATLAB code for the simulation of hysteresis current controller is generated and the simulation result is shown below

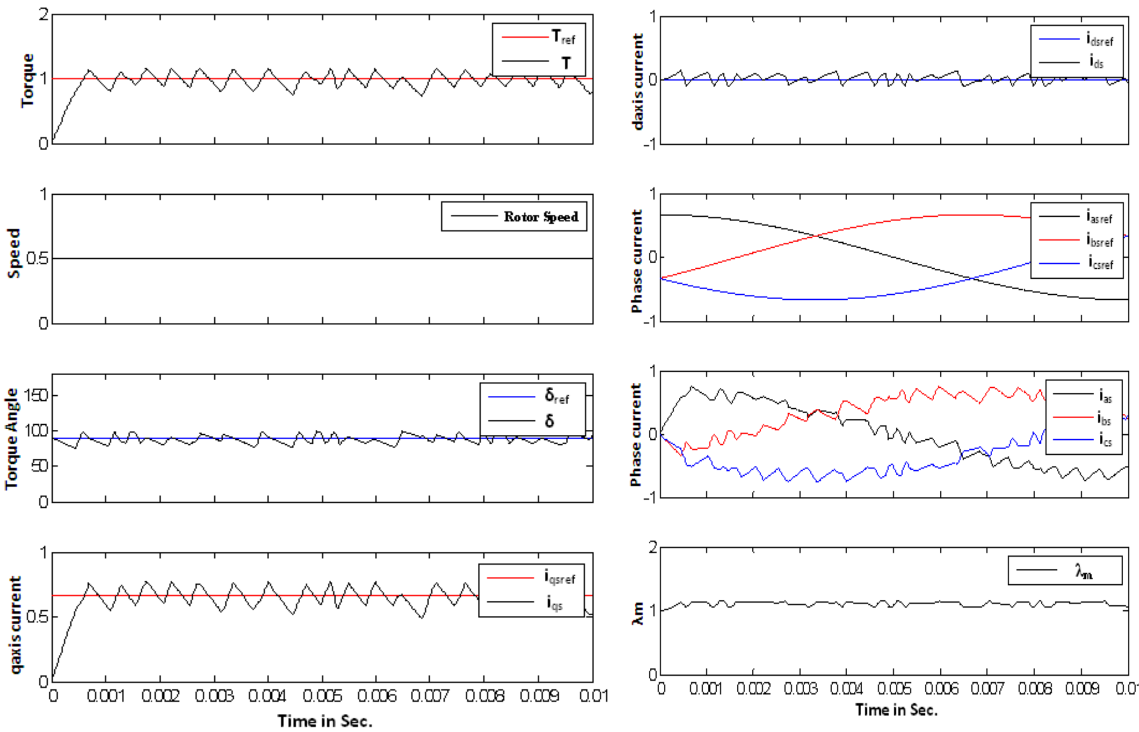

Figure 3 Performance of PMSM with Hysteresis current controller

A sine triangle-based PWM controllers with carrier frequency is 20 kHz is taken for analysis the torque drive performance of the drive the operating condition is same as the hysteresis controller. The MATLAB code for the simulation of PWM current controller is generated and the simulation result is shown below

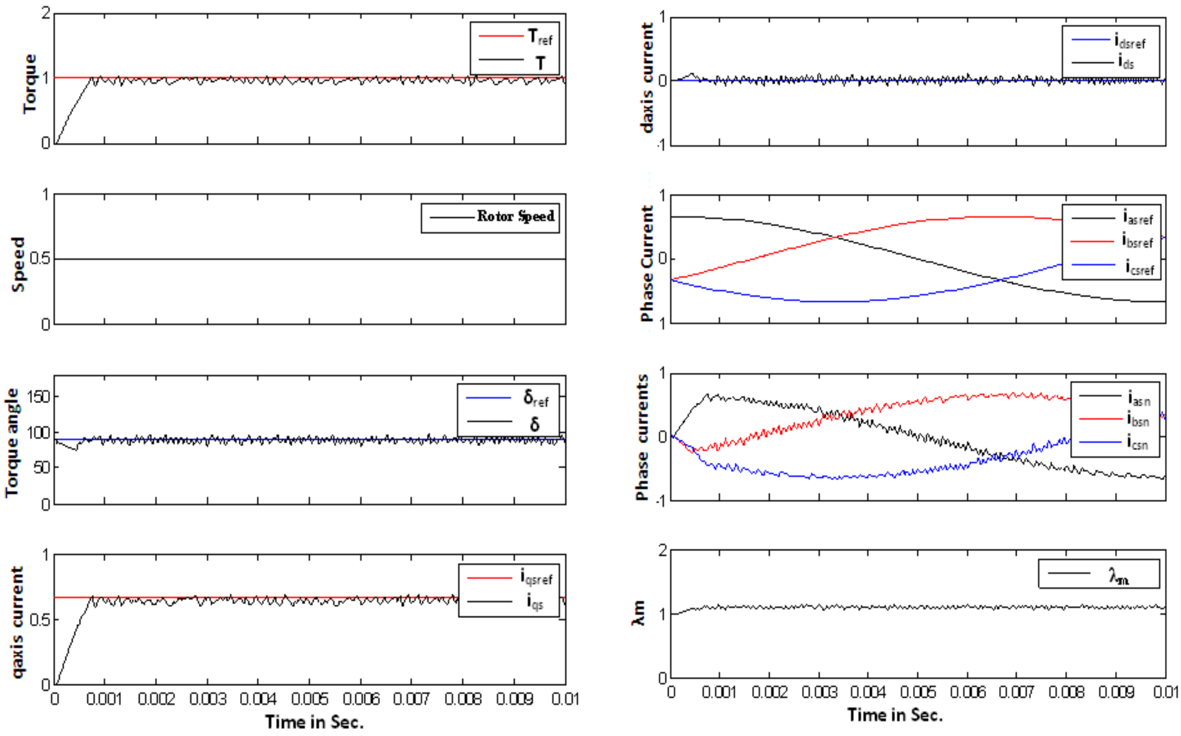

Figure 4 Performance of PMSM with PWM current controller

The result shows the difference in the performance of the two controllers is in the magnitudes of the current ripple and the torque pulsation.

7. COMPARISON

The PWM current controller once determine the duty cycle of carrier cycle by sampling the input voltage, then the voltage (or current) is controlled on an average but not on a instantaneous basis. Continuous duty cycle variation means more than one switching per carrier cycle that is increases the inverter losses, so for instantaneous voltage/current control PWM current controller is not preferred.

This drawback of PWM current controller can be overcome by the Hysteresis controller, in this the voltage source converting to a fast-acting current source whereas the drawback of hysteresis controller says varying the switching frequency and the hysteresis current window can be overcome by PWM controller.

A comparison analysis of the PWM and hysteresis controllers is shown in Table 2.

Table 2 Comparison between the Current Controllers of PMSM

	Hysteresis Current Controllers	**PWM Current Controllers**
Switching frequency	Varying	Fixed at carrier frequency
Speed of response	Fastest	Fast
Current Ripple	high	small
Torque Ripple	high	small
Air gap flux linkages	identical	identical
size of filter	Dependent on Δi	Usually small
Switching losses	Usually high	Low

Table 2 shows, the main disadvantages of the hysteresis controller is the variable switching frequency that can be limited, by varying the hysteresis current window according to the load conditions and the size of the filter in Hyteresis current controller depends upon the magnitude of the current where as in PWM controller the switching frequency is fixed and the size of the controller is independent of the current variation it is usally small in size that make the system cost efficient and stable.

8. CONCLUSION

A torque control scheme for surface mounted PMSM drive system has being developed and operation at the rated speed has been studied using two current control schemes hysteresis current controller and PWM current controller. A comparative study has been made of the two current control schemes. The performance of the PMSM drive system depends upon the controlling system. Figure 3 and 4 shows the comparative analysis between the two controllers the torque pulsations in PWM controller are very small with high switching frequency when compared to a hysteresis control-based drive with a large hysteresis window.

Hysteresis current controller generally preferred in research laboratories due to its simplicity. Mostly PWM current controller is used in industries because the current ripples and the torque pulsations are very small as compared to hysteresis current controller the simulation result verify this fact, whereas the air gap flux linkages are identical in both the schemes.

REFERENCES

[1] Peter Sekerak,Valeria Hrabovcova,Juha Pyrhonen , Lukas Kalamen , Pavol Rafajdus ,and Matus Onufer.Comparison of Synchronous Motors With Different Permanent Magnet and Winding Types. *IEEE Transactions On Magnetics, Vol. 49, No. 3, March 2013.*

[2] Kichiro Yamamoto, Katsuji Shinohara, and Takahiro Nagahama. Characteristics of Permanent-Magnet Synchronous Motor Driven by PWM Inverter with Voltage Booster.*IEEE Transactions On Industry Applications, Vol. 40, No. 4, July/August 2004.*

[3] Gianmario Pellegrino, Alfredo Vagati, Barbara Boazzo, and Paolo Guglielmi.Comparison of Induction and PM Synchronous Motor Drives for EV Application Including Design Examples. *IEEE Transactions on Industry Applications, Vol. 48, No. 6, November/December 2012.*

[4] Gangfeng Yen. Simulation for the Vector Control Algorithm of Permanent Magnet Synchronous Motor. *7th International Conference on Intelligent Human-Machine Systems and Cybernetics (IHMSC), 2015.*

[5] W. Leonard, Control of Electrical Drives. New York: Springer Verlag, 1984.

[6] S S Kulkarni, A G Thosar.Mathematical Modeling and Simulation of Permanent Magnet Synchronous Machine. *International Journal of Electronics and Electrical Engineering Vol. 1, No. 2, June 2013.*

[7] Zhuqiang Lu , Honggang Sheng , H.L. Hess and K.M. Buck. The modeling and simulation of a permanent magnet synchronous motor with direct torque control based on Matlab/ Simulink. *IEEE International Conference on Electric Machines and Drives. 2005.*

[8] Turker Turker, Umit Buyukkeles, and A. Faruk Bakan. A Robust Predictive Current Controller for PMSM Drives. *IEEE Transactions on Industrial Electronics, 2016; Vol. 63, No. 6.*

[9] R.M. Pindoriya, A.K. Mishra, B.S. Rajpurohit and R. Kumar. Performance analysis of control strategies of permanent magnet synchronous motor. *IEEE Region 10 Conference (TENCON), 22-25 Nov. 2016.*

[10] R. Krishnan, Permanent Magnet Synchronous and Brushless DC Motor Drives, CRC, 2010.

[11] Cosmas Ogbuka , Cajethan Nwosu, Marcel Agu. A Fast Hysteresis Current–Controlled Permanent Magnet Synchronous Motor Drive Based On Field Orientation. *Journal of Electrical Engineering, Vol 67 (2016), No2, 69–77.*

[12] P.Mamta , A.K Nadir, Beena Singh. An Adaptive Hysteresis Current Controller for Interior Permanent Magnet Synchronous Motor. *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, 2015.Vol. 4, Issue 7.*

[13] Bor-Jehng Kang and Chang-Ming Liaw. A Robust Hysteresis Current-Controlled PWM Inverter for Linear PMSM Driven Magnetic Suspended Positioning System.*IEEE Transactions on Industrial Electronics. 2001 Vol. 48, No. 5.*

[14] Lokesh N Rai and Avatar Narain Mathur, Analysis of Self-Excited Vibrations In A Large Synchronous Electric Motor – An Investigation, Volume 4, Issue 6, November - December (2013), pp. 19-30, International Journal of Mechanical Engineering and Technology (IJMET)

[15] Bawar A. Abdalla, Zhenar Sh. Faeq and Zrar Kh. Abdul, Exploiting Design of Synchronous Counters Method To Design and Implement Mod 6 Direct Down Counter. International Journal of Electronics and Communication Engineering & Technology, 6(7), 2015, pp. 31-37.

[16] Jung-Ik Ha.Current Prediction in Vector-Controlled PWM Inverters Using Single DC-Link Current Sensor.*IEEE Transactions on Industrial Electronics. 2010,Vol. 57, No. 2.*

[17] G.R.Barse and A.A. Bhole, Analysis of Distance Protection Relay In Presence of Static Synchronous Compensator (Statcom), Volume 6, Issue 5, May (2015), pp. 14-20, International Journal of Electrical Engineering and Technology.

[18] L. Zhong, M. F. Rahman, W. Y. Hu, and K. W. Lim. Analysis of Direct Torque Control in Permanent Magnet Synchronous Motor Drives. *IEEE Transactions on Power Electronics. 1997 Vol. 12, No. 3.*