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# Comparative Analysis of Direct Torque Control based on Hysteresis Modulation and PWM in PMSM

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***Abstract*: The Permanent Magnet Synchronous Motors (PMSM) are having a compact structure with small size and weight, hence they are used in many applications. The open loop operation of the PMSM does not provide good torque and speed response. In order to improve the torque and speed response the Direct Torque Control (DTC) is implemented. The DTC is basically divided into two, the first one is based on hysteresis modulation and the second one is based on pulse width modulation (PWM). This work intends to go for a comparative analysis of Direct Torque Control (DTC) based on hysteresis modulation and pulse width modulation (PWM). The simulation results shown significant improvement in the torque and speed response of the machine.**

***Keywords*: Direct Torque Control (DTC), Permanent Magnet Synchronous Motor (PMSM).**

## 1. Introduction

The Permanent magnet synchronous motors (PMSM) are usually used in industrial, electric vehicle and robotic applications because of their small size, less weight, high torque to inertia ratio, large efficiency, different speed range, silent and robust operations. In a PMSM the permanent magnet is embedded in the rotor which produces a strong magnetic field. The stator consists of windings which carry the three phase AC supply which in turn produces a rotating magnetic field. The interaction of these two magnetic fields results in the operation of the machine. The open loop control of the machine does not provide a smooth operation, it provides uncontrolled torque and speed output.

In order to improve the steady state and dynamic performance of the PMSM drive methods like field oriented control (FOC) with pulse width modulation are used. The major drawback of this scheme is the limited bandwidth which leads to an unsatisfactory control performance during transient state. Thus a direct torque control (DTC) strategy is proposed to improve the dynamic performance of ac machines that need fast transient responses. The DTC is generally divided into two one based on hysteresis modulation and the other based on PWM.

The basic principle of DTC scheme is to select the optimal stator voltage vectors based on the error sign between the torque and the estimated stator flux linkage values. In DTC based on hysteresis modulation the torque and flux errors are fed to a hysteresis controller. In DTC based on PWM the torque and flux errors are fed to a PI controller.

## 2. Permanent Magnet Synchronous Motor (PMSM)

Permanent Magnet Synchronous Motors (PMSM) are widely used in computer peripheral equipment's, robotics, adjustable speed drives and electric vehicles since they consume low power. A permanent magnet synchronous motor uses permanent magnets to produce the air gap magnetic field instead of using electromagnets. These motors attracts the interest of researchers and industry for use in many applications due to their certain advantages.

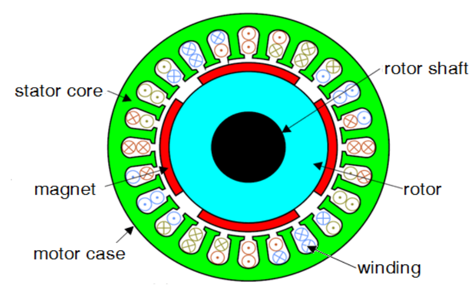


Fig. 1. PMSM Cross section

The Figure 1 shows the cross section of Permanent Magnet Synchronous Machines (PMSM). It consists of a stator, which is the stationary part of the machine. By winding continuous strips of soft steel stator laminations for axial air gap machines are formed. Various parts of the laminations are the teeth slots which contain the armature windings. The magnetic path circuit is completed by the yoke. Depending upon the frequency of the armature source voltage and cost the thickness of the lamination used is decided. Armature windings are commonly double layered and lap wound. The characteristics of a permanent magnet machine are highly dependent on the rotor structure. The rotor construction can be done in many ways. The rotor can be constructed completely without iron by employing the modern permanent magnet materials.

### 3. Mathematical Modelling of PMSM

The assumptions used for modelling PMSM is given below

1. Effect of saturation is neglected.
2. Induced EMF is sinusoidal.
3. Eddy current and hysteresis loss is negligible.
4. There is no effect of field current dynamics.

The modelling is done in the *dq* reference frame. The stator equations of the induction machine in the rotor reference frames using flux linkages are taken to derive the model of PMSM. The rotor frame of reference is chosen because the position of the rotor magnets determines the instantaneous induced emfs and subsequently the stator currents and torque of the machine. Voltage equations in rotor reference frame are given by

$$V_q = R_q i_q + \omega_r \lambda_d + P\lambda_q \quad (1)$$

$$V_d = R_d i_d - \omega_r \lambda_q + P\lambda_d \quad (2)$$

The flux linkages are given by

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

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

Substituting the flux linkages in equation (1) and (2)

$$V_q = R_q i_q + \omega_r (L_d i_d + \lambda_f) + P L_q i_q \quad (5)$$

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

Arranging above equations in matrix form

$$\begin{bmatrix} V_q \\ V_d \end{bmatrix} = \begin{bmatrix} R_q + PL_q & \omega_r L_d \\ -\omega_r L_q & R_d + PL_d \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \begin{bmatrix} \omega_r \lambda_f \\ P\lambda_f \end{bmatrix}$$

The developed motor torque is given by

$$. T = \frac{3}{2}\frac{P}{2}(\lambda_d i_q - \lambda_q i_d) \quad (7)$$

The mechanical torque equation is

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

The rotor mechanical speed is given by

$$\omega_m = \int \frac{T_e - T_L - B\omega_m}{J} dt \quad (9)$$

A PMSM model is developed in Mat lab Simulink by using the above equations as shown in figure 2.

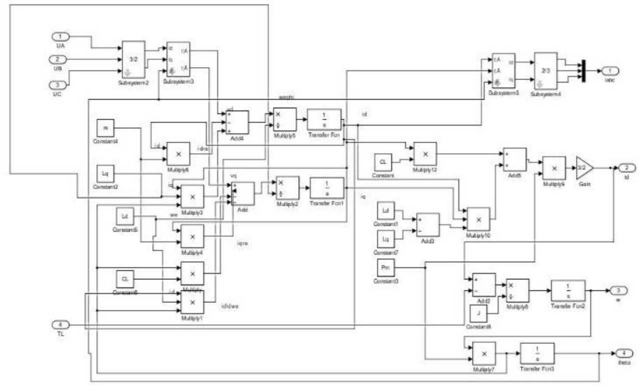

Fig. 2. Simulink model of PMSM

The basic PMSM drive circuit is shown in figure 3. It consists of a DC source, an inverter, pulse width modulator and the PMSM. The inverter converts the DC supply to AC. The gate pulses required for the operation of the inverter is provided by the pulse width modulator. The output voltage from the inverter is provided to the PMSM.

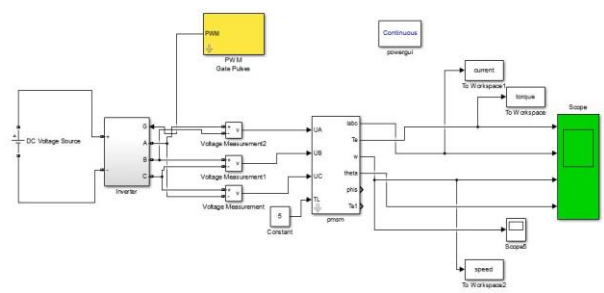

Fig. 3. PMSM drive circuit

### 4. Direct Torque Control

A voltage vector based on the error between requested and actual (sensed and estimated) values of torque and flux, rotor position estimation is to be selected which is working principle of the basic DTC. DTC can work without any external measurement sensor for the rotors mechanical position. The rotor position is required at the motor start up to identify the correct direction of rotation of a PMSM. The basic DTC is simpler when compared with other schemes because it does not require any kind of current regulators, rotating reference frame transformation or a PWM generator. The major advantages of the DTC is to eliminate the dq-axes current controllers, associated transformation networks, and the rotor position sensor. The disadvantages are low speed torque control difficulty, high torque ripple, high current ripple, variable switching frequency, highly noisy in low speed range. Three signals that affect the control action in a DTC system. They are listed below

1. Torque
2. The magnitude of stator flux linkage
3. Angle of resultant flux vector

The most important block in DTC is the torque and flux estimator block. This block estimates the torque and flux values using the below equations. The flux produced with respect to the d and q reference frame are given by

$$\varphi_d = \int (v_d - r_s i_d) dt \quad (10)$$

$$\varphi_q = \int (v_q - r_s i_q) dt \quad (11)$$

From equations (10) and (11) the value of stator flux can be determined.

$$\varphi_s = \sqrt{\varphi_d^2 + \varphi_q^2} \quad (12)$$

The torque output is estimated by using the equation

$$T_e = \frac{3}{2} P (\varphi_d i_q - \varphi_q i_d) \quad (13)$$

Here P is the pole pair.

The direct torque control can be divided into two, one based on hysteresis modulation and the other based on pulse width modulation (PWM). The block diagram of DTC based on hysteresis modulation is shown in figure 4. Here at first the torque and flux errors are calculated and then it is fed to a hysteresis controller to limit its value. Then by using the output of these hysteresis controllers and the flux angle sector selection is made by using a switching table. Thus we generate a sequence of switching pulses which will be provided to the inverter as gate pulses.

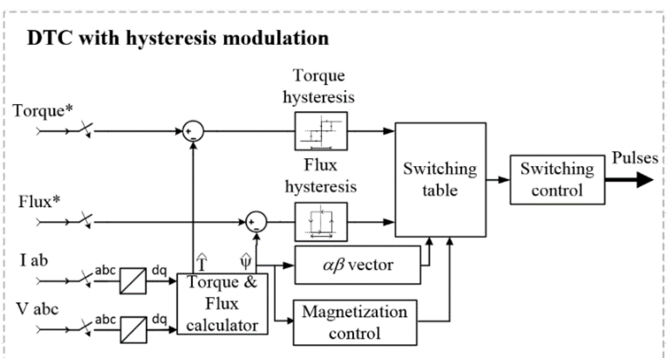


Fig. 4. DTC with hysteresis modulation

Second one is the DTC based on PWM. Here the torque and flux errors are provided to a PI controller. The output of these controllers are fed to a pulse width modulator which will generate the switching pulses to drive the inverter. This DTC technique does not require a switching table. The block diagram representation of DTC based on PWM technique is shown in figure 5.

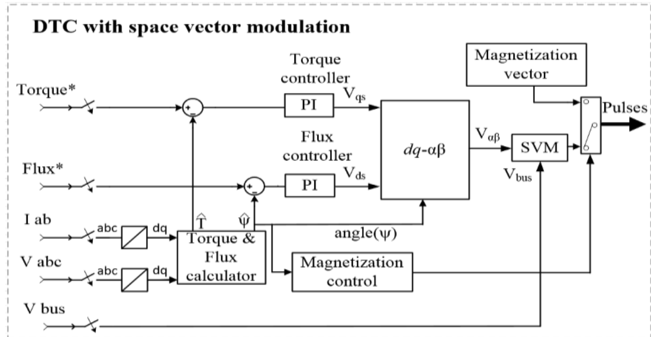


Fig. 5. DTC with PWM

The simulink model of DTC with hysteresis modulation in shown in figure 6.

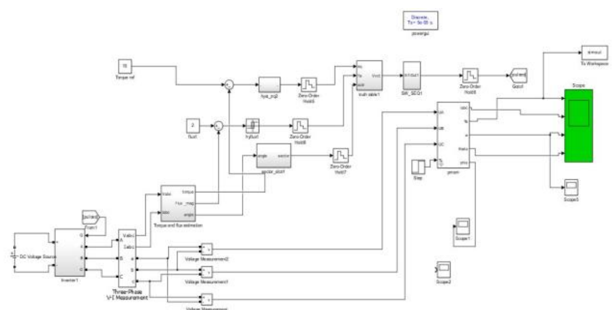

Fig. 6. Simulink model of DTC with hysteresis modulation

The Simulink model of DTC based on PWM is shown in figure 7.

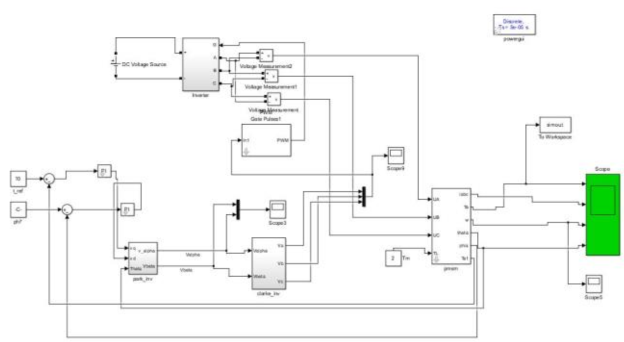

Fig. 7. Simulink model of DTC with PWM

## 5. Simulation Results

The PMSM drive circuit is simulated by using Mat lab Simulink. The parameters used for modelling the PMSM is given below.

1. Operating voltage: 415 V
2. Stator resistance: 2.875$\Omega$
3. Number of poles: 4
4. $C_L$=0.175 Wb
5. $L_d = 0.0085$ H
6. $L_q = 0.0085$ H
7. $J = 0.0008$ Kg $m^2$

The torque output of the PMSM drive circuit is shown in figure 8. Here the torque output is not in control and does not produce the desired output. The torque output contains large quantity of ripple having higher magnitude. After 0.2 seconds it is observed that the torque output reaches a steady value and it remains constant.

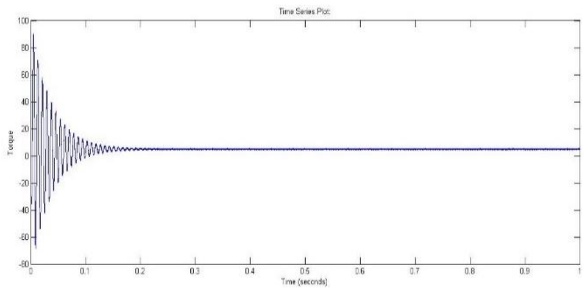


Fig. 8. Torque response of PMSM

The three phase stator current waveform obtained from the PMSM drive circuit is shown in figure 9. Here the simulation time is set as 1 and the curve obtained are sinusoidal.

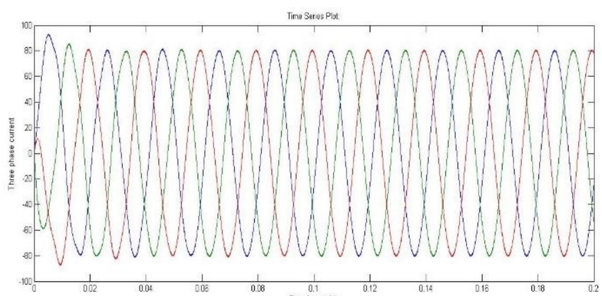


Fig. 9. Stator current of PMSM

.The speed output of the PMSM drive circuit is shown in figure 10. Here it is observed that the speed output shows large variations in the initial stages of the simulation and then it settles at the synchronous speed.

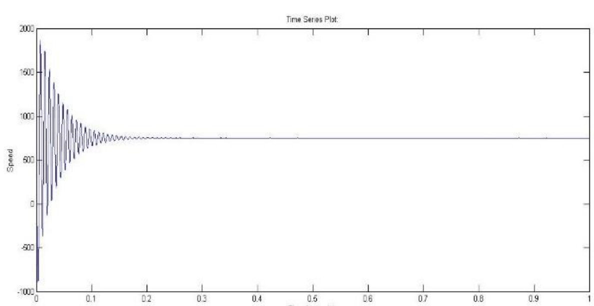


Fig. 10. Speed response of PMSM

The speed output of the PMSM drive circuit is shown in figure 10. Here it is observed that the speed output shows large variations in the initial stages of the simulation and then it settles at the synchronous speed.

In order to obtain better control and torque response the DTC based on hysteresis modulation is studied and simulated. Figure 9.8 shows the torque output obtained after applying DTC based on hysteresis modulation with a constant load. Here it is observed that the magnitude variation and the ripple content is large.

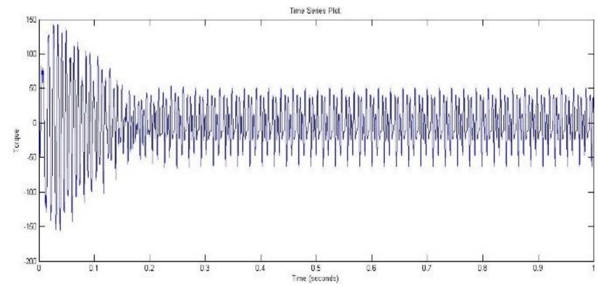


Fig. 11. Torque response of DTC with hysteresis modulation

Figure 12 shows the torque output obtained after applying DTC based on hysteresis modulation with a step load. The simulation run time is set as 1 second. The step load is set to have a magnitude of 0 Nm for a period of 0.2 seconds, then after that it is having a magnitude of 20 Nm.

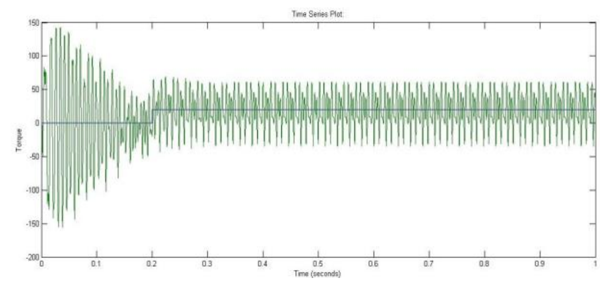


Fig. 12. Torque response of DTC with hysteresis modulation (step load)

Figure 13 shows the torque output obtained after applying DTC based on hysteresis modulation with a stair load. The simulation run time is set as 1 second. The stair load is set to have a magnitude of 0 Nm for 0.2 seconds, 20 Nm for period between 0.2 seconds and 0.5 seconds, 30 Nm for period between 0.5 seconds and 0.8 seconds and finally 10 Nm for period between 0.8 seconds and 1 second. Here it is observed that depending upon the variation in load torque which is the stair input, there occurs changes in the output torque. It can also be observed that there is large quantity of ripple content present in the torque output.

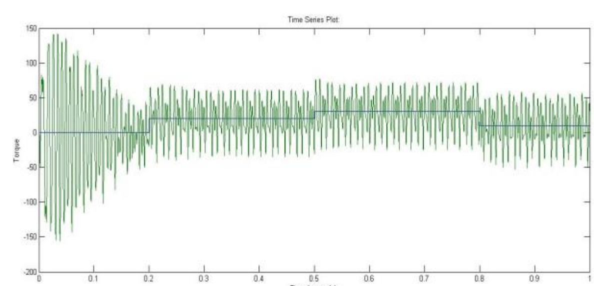


Fig. 13. Torque response of DTC with hysteresis modulation (stair load)

Figure 14 shows the current output obtained after applying DTC based on hysteresis modulation with a simulation run time of 0.2 seconds. Here it is observed that the current output is not exactly sinusoidal.

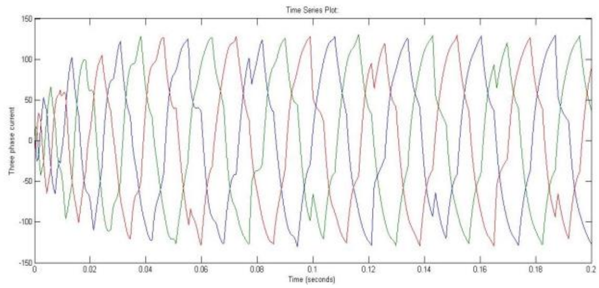

Fig. 14. Current output of DTC with hysteresis modulation

Figure 15 shows the speed output of the PMSM after applying DTC based on hysteresis modulation. The speed output also shows large amount of ripples. The speed output lies within a range of 0 to 1000 rpm.

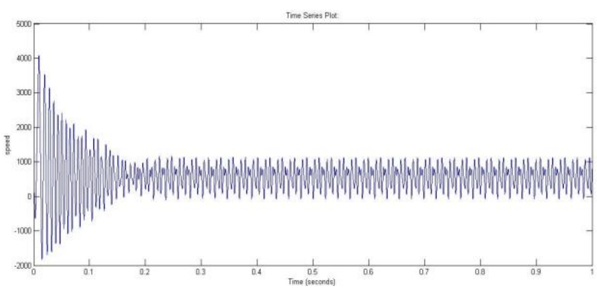

Fig. 15. Speed output of DTC with hysteresis modulation

Figure 16 shows the torque output obtained after applying DTC based on PWM with a constant load of 2 Nm. Here it is observed that there exists magnitude variation and ripple content in the torque output but when compared with the DTC based on hysteresis modulation it is reduced.

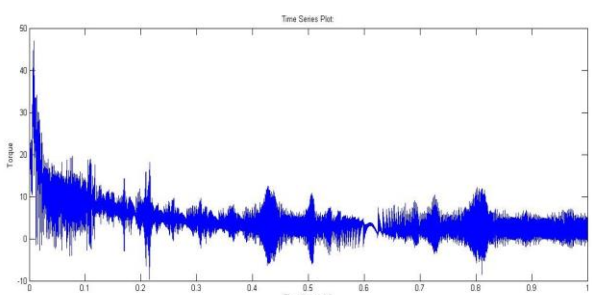

Fig. 16. Torque response of DTC with PWM

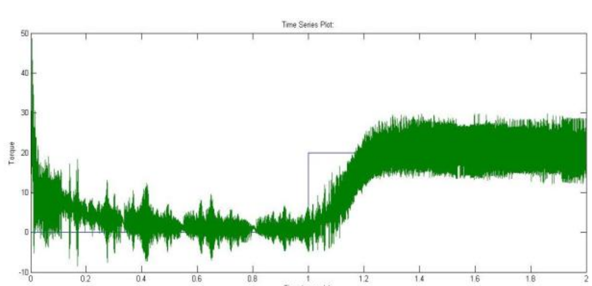

Fig. 17. Torque response of DTC with PWM (Step load)

Figure 17 shows the torque output of the PMSM after applying DTC based on PWM with step load. The simulation run time is set as 2 second. The step load is set to have a magnitude of 0 Nm for a period of 1 second, then after that it is having a magnitude of 20 Nm. Here it is observed that the torque output almost follows the reference step load but there is magnitude variation as well as presence of ripple content. When compared with DTC based on hysteresis modulation the magnitude variation and ripple content in the torque output is reduced.

Figure 18 shows the torque output of the PMSM after applying DTC based on PWM with stair load. The simulation run time is set as 1 second. The stair load is set to have a magnitude of 0 Nm for 0.2 seconds, 20 Nm for period between 0.2 seconds and 0.5 seconds, 30 Nm for period between 0.5 seconds and 0.8 seconds and finally 10 Nm for period between 0.8 seconds and 1 second. Here it is observed that the torque output follows the load torque but at some instants it contains large quantity of ripples and shows large magnitude variation.

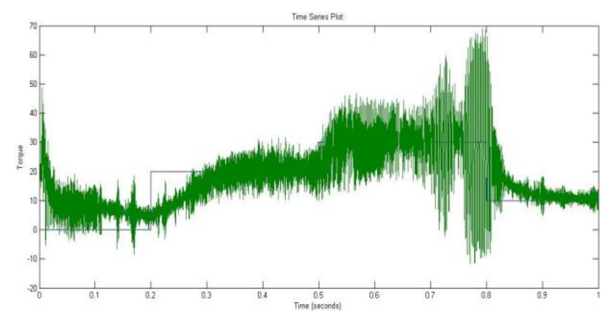

Fig. 18. Torque response of DTC with PWM (Stair load)

Figure 19 shows the current output obtained after applying DTC based on PWM. Here it is observed that at the initial stages of the simulation the current output is not exactly sinusoidal but after that it becomes sinusoidal. It is also observed that at the starting condition there is an increase in the stator current and later it decreases and becomes constant.

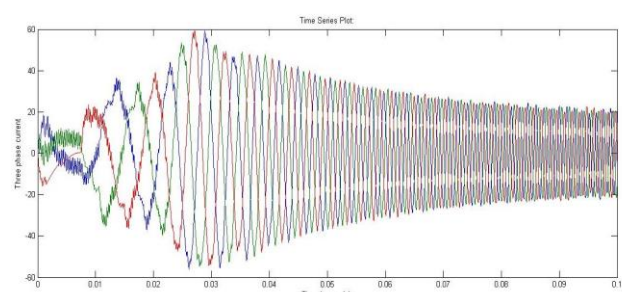

Fig. 19. Current output of DTC with PWM

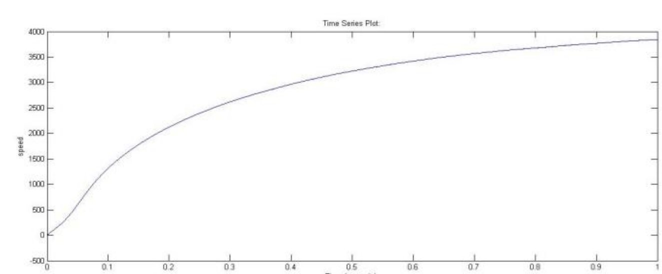

Fig. 20. Speed output of DTC with PWM

Figure 20 shows speed output obtained after applying DTC based on PWM. Here it is observed that the ripple content present in the speed output is eliminated. The reference speed provided is 3000 rpm but the machine goes a little over 3000 rpm. When compared with the DTC based on hysteresis modulation there is significant changes in the torque and speed output by applying this method.

## 6. Conclusion

This paper presents the comparative analysis of direct torque control of PMSM by using hysteresis modulation and PWM. At first the PMSM drive is mathematically modelled and simulated in matlab simulink. The torque and speed response obtained from the PMSM drive circuit is uncontrolled. In order to improve the dynamic response, torque and speed output and of the PMSM the DTC is implemented. The DTC with hysteresis modulated and PWM is simulated. From the simulation results it is found that the DTC with PWM produce better results when compared with DTC based on hysteresis modulation.

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