Comparison and Analysis of Different Techniques for Speed Control of Brushless DC Motor using Matlab Simulink

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***Abstract* —** *This paper presents the comparison and analysis of different control techniques which are required to run the Brushless Direct Current(BLDC) motor at specified speed. Various BLDC motor speed control techniques have been developed in recent years due to increasing demand leads to further advancements in control techniques. Speed control techniques based on electronic commutation which can be sensor based or sensorless. Methods like Back-EMF, Sinusoidal Pulse Width Modulation (SPWM) and Space Vector Pulse Width Modulation (SVWM) provided with proportional Integral (PI) controller are implemented in Matlab simulink models. These different control models applied to BLDC motor under different loading conditions. The simulation results shows the speed , torque, voltage and current waveforms of BLDC motor using different control models which are compared and analyzed to evaluate the performance of speed controllers.*

Keywords — *Brushless DC motor ,Inverter, Back-emf, Sinusoidal pulse width modulation, Space vector pulse width modulation.*

I. Introduction

Brushless DC motor is defined as synchronous motor which is controlled by electronic commutation through integrated inverter circuit which is powered by a DC. Where rotor is permanent magnet with additional rotor position sensors and related commutation circuit could be sensor based or sensorless. The speed-torque characteristics of the BLDC motor are same as DC motor that's why this motor called BLDC. Brushless motors offer, increased efficiency, increased reliability, reduced noise, longer lifetime (no brush and commutator erosion) more torque per weight as compared to DC motor.

II. Principle of Operation of BLDC motor.

A. *Principle of operation.*

BLDC motor operate by delivering current to its stator in reference to the rotor through inverter. The flux generated by the stator current interacts with the permanent magnet rotor flux which develops torque. The rotor rotates in a specific direction to align with the stator flux at synchronous speed. The stator current is commutated or switched electronically by inverter circuit into other phases once the rotor has reached a new location to provide a unidirectional rotation.

B. Mathematical equations for modelling of BLDC motor.

Electrical equations:

$$V_a = Ri_a + (L-M)\frac{d_{i_a}}{d_t} + e_a$$

$$V_b = Ri_b + (L-M)\frac{d_{i_b}}{d_t} + e_b$$

$$V_c = Ri_c + (L-M)\frac{d_{i_c}}{d_t} + e_c$$

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_m}$$

$$e_a = K_e\ \omega_m F(\theta_e)$$

$$e_b = K_e\ \omega_m F(\theta_e - \frac{2\pi}{3})$$

$$e_c = K_e\ \omega_m F(\theta_e - \frac{4\pi}{3})$$

V_a , V_b ,V_c are phase voltages
i_a , i_b ,i_c are phase currents
e_a , e_b ,e_c are phases back emf.
L is phase inductance of each phase
T_e=electrical torque
ω_m= rotor mechanical speed
K_e=back emf constant
F gives trapezoidal waveform of back emf
θ_e= electrical angle

Mechanical equation:

$$T_e = B\omega_m + J\frac{d_{\omega m}}{d_t} + T_l$$

Motion Equation:

$$\frac{d_{\omega_m}}{d_t} = \left(\frac{1}{j}\right)(T_e - T_l - \frac{B2\omega_e}{p})$$

B= friction constant

J=moment of inertia
T_l=load torque
ω_m= rotor mechanical speed
ω_e= rotor electrical speed
$\omega_e = d\theta_e/dt$
$\omega_e = p/2 * \omega_m$
so $\omega_m = 2/p * \omega_e$
where p = number of poles.

III. SPEED CONTROL OF BLDC MOTOR

In order to BLDC to operate, the rotor position must be known for the electronic commutation to take place . The rotor position detection is performed through the use of physical position sensors such as Hall Effect (HE) magnetic sensors, encoders or another sensorless techniques fed to the controller to trigger the sequential electronic control of the inverter circuit. The controller executes the switching sequence to the three phase inverter, consisting of six power semiconductor transistors, to commutate the power electronically to the motor phases from the dc voltage source. The output voltage and frequency of three phase power which is fed to BLDC motor are depend upon switching state of inverter. The controlling of inverter switches is done by various control techniques. Recent developments in power electronics to control the inverter circuit lead to different control techniques for BLDC motor.
A. Back-EMF zero crossing detection technique.
B. Sinusoidal Pulse width modulation.
C. Space Vector Pulse width modulation.

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A. Back-EMF zero crossing detection technique.

The Zero-crossing back-EMF sensing technique is based on detecting the instant at which the back-EMF crosses zero. This zero crossing triggers a pulses , which on off the switches of inverter. To detect the back-EMF zero crossing hall effect sensors are used. Hall effect sensors are considered as cost effective solution in comparison to other position measuring encoders. Rotor position is sensed using three Hall-effect sensors embedded into the BLDC motor .These hall sensors are displaced from each other by 120^0 . The figure 1 shows the configuration of three phase six stepped BLDC motor with three phases spaced by 120^0 electrical. The rotor position is fed controller via hall effect sensor signals. The controller executes the switching sequence to the three phase inverter, consisting of six power diodes. The commutation pattern of the currents to the motor phases illustrated in the figure 1 whenever back-emf crosses zero value at 30^0 HE sensors gives position signal to controller which triggers the specific switches and each phase conducts for every 120^0 electrical.

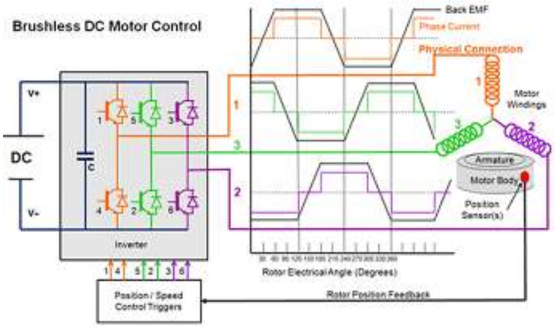

Fig.1.Back-EMF Technique

B. PWM Techniques.

Pulse-width modulation is a technique in which the ON-OFF sequence of switches is controlled by reference wave. In this the intersection between a reference wave and a carrier wave produces the pulses according to which the inverter switches are switched ON and OFF. By controlling the ON-OFF time of the switches speed of BLDC motor can be controlled . There are different PWM techniques which are as follows:

1) Sinusoidal PWM

2) Space Vector PWM

1) Sinusoidal Pulse Width Modulation(PWM)

The sinusoidal pulse-width modulation (SPWM) technique is the most common and easy to generate pulses for the inverter to control the switching . In this method the trigger pulses are generated by controlling the frequency and amplitude of a modulating or reference signal. The variation in the frequency and amplitude of the reference signal change the pulse-width of the switching pulses thus changes the output voltage. The principle of SPWM technique is, a low frequency sinusoidal reference signal is compared with a very high-frequency carrier signal. The carrier signal has triangular wave shape. The switching pulses changes when the reference signal intersects with the triangular carrier signal. The intersection positions determines the switching time of inverter. Frequency of output voltage depends on the frequency of the reference sinusoidal signal and switching frequency depends on frequency of triangular carrier signal. In a SPWM, we compare the sinusoidal reference signals (Va , Vb and Vc), which are 120 degree apart with each other with a triangular carrier signal (VT). Intersection of triangular signal with each phase of the sinusoidal reference signal produces switching pulses for each phases of the inverter. An inverter has six switching devices 1 to 6 with output of each phase is connected to the centre of each inverter leg as shown in figure 2. There are two switches in each leg of the inverter and ON and OFF in a complementary sequence. That is, only one switch in one leg of inverter will conduct at any instant of time.

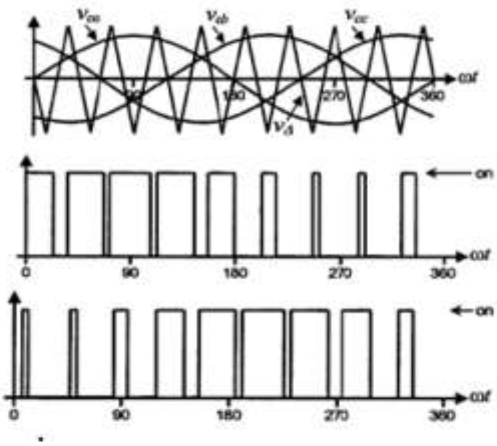

Fig.2 Sinusoidal PWM

2) Space vector PWM :

In this technique three phase voltages are transformed to two phase voltages either in stationary reference frame or synchronous rotating reference frame. Using this two phase voltage reference components of stationary frame the inverter output can be controlled. SVPWM technique is developed as a vector approach to pulse width modulation for three phase inverters. In SVPWM technique the reference signal is revolving reference voltage vector and the carrier signal is high frequency triangular signal. The intersection of these two signals gives the gate pulses to inverter switches to control the voltage and frequency of the inverter.

Voltage vector control is achieved by adjusting the timing and duty ratio of the eight switching states of the inverter. Assuming that stator coils in the three phases are identical and each switching state of the three- phase inverter corresponds to a voltage vector in the three-phase stator coil frame. Therefore corresponds to eight switching state of inverter there are eight voltage vector (v0 to v7). v0 and v7 are zero voltage vectors having zero magnitude v1 to v6 are six active voltage vectors with fixed magnitude and 60° apart from each other. For any reference voltage vector which falls in the three-phase stator frame, this vector can be resolved using the combination of the eight voltage vectors. For example, the reference frames 1.

Vector shown in Figure 3 can be resolved by using two adjacent vectors v1, v2 and the zero vectors v0, v7.

v =d1v1+ d 2 v 2+ d 3v 0+ d 3v 7

in which d1 and d2 is the duration for which vector v1 and v2 is applied and d3 is the duration for which zero vectors (v0 and v7) are applied. Any voltage vector which is located in the six sectors can be expressed as:

v =d1 v k +d 2 v k + d 3 v 0+ d 3 v 7,

As Compared to sinusoidal pulse width modulation Method (SPWM), SVPWM has many advantages, which are less switching losses, less total harmonic distortion, and better utilization of dc-bus voltage.

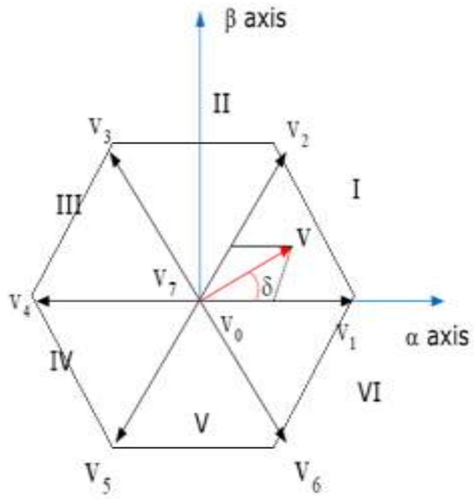

Fig.3 Space Vector PWM

IV. *Matlab Simulink Model Design.*

A. Matlab simulink model Design for Back-EMF zero crossing detection control.

Matlab simulink model for Back-EMF zero crossing detection technique for speed control of BLDC motor illustrated in Fig.4.In this model rotor postion is detected by using three hall sensors which are displaced by 120 degree on rotor shaft. The hall signal from these sensors is fed to block 1.In which the function of block 1 is to extract the back-emf zero crossing points from the hall signals. The zero detecting module following the truth table for high and low values from hall signals which is shown in table 1.And these zero crossing points when detected fed to the block 2. In block 2 pulses are generated with logic control circuit reference to detected zero crossing points. These trigger pulses gives gate signal to turn ON the six IGBT switches of inverter in a sequence. Proportional-Integral (PI) acts as speed regulator which control the voltage level accordingly reference to error signal . The transfer function of PI controller is G(s). Values of K_p and K_i are tuned to ensure stability.

$G(s)= K_p+K_i/s$

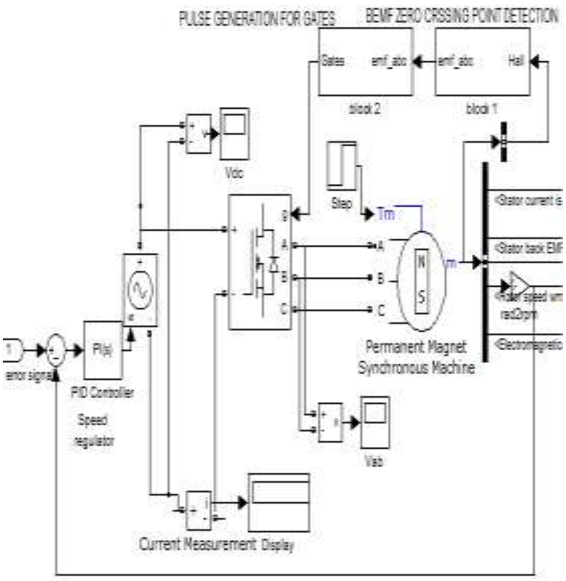

Fig.4 Simulink model of BEMF control.

The hall signals gives following signals showing in table. 1 either 1 or 0 at specific back-emf zero crossing points. The switching pattern of six switches of inverter is shown in the table. 2 states for on switch and 0 states for off switch.

Table.1

Sequence No.	**Hall signals at Back-emf zero crossing points**					
	Hall signals			**Back-emf**		
	ha	hb	Hc	ea	eb	ec
1	0	0	0	0	0	0
2	0	0	1	0	-1	+1
3	0	1	0	-1	+1	0
4	0	1	1	-1	0	+1
5	1	0	0	+1	0	-1
6	1	0	1	+1	-1	0
7	1	1	0	0	+1	-1
8	1	1	1	0	0	0

Table.2

Switching states of six switches					
Q1	Q2	Q3	Q4	Q5	Q6
0	0	0	0	0	0
0	0	0	1	1	0
0	1	1	0	0	0
0	1	0	0	1	0
1	0	0	0	0	1
1	0	0	1	0	0
0	0	1	0	0	1
0	0	0	0	0	0

B. Matlab Simulink model Design for Sinusoidal Pulse Width Modulation.

SPWM model design is illustrated in figure.5 in which three voltages Va, Vb, and Vc are reference signals modulated with carrier signal which is triangular waveform. The intersection of these two signals gives trigger pulses in PWM generation block. These pulses give gate signals to turn ON the switches in a sequence. The variation in the frequency and amplitude of the reference signal change the pulse-width of the switching pulses thus changes the output voltage. In this model PI controller acts as speed regulator gives control signal with reference to error in speed.

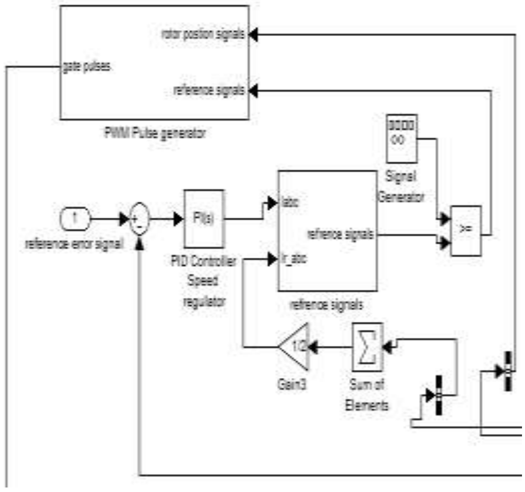

Fig.5 Simulink model of SPWM control.

C. Matlab Simuink model Design for Space Vector Pulse Width Modulation.

Matlab simulink model design for SVPWM is illustrated in figure.6.In this three phase currents i_{abc} from BLDC motor are fed to dqo transformation block. In this block reference currents i_{abc} are generated by dqo transformation. Then these reference currents are compared with actual currents which comes from BLDC motor and current errors ir_{abc} are generated. Then these current errors ir_{abc} fed to pulse generation block. In pulse generation block these current errors are modulated with triangular signal . With the intersection of these two signals pulses are generated for gates of switches. The transformation of dq0 current components to abc components is done in dqo transformation block which is illustrated in figure6. By following these equations:

$$I_a=I_d \sin(\omega t) + I_q \cos(\omega t) + I_0$$

$$I_b=I_d \sin(\omega t-2\Pi/3)+I_q \cos(\omega t-2\Pi/3)+I_0$$

$$I_c=I_d\sin(\omega t+2\Pi/3)+I_q\cos(\omega t+2\Pi/3)+I_0$$

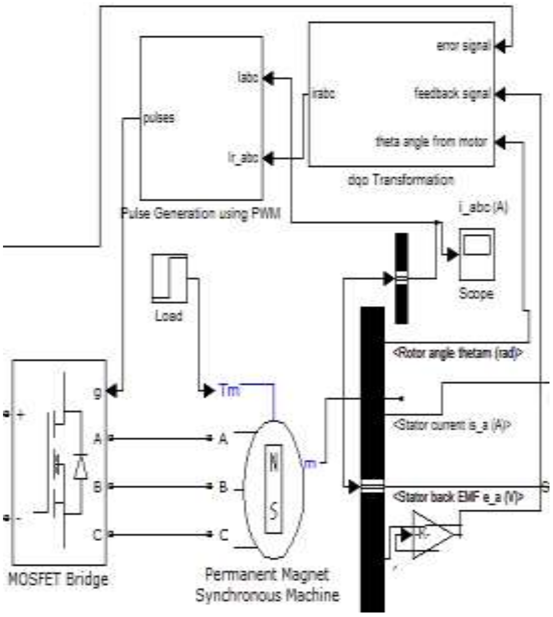

Fig.6 Simulink model of SVPWM

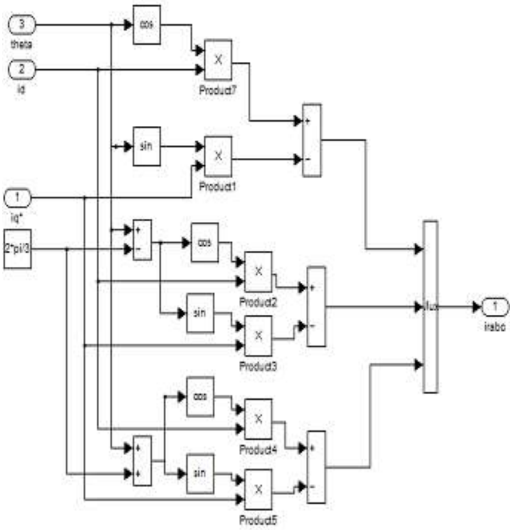

Fig. 7 dq0 currents to abc currents transformation

V. Simulation Results

Simulations results for three control techniques motor parameters are same, Input DC voltage level is 500 for all the three control models and also same reference speed 3000 rpm. BLDC motor parameters kept constant for all three control techniques are as follows:

BLDC motor parameters	
Stator phase resistance ,Rs(ohm)	.18
Stator phase inductance, Ls(H)	8.5e-3
Flux linkage by magnets(V.s)	0.07145
Inertia J(kg.m^2)	.00062
Friction factor	.0003035
Pole pairs	4

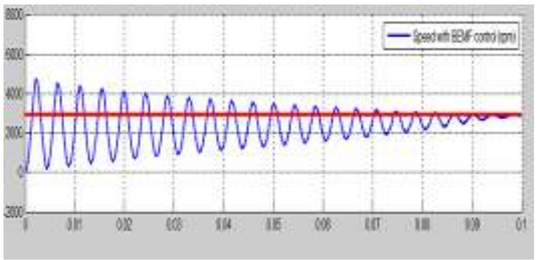

Fig.8 Speed (rpm) of BLDC motor with BEMF control under no load condition.

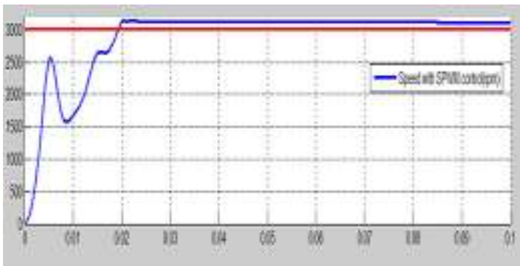

Fig.9 Speed(rpm) of BLDC motor with SPWM control under no load condition.

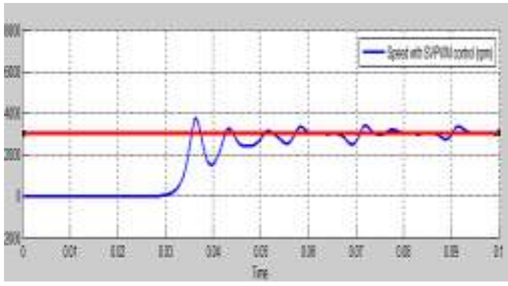

Fig.10 Speed(rpm) of BLDC motor with SVPWM control under no load condition.

Simulation results for different load torque values. Mechanical input set point values for load torque are as follows 2N-m, 3N-m and 4 N-m.

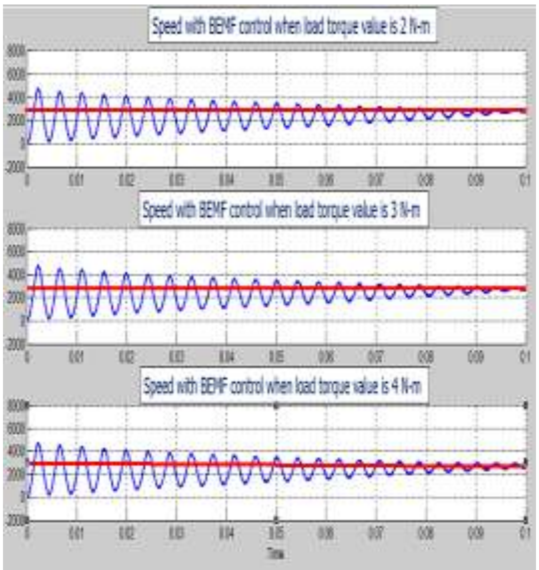

Fig.11 Speed(rpm) with BEMF control for different load torque values 1N-m,2Nm, 3N-m.

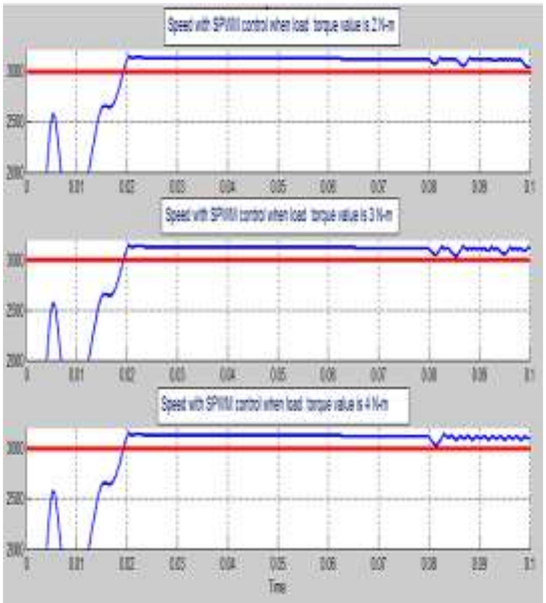

Fig.12 Speed(rpm) with SPWM control for different load torque values 1N-m,2N-m,3N-m.

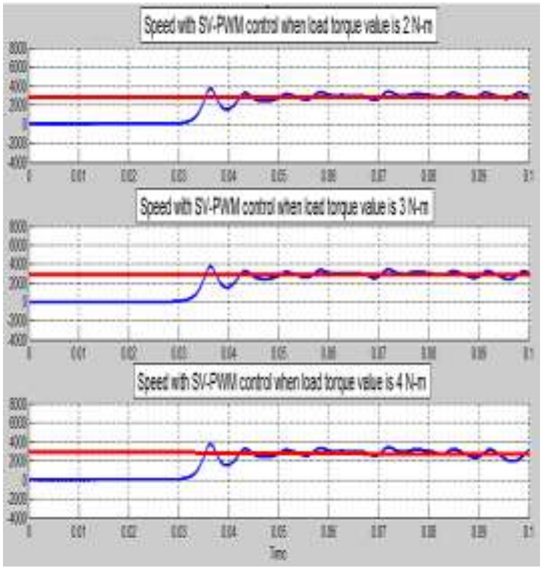

Fig.13 Speed(rpm) with SVPWM control for different load torque set values 1N-m,2N-m,3N-m.

VI. CONCLUSION.

Results for BLDC motor Simulation using different techniques:

Performance of BLDCM under no load condition with different control techniques.

Control Techniques	Overshoot/ Undershoot	Speed Regulation	Settling Time
For BEMF	50% Overshoot	96.0%	.095
For SPWM	50% Undershoot	96.1%	.093
For SVPWM	33% Overshoot	98%	.075

Performance of BLDCM under different loading conditions with different control techniques.

	Load Torque Values	Speed regulation
For BEMF	2 N-m	92%
	3 N-m	90%
	4 N-m	87%
For SPWM	2 N-m	98%
	3 N-m	96%
	4 N-m	97%
For SVPWM	2 N-m	99%
	3 N-m	98%
	4 N-m	98%

The performance of brushless DC motor is evaluated by modelling of different control techniques which are BEMF zero crossing technique, Sinusoidal PWM and Space Vector PWM. Different speed control models are simulated under different load torque values gives speed response, current values and waveforms. From simulation results speed response and other factors are analysed and it is concluded that SVPWM technique give better speed control under all load torque values then the other control techniques. There are also many advantages to use SVPWM technique over other control techniques because in this technique no hall sensors or other position sensors are used , which increases the cost of speed controller and also size of the BLDC motor is reduced by elimination of rotor sensors.

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