Comparison of BLDC Motor Performance with Diode Clamped and Cascaded H-Bridge Multilevel Inverter

Ravichandran .R[1], Sivaranjani .S[2]

[1]P.G Scholar, Department of Power Systems Engineering, V.S.B. Engineering College, Karur, India

[2]Assistant Professor, Department of Electrical and Electronics Engineering, V.S.B. Engineering College, Karur, India

Abstract: ***Permanent magnet synchronous machine is modeled sinusoidal and trapezoidal Back EMF. Stator is modeled by abc transformation that is trapezoidal Back EMF called as Brushless DC Motor. BLDC motor widely used for industrial applications. It has constant torque under ideal conditions but practical case torque ripple appeared due to the freewheeling of inactive phases and commutation failure. Torque ripple affects the smoothness of variable speed control. Various control techniques and methods are used to reduce the torque ripple. In this paper analyze the performance of BLDC motor with cascaded H-Bridge multilevel inverter and diode clamped multilevel inverter. This has been simulated using MATLAB simulation software and the torque ripple is calculated.***

Keywords: Brushless DC Motor (BLDC), Diode Clamped Multilevel Inverter, Cascaded H-Bridge Multilevel Inverter, Torque Ripple, Adaptive Neuro Fuzzy Inference System (ANFIS), Sinusoidal Pulse Width Modulation (SPWM).

1. Introduction

Brushless direct current (BLDC) motors have characteristics of high reliability, simple frame, and small friction. By comparing with PMSM, BLDC motor has the advantages of high speed adjusting performance and power density [15].The torque ripple reduction and the control performance improvement of BLDC mainly focused on commutation torque ripple, the torque ripple produced by diode freewheeling of inactive phase, and the torque ripple caused by the non ideal back electromotive force (EMF). For the commutation torque ripple, Calson *et al.* proposed that relative torque is related to current and varies with speed [16]. In [7], a single dc current sensor and an adaptive phase-change point regulation scheme should be used to suppress the commutation torque ripple, but the diode freewheeling of inactive phase was not considered. Chuang *et al.* have analyzed the domination of different pulse width modulation (PWM) patterns on the commutation torque ripples according to the BLDC motors with ideal trapezoidal back EMF [6], the proportional integral (PI) controller is a well known system in control engineering. Transfer function of PI controller.

$$G(s) = K\left(1 + \frac{1}{T.s}\right) \qquad (1)$$

Where,
G(s) is the gain and K is the Control parameter. Sensor less control technique is used to determine the current position of the rotor. Based on the rotor position switching pulses are generated by sinusoidal pulse width modulation. Depend upon that pulses inverter is provide supply for BLDC Motor.

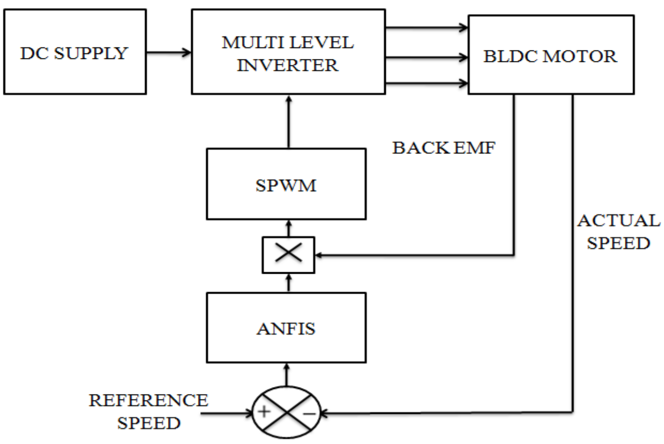

Figure 1: Block diagram of BLDC drive system

BLDC Motor actual speed and reference speed is compared to provide input (error signal –difference between both speeds) to controller. PI controller K_p is determines current error and K_i determines future error. PI controller output and measured Back EMF is multiplied to provide the reference signal for the sinusoidal pulse width modulation. PI controller's trained data is used for ANFIS training. Sinusoidal PWM is used to shift the lower order harmonics to higher order harmonics. Because, lower order harmonics frequency near to the fundamental frequency so it leads difficulty for filtering and lower order harmonics requires high pass filter to increase filter cost. ANFIS is trained based on the previously simulated PI controller data's. PI controller tuning is difficult and it requires an experts to tune and it have slow response. But ANFIS have the advantage of both Fuzzy logic and Artificial Neural Network.

2. Brushless DC motor

BLDC motor rotor part is having permanent magnet and stator part having three phase winding. So it has less inertia and friction. But the speed control is difficult due to the absence of field winding. The Brushless DC motors have many advantages like better mechanical characteristics, high efficiency, high dynamic response, small size and easy construction [9]. In the last years, brushed dc motors and induction motors for small applications can be replaced by brushless dc motors [11].

The three phase model is selected for simulating BLDC, stator and rotor voltage equations are defined in [10],

$$\begin{bmatrix}u_a\\u_b\\u_c\end{bmatrix} = \begin{bmatrix}R_a & 0 & 0\\0 & R_b & 0\\0 & 0 & R_c\end{bmatrix}\begin{bmatrix}i_a\\i_b\\i_c\end{bmatrix} + \begin{bmatrix}L_a & M_{ab} & M_{ac}\\M_{ba} & L_b & M_{bc}\\M_{ca} & M_{cb} & L_c\end{bmatrix} P \begin{bmatrix}i_a\\i_b\\i_c\end{bmatrix} + \begin{bmatrix}e_a\\e_b\\e_c\end{bmatrix} + U_n \begin{bmatrix}1\\1\\1\end{bmatrix} \qquad (2)$$

Where,

u_a, u_b, u_c : Stator winding phase voltage (V)
R_a, R_b, R_c : Stator winding resistance (Q)
i_a, i_b, i_c : Stator winding phase current (A)
e_a, e_b, e_c : Stator winding back EMF (V)
L_a, L_b, L_c : Self inductance (H)
M_{ab}, M_{ac}, M_{cb} : Mutual inductor (H)
Equation (2) can be written as,

$$\begin{bmatrix}u_a\\u_b\\u_c\end{bmatrix} = \begin{bmatrix}R & 0 & 0\\0 & R & 0\\0 & 0 & R\end{bmatrix}\begin{bmatrix}i_a\\i_b\\i_c\end{bmatrix} + \begin{bmatrix}L-M & 0 & 0\\0 & L-M & 0\\0 & 0 & L-M\end{bmatrix} P \begin{bmatrix}i_a\\i_b\\i_c\end{bmatrix} + \begin{bmatrix}e_a\\e_b\\e_c\end{bmatrix} + U_n \begin{bmatrix}1\\1\\1\end{bmatrix} \qquad (3)$$

$$T_e = \frac{1}{w}(e_a i_a + e_b i_b + e_c i_c) \qquad (4)$$

Electromagnetic torque produced by the stator winding is,

$$J\frac{dw}{dt} = T_e - T_L - B_w \qquad (5)$$

Where,
T_e : Magnetic torque (N*M)
T_L : Load torque (N*M)
B : Damping Factor (N.m.s/rad)
w : Motor speed (rad/ s)
J : Motor moment of inertia (Kg/m)

3. Multilevel Inverter

3.1 Diode clamped Multilevel Inverter

A three phase five level diode clamped multilevel inverter topology is shown in figure 2. Three phase inverter output voltage shares common dc bus voltage and it is divided for five levels using dc capacitors. In this multi level inverter have three legs. Each leg has switches, clamping diodes and freewheeling diodes for each leg have upper and lower legs. Voltage across the each capacitor is $\frac{V_{dc}}{4}$ and clamping diodes are used to limit voltage stress across the switching devices. Switches are denoted as $S_{a1}, S_{a2}, \dots S_{a3}', S_{a4}'$, $S_{b1}, S_{b2}, \dots S_{b3}', S_{b4}'$ and $S_{c1}, S_{c2}, \dots S_{c3}', S_{c4}'$. Clamping diodes are denoted $D_1, D_2, \dots D_4'$. The required number of capacitors (C), clamping diodes (j) and freewheeling diodes (d) can be calculated from the following formulas,

$$c = m - 1 \qquad (6)$$
$$d = 2(m-1) \qquad (7)$$
$$j = (m-1)(m-2) \qquad (8)$$

Where,
m is number of levels

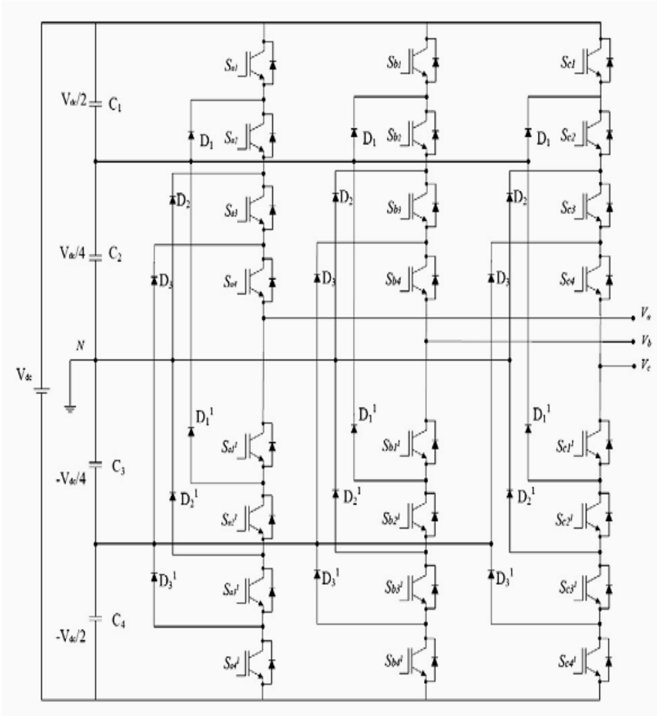

Figure 2: Three phase five level topology of diode clamped multilevel inverter.

For five level diode clamped multi level inverter lookup table is shown in table 1. From table 1 switches ON and OFF to get required voltage levels. In this table 1 denotes ON and 0 denotes OFF position of the switches. For each time four switches must be in ON condition reaming switches are OFF condition, same switches in the upper and lower leg is don't turn ON. Different voltage levels are described in table 1 i.e., v_{an}. The first switching state $\frac{v_{dc}}{2}$ is obtained by turn ON switches $s_{a1}, s_{a2}, s_{a3}, s_{a4}$ and remaining switches are in OFF condition.

Table 1: Voltage levels of five level diode clamped multilevel inverter and switching states.

Voltage V_{an}	Switching state							
	S_{a1}	S_{a2}	S_{a3}	S_{a4}	S_{a1}'	S_{a2}'	S_{a3}'	S_{a4}'
$V_4 = V_{dc}/2$	1	1	1	1	0	0	0	0
$V_3 = V_{dc}/4$	0	1	1	1	1	0	0	0
$V_2 = 0$	0	0	1	1	1	1	0	0
$V_1 = -V_{dc}/4$	0	0	0	1	1	1	1	0
$V_0 = -V_{dc}/2$	0	0	0	0	1	1	1	1

Diode clamped multilevel inverter have more efficiency under fundamental frequency and high frequency switching. But increase number of levels, increase number of diodes and topology makes more complex.

3.2 Cascaded H-Bridge Multilevel Inverter

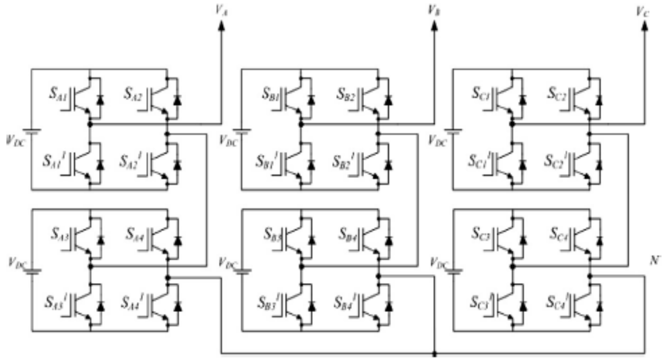

Figure 3: Three phase five level Cascaded H-Bridge multilevel inverter topology

The cascaded H-bridge inverter dc source on the dc side, which can be obtained from batteries, fuel cells, or ultra capacitors, and series-connected on the ac side. The advantage of this topology is that the modulation, control, and protection requirements of each bridge are modular. It should be pointed out that, unlike the diode-clamped and flying-capacitor topologies, isolated dc sources are required for each cell in each phase. Number of levels can be increased by adding the bridges series. Switches in same leg does not conduct at same time because of avoid the short circuit.

4. Adaptive Neuro Fuzzy inference system training

In the five level diode clamped multi level inverter fed BLDC have one PI controller. ANFIS controllers are derived from the PI controlled system.

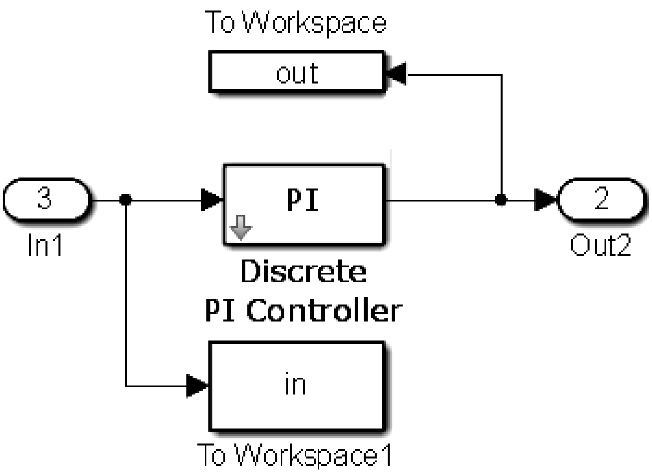

Figure 4: PI controller data's load to workspace

For ANFIS training first step are get data (PI controller input and output) from workspace and select that data's from workspace in and out. The out data is copy and paste to in column of workspace.

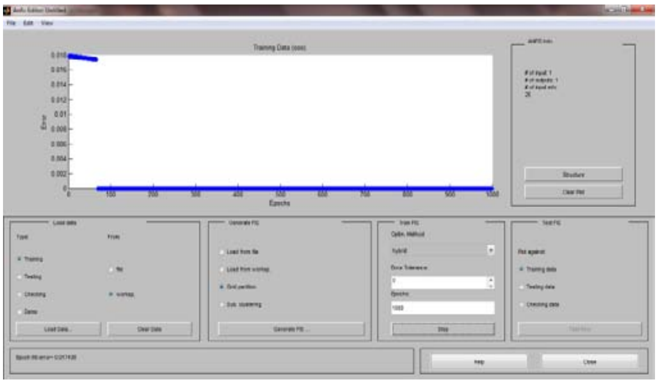

Figure 5: ANFIS training.

After that to load the data's from workspace and select grid partition and generate FIS option for give the number of rules. Member functions are 15 in this paper, input is 1 and output is 1. To train until reach error is zero and epochs give nearly 100000 (i.e., Based on the error level).

5. Simulation and Results

Figure 6 shows the simulation diagram of five level diode clamped multilevel inverter fed BLDC motor. The motor output speed and reference speed can be compared and that error signal given input for ANFIS. ANFIS output is multiplied with the Back EMF. This multiplied signal is given to reference signal of Sinusoidal pulse width modulation, based on the reference signal gate pulses generated and given to Diode clamped multilevel inverter. So the rotor position is sensed by sensor less technique that is Back EMF is measured to detect rotor position.

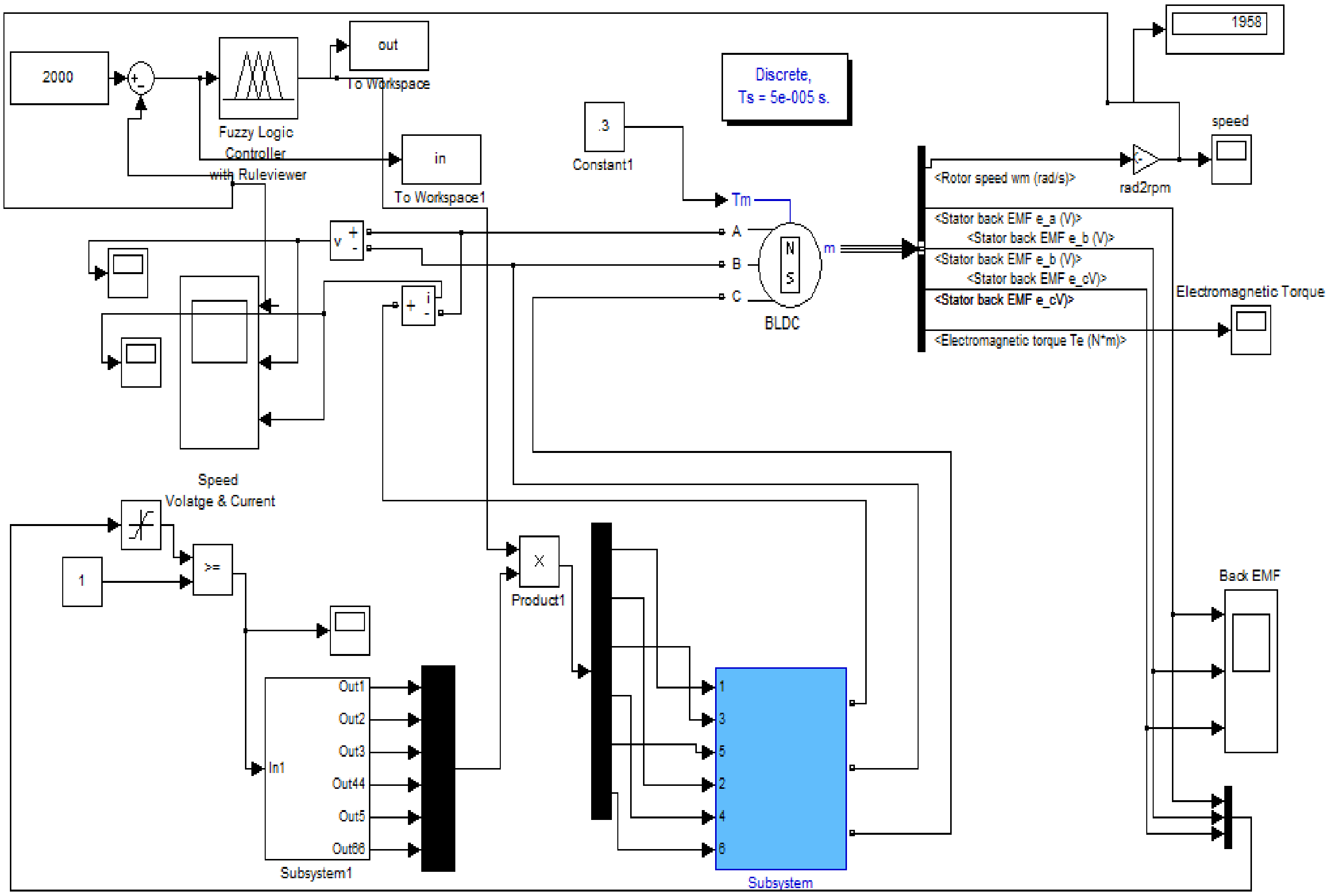

Figure 6: Simulation diagram for five level diode clamped multilevel inverter fed BLDC motor

Figure 7 shows the cascaded H-Bridge multilevel inverter fed BLDC motor with ANFIS. This is done by using previously simulated PI controller data's. Train Adaptive Neuro Fuzzy Interferance System several times to get better result, that is error is zero. ANFIS simulation file is generated at the end of training. PI controller is replaced by ANFIS.

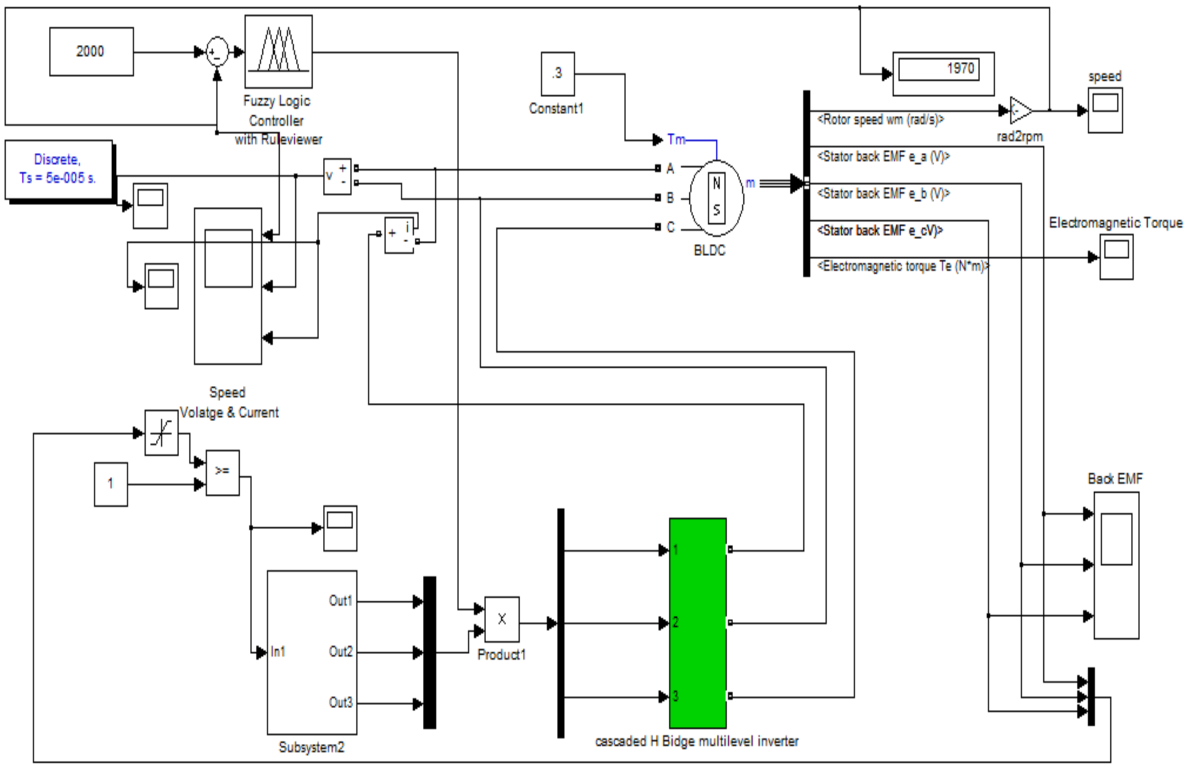

Figure 7: Simulation diagram for five level cascaded H-Bridge multilevel inverter fed BLDC motor.

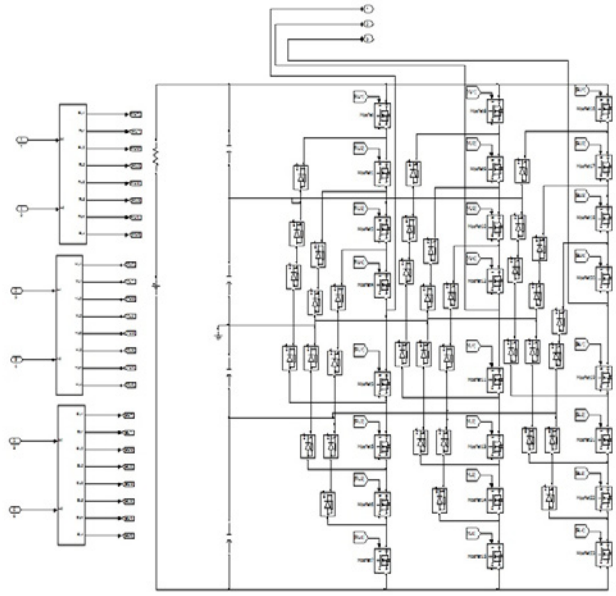

Figure 8: Simulation diagram for five level diode clamped multi level inverter

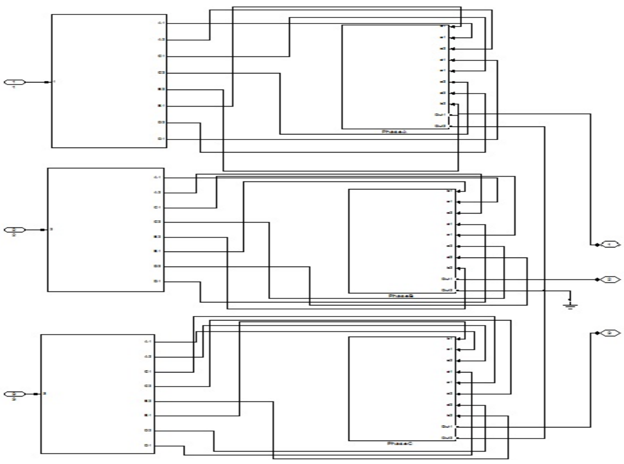

Figure 9: Simulation diagram of fivelevel cascaded H-Bridge multilevel inverter.

Figure 8 and 9 shows the simulation diagram of five level diode clamped multilevel inverter and cascaded H-Bridge multilevel inverter fed BLDC motor. Figure 10 shows the speed of BLDC motor, Speed of diode clamped MLI fed BLDC motor is have more deviation compare to cascaded H-Bridge MLI fed BLDC motor output speed, here set speed is 2000rpm.

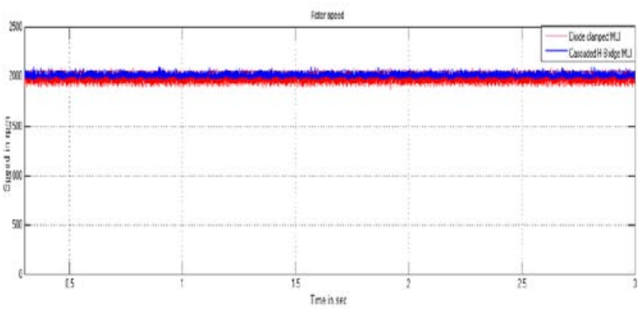

Figure 10: Output Speed

6. Torque Ripple Calculation

Torque ripple produced in BLDC motor due to freewheeling of inactive phases and commutation failure. It is affect the variable speed control of system and smoothness.Torque ripple can be minimized by two techniques, they are improve motor design and motor control schems. Torque ripple is defined as percentage of difference between maximum torque(t_{max}) and minimum torque (t_{min}) compared to the average torque (t_{avg}). Equation (14) is used for determine torque ripple.

$$(T_{max} - T_{min})/T_{avg} * 100\% \quad (9)$$

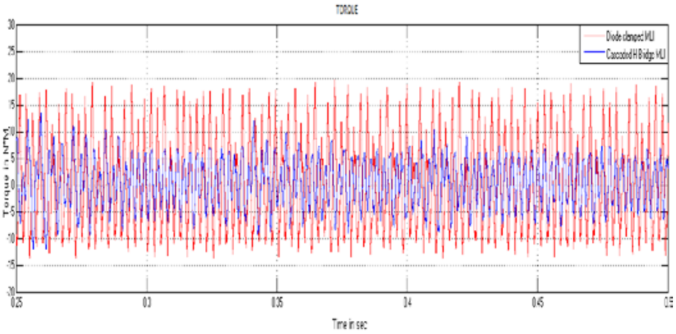

Figure 11: Electromagnetic Torque

Figure 11 shows electromagnetic torque of BLDC motor. Let us take values from figure 11 for one cycle. For diode clamped multilevel inverter fed BLDC motor maximum torque (t_{max}) is 20.78, minimum torque (t_{min}) is 14.5 ,average torque (t_{avg}) is 17.64. Substitute above values in equation (9) to get torque ripple is 35.60%. For cascaded H-Bridge multilevel inverter fed BLDC motor maximum torque (t_{max}) is 11.905, minimum torque (t_{min}) is 10.5, average torque (t_{avg}) is 11.2025 by substitute these values in equation (9) to get torque ripple is 12.5418%.

7. Conclution

Torque pulsations in BLDC motor leads to audible noise and visible vibrations in the high precision applications. In this paper five level diode clamped multilevel inverter and cascaded H-Bridge multi level inverter fed BLDC motor presented and analyzed the torque ripple, Speed. From the simulation BLDC motor results are analyzed and torque ripple was calculated for both diode clamped and cascaded H-Bridge multilevel inverter. From the simulation results proved that the torque ripple is reduced in cascaded H-Bridge multilevel inverter is better than diode clamped multilevel inverter. Also the speed controlled by cascaded H-Bridge multi level inverter is better than diode clamped multilevel inverter.

References

[1] M.ArunNoyal Doss, E.Premkumar, G.Ranjith Kumar and Jahir Hussain,"Harmonics and Torque Ripple Reduction of Brushless DC Motor (BLDCM) using Cascaded H-Bridge Multilevel Inverter," IEEE

International Conference on Power, Energy and Control (ICPEC), 2013.

[2] Jiancheng Fang, Haitao Li, and Bangcheng Han," Torque Ripple Reduction in BLDC Torque Motor With Nonideal Back EMF", IEEETransactions on power Electronics,Vol,27,NO,11,NOVEMBER 2012.

[3] R.Goutham GovindRaju, S.JohnPowl, A.Sathishkumar and P.Sivaprakasam," Mitigation of Torque for Brushless DC Motor: Modeling and Control," International Journal of Scientific & Engineering Research Volume 3, Issue 5, May- 2012.

[4] S.B.Ozturk,W. C. Alexander, and H. A. Toliyat, "Direct torque control of four-switch brushless DC motor with non-sinusoidal back EMF," IEEE Trans. Power Electronvol vol no. 2, pp. 263–271, Feb. 2010.

[5] T.N.Shi,Y.T.Guo, P.Song, andC.L.Xia, "A newapproach of minimizing commutation torque ripple for brushless DC motor based on DC-DC converter," IEEE Trans. Ind. Electron., vol. PP, no. 99, pp. 1–9, 2010.

[6] H.S.Chuang and Y.-L.Ke, "Analysis of commutation torque ripple using different PWM modes in BLDC motors," in Conf. Rec. IEEE Ind. Commercial Power Syst. Tech. Conf., pp. 1–6, 2009.

[7] D.Chen and J.C.Fang, "Commutation torque ripple reduction in PM brushless DCmotor with nonideal trapezoidal backEMF ,"inProc.CSEE, vol. 28, no. 30, pp. 79–83 ,Oct. 2008.

[8] Z.Wu and J. Y. Zhang, "Dynamics and control of gimbal servo systems for control moment gyroscopes," J. Basic Sci. Eng., vol. 15, no. 1, pp. 130– 136, Jul. 2007.

[9] Gencer, M. Gedikpinar "Modeling and Simulation of BLDC Using MATLAB/SIMULINK, Jornal of Applied Scineces vol 6 no 3, 2006.

[10] Yiming. Li, Jun .Rong,"The Study of New Modeling Method for Permanent Magnet Brushless DC motor"' International Conference on Electronic & Mechanical Engineering and Information 12 -14 August china, pp -4 713 4 716, 2011.

[11] M. A. Elgendy, B. Zahawi, D. 1. Atkinson, D. Giaouris "Dynamic Behaviour of DC Motor- Based Photovoltaic Pumping Systems under Searching MPPT Algorithms "' POWERENG 2009, Lisbon, Portugal, March 18 -20 , pp 413-418, 2009 .

[12] K. Wei, C. S. Hu, and Z. C. Zhang, "A novel commutation torque ripple suppression scheme in BLDCM by sensing the DC current," in 36th IEEE Power Electron. Spec. Conf., pp. 1259–1263, 2005.

[13] T. Wei and J. C. Fang, "Dynamics modeling and vibration suppression of high-speed magnetically suspended rotor considering first-order elastic natural vibration," in Proc. 9th Int. Symp. Magn. Bearings, 2004.

[14] G. J. Su and J. W. McKeever, "Low-cost sensorless control of brushless DC motors with improved speed range," IEEE Trans. Power Electron., vol.19, no.2, pp.296-302, Mar. 2004.

[15] T.-H. Kim and M. Ehsani, "Sensorless control of the BLDC motors from near-zero to high speeds," IEEE Trans. Power Electron., vol. 19, no. 6, pp. 1635–1645, Nov. 2004.

[16] R. Calson, L.-M. Milchel, and J. C. Fagundes, "Analysis of torque ripple due to phase commutation in brushless dc machines," *IEEE Trans. Ind. Appl.*, vol. 28, no. 3, pp. 632–638, May/Jun. 1992.