© 2014 IJEDR | Volume 2, Issue 2 | ISSN: 2321-9939

# Regenerative braking of brushless dc motor

Nirav Kantharia

PG student
Department of Electrical Engineering, Sarvajanik College of Engineering & Technology, Surat, India

***Abstract*** **—This paper describes an optimal regenerative braking control scheme for a permanent magnet brushless DC motor to achieve goals of the electric brake with energy regeneration. During the braking period, the proposed method only changes the switching sequence of the inverter to control the inverse torque so that the braking energy will return to the battery. Compared with the presented methods, the proposed solution simultaneously achieves dual goals of the electric brake and the energy regeneration without using additional converter, ultra capacitor, or complex winding-changeover technique. Since the braking kinetic energy is converted into the electrical energy and then returns to the battery, the energy regeneration could increase the efficiency of BLDCM drive.**

***Index Terms*—Brushless dc motor (BLDCM), electric brake, energy regeneration**

## I. Introduction

Brushless dc motors (BLDCMs) have many advantages over brushed dc motors and induction motors, such as robust structure, high efficiency, high dynamic response, higher speed range, large starting torque, noiseless operation, etc. In particular, the BLDCM of the hub type is widely used in the Electric Vehicles.

Conventionally, EVs use mechanical brake to increase the friction of wheel for the deceleration purpose. However, from the viewpoint of saving energy, the mechanical brake dissipates much energy since the EV's kinetic energy is converted into the thermal one. In view of this, this paper discusses how to convert the kinetic energy into the electrical one that can be recharged to the battery. Thus, both the electric brake and energy regeneration are achieved. Thus far, many articles have discussed the braking energy regeneration of the EV [1]–[10].The so-called energy regenerative brake mainly employs the back electromotive force (EMF) of the motor in the braking process. The back EMF is regarded as a voltage source to recharge in the battery. However, the maximum back EMF is generally lower than the battery voltage even if the BLDCM is driven at its highest speed. Thus, if one would like to recharge the back EMF to the battery, the back EMF voltage must be boosted. Therefore, many articles have proposed a dc/dc converter to achieve the braking energy regeneration [1]–[3].Unfortunately, these methods need an additional dc/dc converter to reach the purpose has the efficiency problem that results in additional energy dissipation.

Moreover, electronic gearshift technology is used with the energy-regenerative brake for BLDCM [4]-[5]. To implement the electronic gearshift, the motor must be designed as a multiple winding-connection type to provide the BLDCM with various output torques.

The electronic gearshift, except the aforementioned disadvantages of the ultra capacitor, has the following problems. The first is that the motor windings must be specially designed; the next is the winding changeover depends on many high-powers witches (or latching relays) to finish the complex connections; and then it is difficult to have a smoothness of the gear shift transient, because the gearshift point is much related to the torque curve of each gear. Additionally, the gearshift condition, considering the motor efficiency curve to each gear, makes the problem more complicated. Accordingly, if the electronic gearshift is applied in the energy-regenerative area, it becomes very complicated for the controlled logic.

In view of the aforementioned methods, this paper, based on the general BLDCMs without using boost converter, ultra capacitor, and multiple winding, is dedicated to developing a simple but effective method to convert the braking energy into the electrical one and then store up it in the battery. The method has the properties of the electric brake and energy regeneration to increase the efficiency of the BLDCM.[6][9]

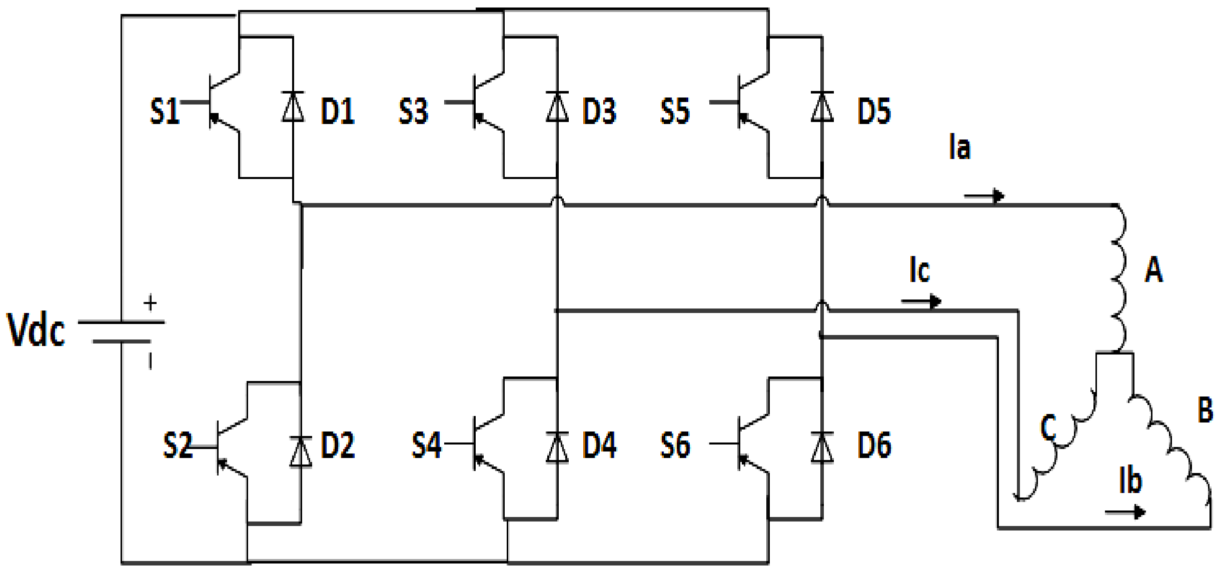


Fig:-1Voltage source inverter and equivalent circuit of BLDCM

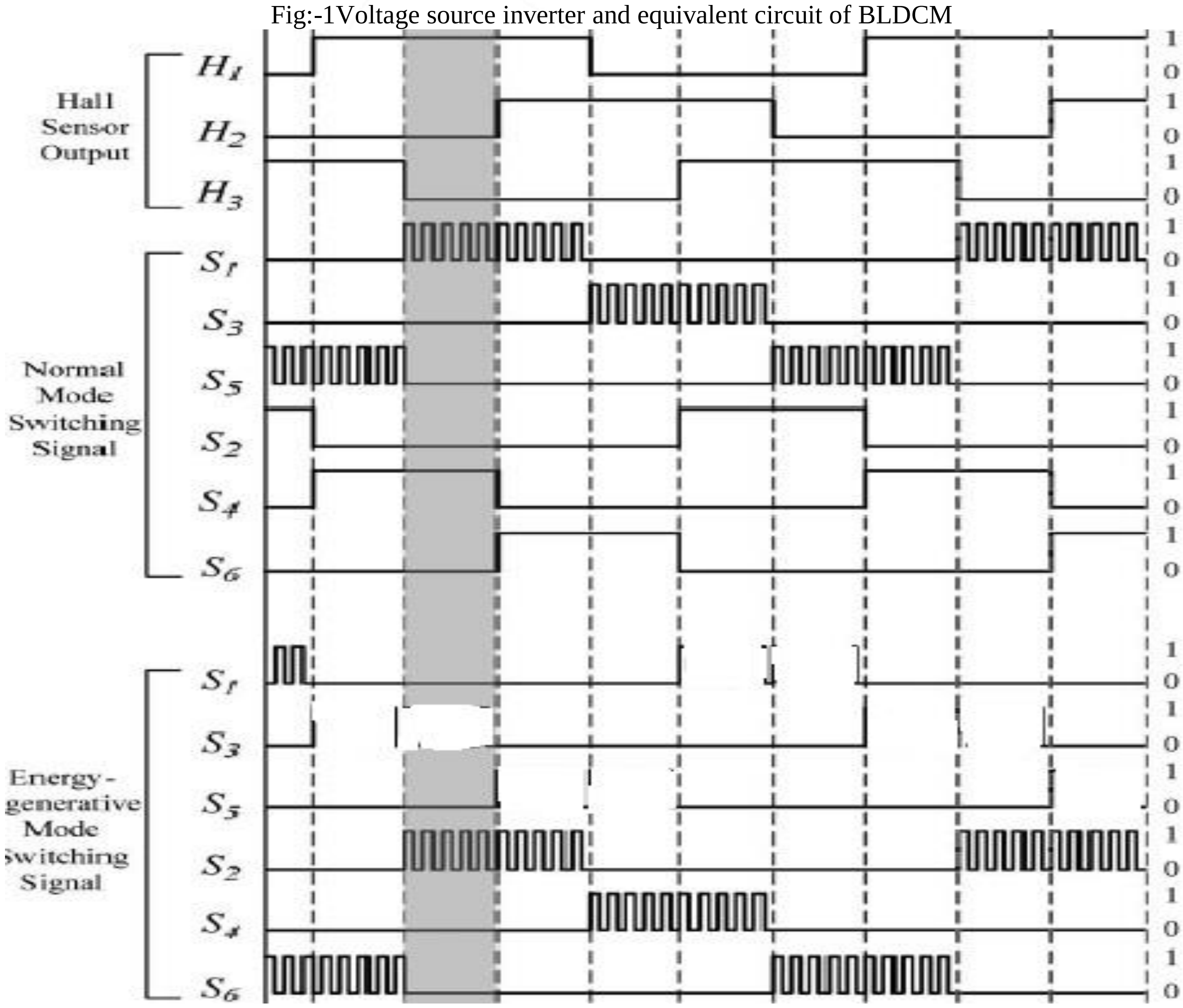


Fig:-2Hall sensor signals, back EMFs, and switching signal sequences of normal and energy-regenerative modes.[9]

## II. ANALYSIS AND OPERATING PRINCIPAL OF ENERGY REGENERATION

This work employs a hub BLDCM with trapezoidal back EMF. Fig.Shows an inverter and the equivalent circuit of the BLDCM. In Fig. , R and L are, respectively, the armature resistance and inductance; ea, eb, and ec are, respectively, the armature back EMFs of the phase a, b, and c; $i_a$, $i_b$, and $i_c$are, respectively, the armature currents of the phase a, b, and c. Fig. 1and Fig. 2 shows the switching sequences of the normal andenergy-regenerative modes for the BLDCM. In Fig. 2, $E_{ab}$,$E_{bc}$, and $E_{ca}$ are the line-to-line armature back EMFs; $H_1$ - $H_3$are the commutation signals (Hall sensor signals); $S_1$ - $S_6$are the switching signals of the six power switches. During the normal mode, the lower side switches $S_2$, $S_4$, and $S_6$ are operated in pulse width modulation

(PWM) switching mode; the high side switches $S_1$, $S_3$, and $S_5$ are operated in normal high or low. To the contrary, lower leg switches are operated in PWM switching mode during the energy-regenerative mode.

## III. NORMAL MODE

It can be seen from Fig.  that a complete commutation sequence consists of six state intervals (states I–VI). For convenient analysis, Fig. 2 is simplified as Fig. 2(a) which shows one of six state intervals (state I) and its equivalent circuit. During state I, the conduction mode represents that the switches $S_1$ and $S_4$ are turned on simultaneously. The inductor current iab would be increased by the energized current loop ion of the winding. At this time, since the magnetic field of the winding is increased due to $I_{ab}$ increase, a reverse induction voltage $E_{ab}$ has to resist the variation of the magnetic field according to Lenz's Law. That is the so-called the armature back EMF of the motor. During another mode (freewheeling mode), the switch S1 is turned off, and S4 is still on such that the inductor current will flow into the freewheeling diode D6 and the switch S2, which makes a discharging current path $I_{off}$. Accordingly, the corresponding sequences of $S_1$, $S_4$, input current $I_{in}$ and phase current $I_{ab}$ are shown in Fig. 2(b). The switching patterns of the states II–VI of Fig. 1(b) are similar to the state I, thus the analyses of states II–VI are omitted [7].

Table 1Truth table for motoring operation

| H1 | H2 | H3 | S1 | S2 | S3 | S4 | S5 | S6 |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 |
| 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 0 |
| 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 |

## IV. ENERGY REGENERATION MODE

When brushless PM motor is forward driving in half bridge modulation mode, six-step 120 drive scheme is used, that is, two-phase power devices which belong to high bridge arm and low bridge arm of the inverter respectively are conducted at any time, and the power device at the low bridge arm is controlled by PWM in speed control of motor. Tab.4.2 shows the corresponding relation of HALL states and conductive power devices when the motor is forward driving. When the motor is forward braking in half bridge modulation mode, only three power devices ($T_2$ ,$T_4$ ,$T_6$ ) at the low bridge arm are switched on and off at a controlled duty cycle for 120 electrical degrees respectively while the other three power devices ( $T_1$ , $T_3$ , $T_5$ ) at the high bridge arm are always switched off, and the conductive time of $T_2$ ,$T_4$ ,$T_6$ is that of $T_5$ ,$T_1$ ,$T_3$ (forward driving) respectively[7]. The corresponding relation of HALL states and conductive power devices when forward braking is shown in Table 4

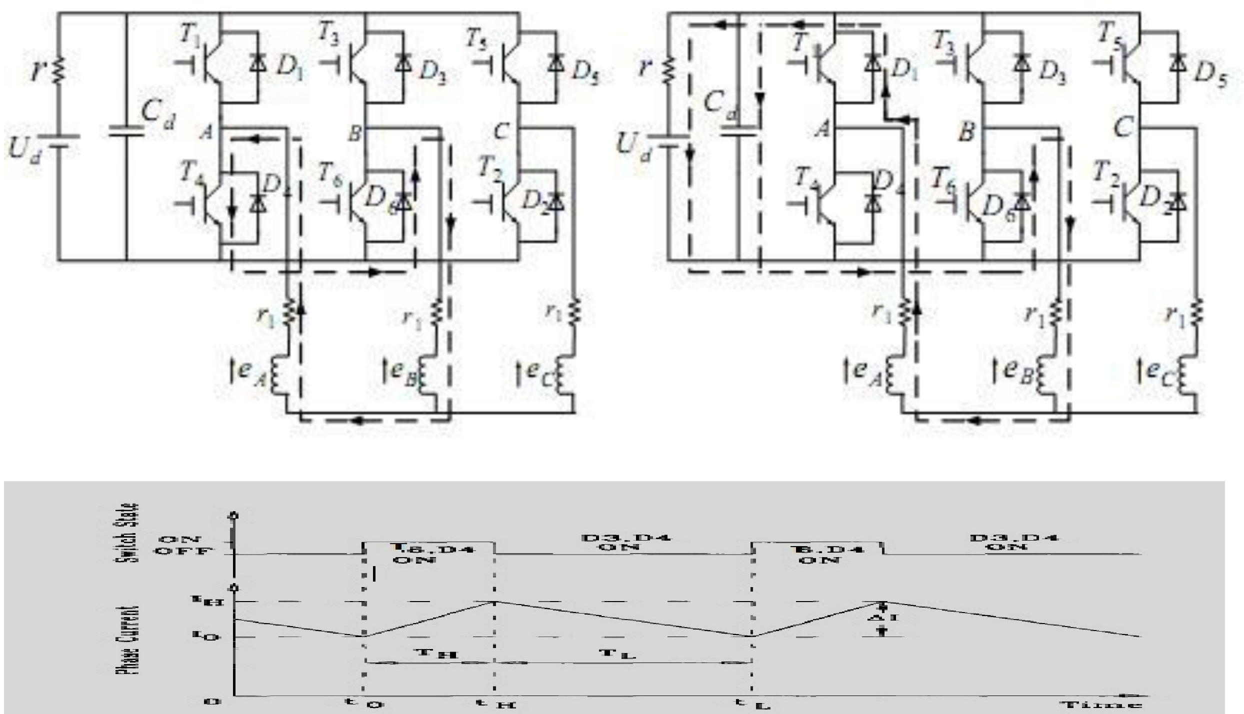


Fig:-3Current regeneration while energy regeneration[9]

Table 2truth table for energy regeneration

| H1 | H2 | H3 | S1 | S2 | S3 | S4 | S5 | S6 |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |

## V. SIMULATION AND RESULTS

This chapter describes MATLAB simulation for control strategies for regenerative braking BLDC motor.

Table 3Simulation parameters

| BLDC motor parameter | | | |
|---|---|---|---|
| Phase Resistance | 0.5Ω | Pole Pair | 4 |
| Phase Inductane | 1.65mH | Rated Torque | 0.32 N.m |
| Rated Voltage Vdc | 36 V | Inertia | 17.3*e-4 Kg*m^2 |
| Speed | 3500 RPM | Rated Current | 10amp |

Figure 4 shows the basic BLDC drive system in which the first block defines the gating pulses to motor whether its operates in motoring mode or in energy regeneration mode. A second block defines the inverter circuit with PWM, and the third section is BLDC motor. Over here in figure 5 shoes the gating pulses to inverter switches according to hall sensor pattern shows in Table 1 in motoring mode of operation.

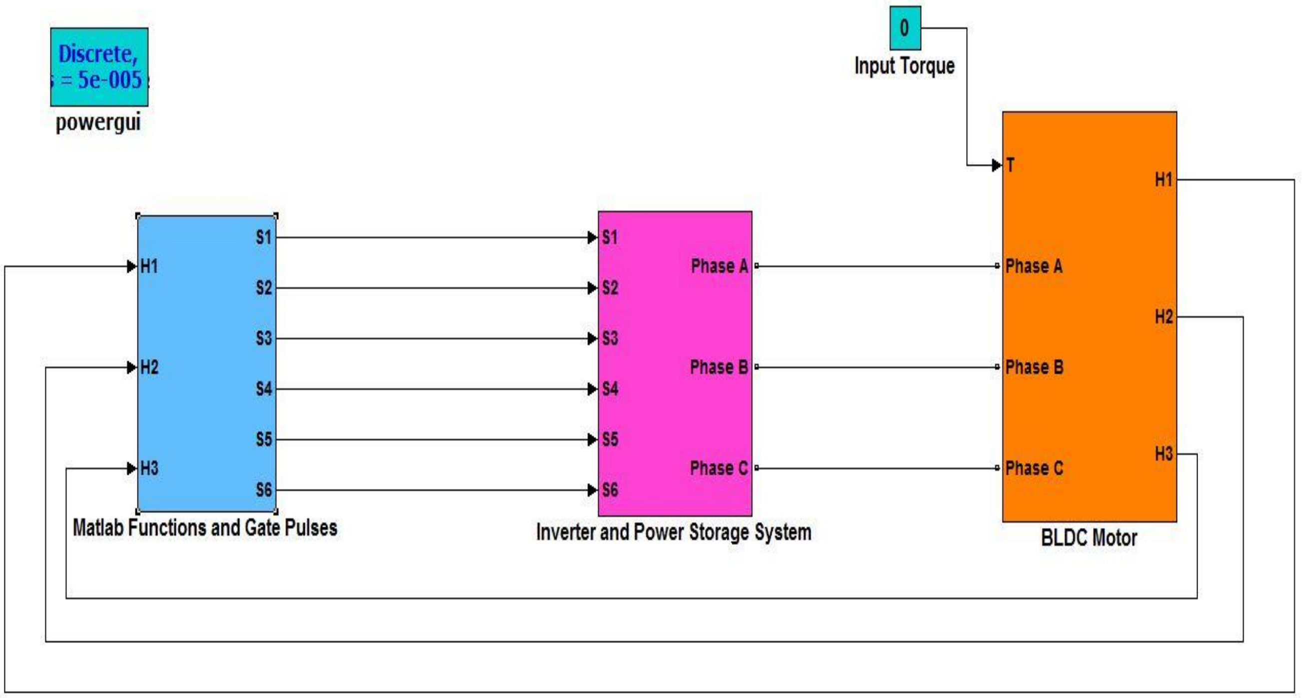


Fig:-4Basic BLDC drive system

Here the simulation is carried out with two different duty ratios. Figure 5 to Figure 7 shows the differ parameter at 50% duty cycle.over here in simulation results the first four seconds shows the motoring mode of operation after 4 sec the energy regeneration sequence is applied to inverter switches during 4 sec to 5.3 sec motor runs in energy regeneration mode.

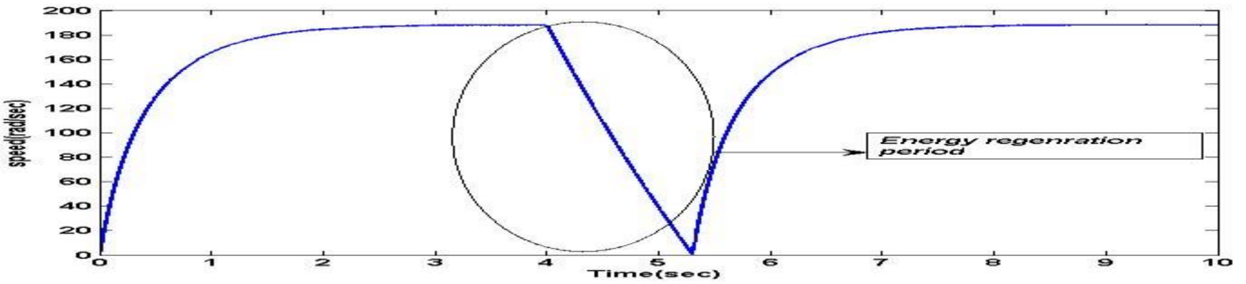


Fig:-5Speed of motor in motoring and energy regeneration mode

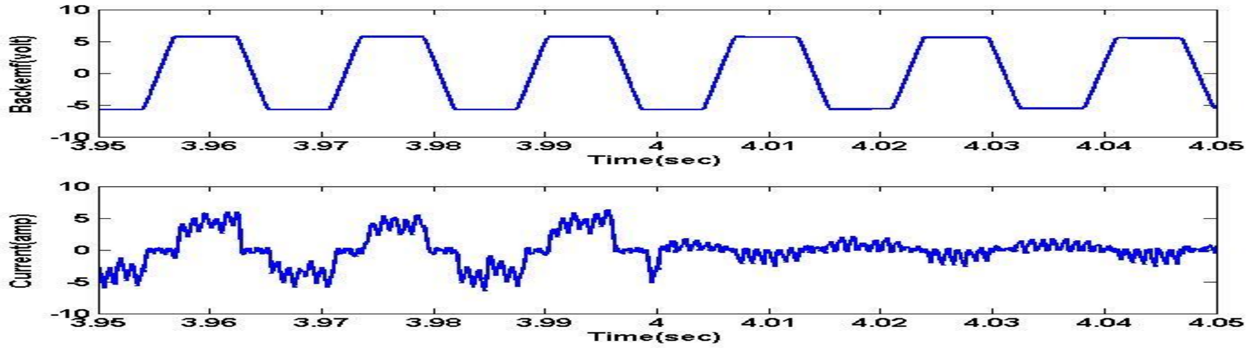


Fig:-6Back emf and Stator current in motoring and energy regeneration mode

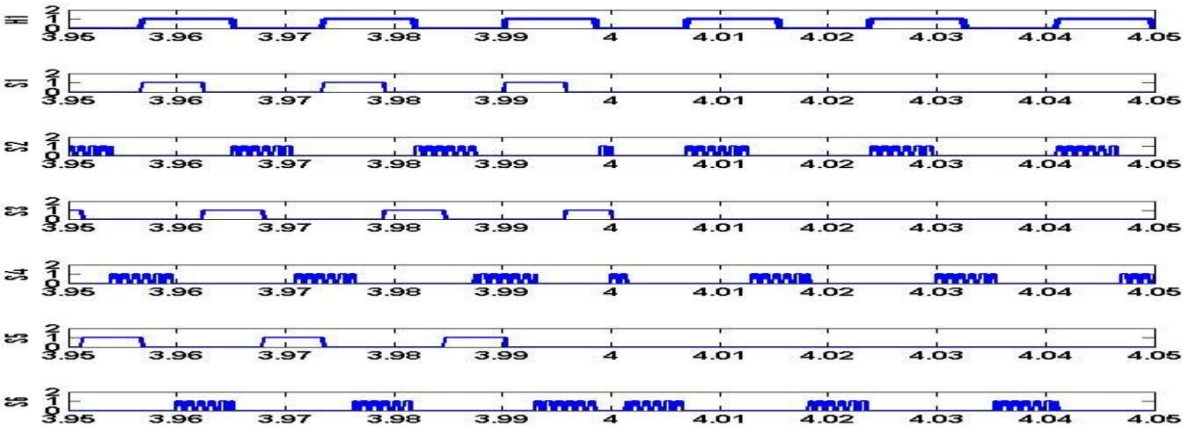


Fig:-7switching to inverter switch in both mode

Figure 8 to Figure 10 shows the different parameter of the motor at 70% of the pulse width 0 to 4 sec shows the motoring mode and after 4 to 5.6 sec the motor runs in second mode. in to the figure 10 its clearly shows that the stator current is 180 degree out of phase with back emf which conclude that the current direction is reversed in particular section of energy regeneration.

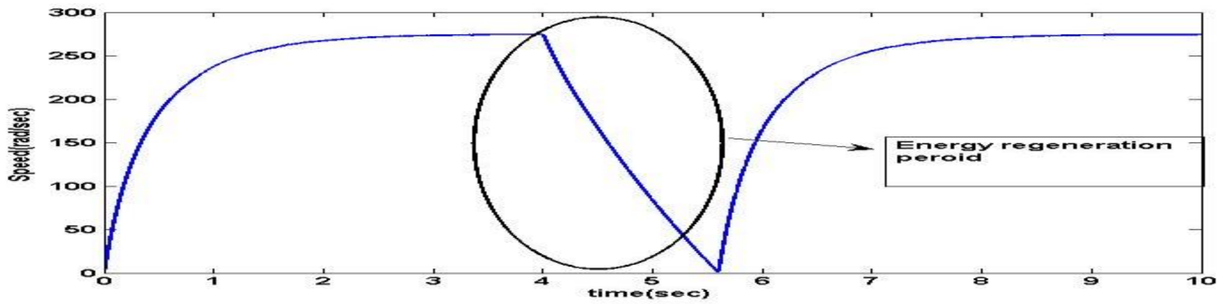


Fig:-8speed of BLDCM at 70% duty ratio

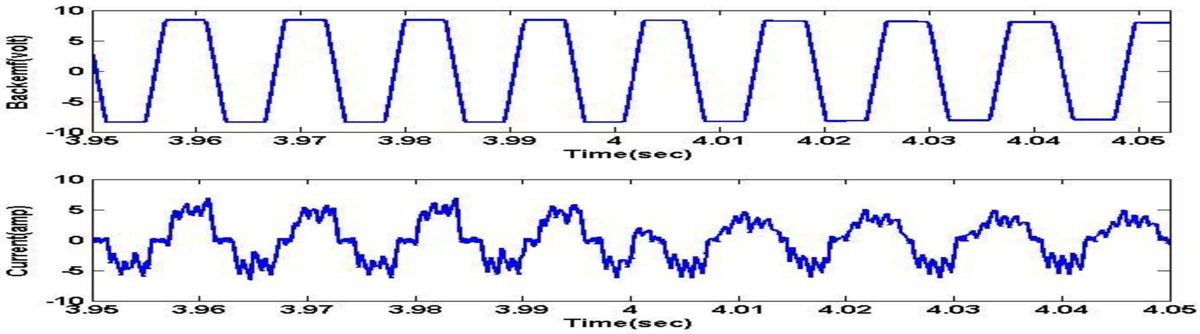


Fig:-9Back emf and Stator current

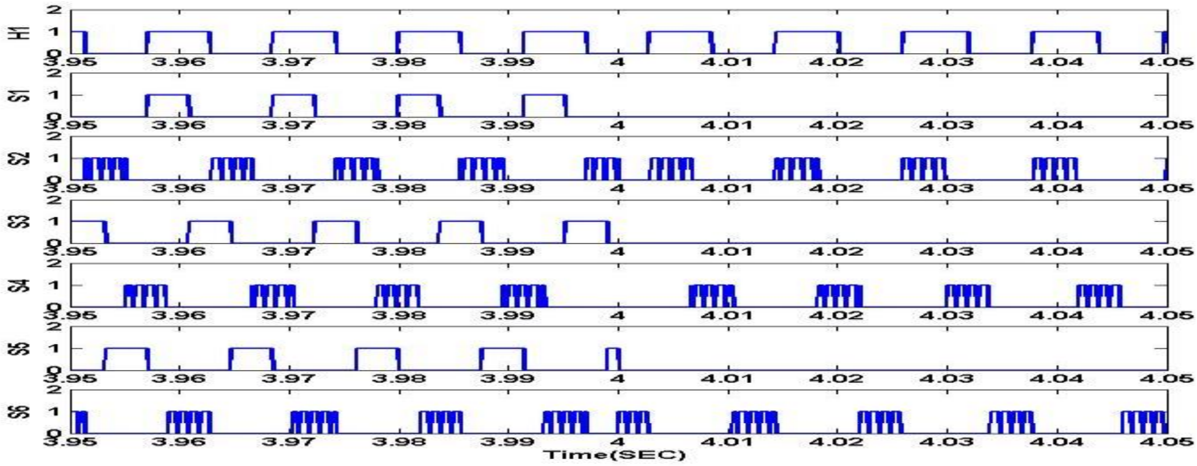


Fig:-10switching signal to inverter in both mode

Figure 11 to Figure 12 shows the different parameter of the motor at 70% of the pulse width 0 to 4 sec shows the motoring mode and after 4 to 5.6 sec the motor runs in second mode. in to the figure 11 its clearly shows that the electromagnetic torque is negative after 4 second..And the Figure 12 shows the direction of stator current at DC link side. Its shows that the current is also negative after 4 second hence its proved that the current direction is from stator to DC link side.

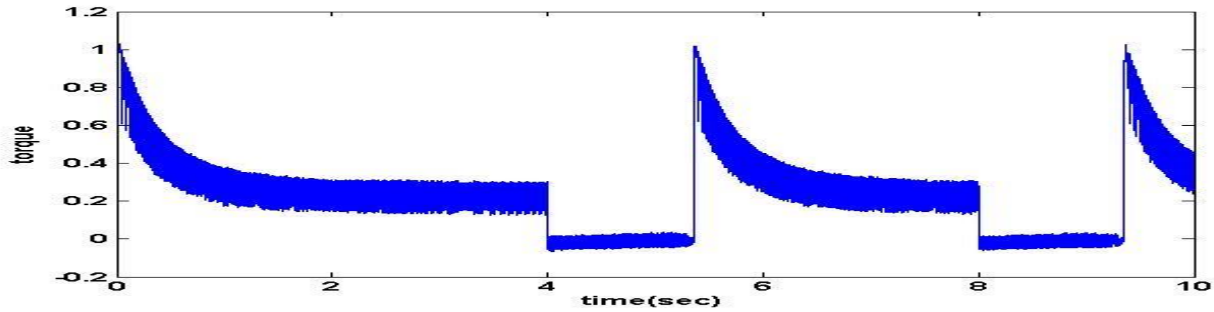


Fig:-11Electromagnetic torque of BLDCM

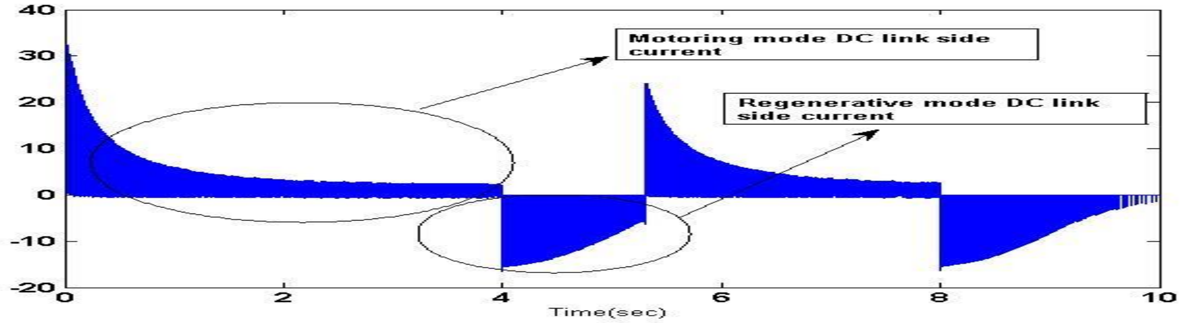


Fig:-12Current directions at dc link side at 70% duty ratio

## VI. Conclusion

This paper has studied deeply the relationship between regenerative braking current and PWM duty cycle in mode of the regenerative braking scheme for BLDCM.The proposed method could only change the switching signals of motor driver to control the BLDCM in motoring and regenerative braking mode without additional converter or changing windings of the motor stator as the methods proposed by other papers.The feasibility of the discussed method was proved by simulation results.from the above results we conclude that the the direction of current is reversed and in regenerative mode the current is reversed and it can be stored in to battery or in capacitor.

## REFERENCES


[1] J. W. Dixon and M. E. Ortlizar, " Ultracapacitor + DC-DC Converter in Regenerative Braking System," *IEEE Aerospace and Electronic system Magazine*,vol 17, No 8 pp. 16-21, August 2002.

[2] C. Lin, H. Liu and C. Wang,"Design and Implementation of a Bi-directional Power Converter for Electric Bike with Charging Feature,"*5th IEEE Conference on Industrial Electronics and Applicationsis,* PP.538-543, 2010.

[3] M. Marchesoni and C. Vacca, "New DC–DC converter for energy storage system interfacing in fuel cell hybrid electric vehicles,"*IEEE Trans. Power Electron.*, vol. 22, no. 1, pp. 301–308, Jan. 2007.

[4] Y. P. Yang and T. H. Hu "A new energy management system of directly driven electric vehicle with electronic gear shift and regenerative braking,"*inProc.Amer .Control Conf.jul 2007*, pp.4419-4424.

[5] Y. P. Yang, J. J. Liu, T. J. Wang, K. C. Kuo, and P. E. Hsu, "An electric gearshift with ultracapacitors for the power train of an electric vehicle with a directly driven wheel motor,"*IEEE Trans. Veh. Technol.*, vol. 56, no. 5, pp. 2421–2431, Sep. 2007.

[6] T. Jahns, R. C. Bccerra, and M. Ehsani, "Integrated current regulation for a brushless ECM drive," *1EEE Trans. Power electronics,* vol. 6, no. I, pp. 118-126, Jan. 1991.

[7] Ming-Ji Yang, Hong-Lin Jhou, Bin-Yen Ma, and Kuo-Kai Shyu," A Cost-Effective Method of Electric Brake With Energy Regeneration for Electric Vehicles,*" IEEE Trans. On Industrialelectronics*,vol. 56, no. 6, June 2009.

[8] Feili Huang, Xinjian Jiang, Yaoming Wang, "A Dedicated Permanent Magnet Synchronous Motor Drive System For Electric Vehicle,"*power electronics specialist conference 1995*, pg no. 252-257 vol 7, 18-22 june 1995.

[9] Wei Cui, Hang Zhang, Yan-li Ma, Yue-jin Zhang, "Regenerative Braking Control Method and Optimal Scheme for Electric Motorcycle,"*Proceedings of the 2011 International Conference on Power Engineering, Energy and Electrical Drives Torremolinos (Málaga),* Spain. May 2011.

[10] PadmarajaYedamale, "Brushless DC (BLDC) motor Fundamentals," 2003, http://ww1.microchip.com/downloads/en/AppNotes/00885a.pdf