Design, Modelling and Control of Bidirectional DC-DC Converter (for EV)

Jaya Aniruddha Mane*, Prof. A.M Jain†
* Department of Electrical Engineering, K. K. Wagh Institute of Engineering Education & Research, Amrutdham,Panchavti, Nashik-422003, India. E-mail: jayamane.11@gmail.com.
† Department of Electrical Engineering, K. K. Wagh Institute of Engineering Education & Research, Amrutdham, Panchavati, Nashik-422003, India. E-mail: amjain@gmail.com

***Abstract*—This paper explains modelling design and control of a bidirectional dc-dc converter for EV applications. The provision for energy regeneration is achieved by using half bridge non isolated dc-dc converter. Small signal modelling of the system is done by the state space averaging technique. A PI controller has been implemented for the speed control. The soft switching technique has also been incorporated to minimize the switching losses. The system model has been simulated in the MATLAB/SIMULINK.**

***Keywords*—Bidirectional converter, Electric Vehicle (HEVs), soft switching techniques, PI controller.**

NOMENCLATURE

K_i	= Integral Gain
K_p	= Proportional Gain
K_d	= Derivative Gain
V_i	= Input Voltage.
R_a	= Armature Resistance.
L_a	= Armature Inductance.
J	= Moment of Inertia.
b	= Coefficient of friction.
K	= Torque Constant.

I. INTRODUCTION

The importance of developing vehicles using alternative energy sources has raised interest in bidirectional DC-DC converter.This eventually results in increasing the overall efficiency of vehicle. Electric energy flows in both direction i.e from motor to battery and from battery to motor side in battery fed electric vehicles (BFEVs). The vehicle can be powered only by batteries or other electrical energy sources in order to achieve zero emissions. Few features of batteries that make them suitable to use in an electric vehicles are high energy density, compact size, and reliability. In Hybrid Electric Vehicles a battery along with IC engine can be used as an energy storage element to provide desired power management and therefore energy storage devices act as catalysts.

But due to short driving range and high initial cost, battery fuelled electric vehicle has its limited application. Therefore bidirectional converters forms the main element of the traction systems. In addition to this, bi-directional converter helps in suitable control in both motoring and regenerative braking operations, and it also contributes in significant increase in the total efficiency of the drive system. Therefore different converter topologies with different soft switching techniques have been analysed to increase the transfer efficiency [1].

Bi-directional converters with hysteresis current controller are introduced using coupled inductor in [2]. Zero-voltage and zero-current switching techniques are developed for Bi-directional converter in order to reduce switching losses and to improve reliability [3]. For high power applications a multiple phase Bi-directional converter is preferred. Converters can be connected in series or parallel in order to achieve high voltage rating or current rating, keeping switching frequency to lower level [4]. A PI current controller that provides complementary switching between switches was introduced for Bi-directional converter [5]. Selection of bidirectional converter topology greatly affects the overall system efficiency [6]-[7]. There is no need for galvanic isolation in hybrid energy storage system (HESS),as the energy storage is bonded to the vehicle chassis and battery is charged through the main [8]. Thus,when dc conversion ratio is relatively small non-isolated converters are preferred as the interface between the on-board energy sources due to their simple structure, smaller size, and high efficiency . High Frequency, power density, efficiency,and reliability are the factors that makes bidirectional converter a suitable option for EV [9][10]. However, the conventional bidirectional converters still face some shortcomings such as reduced switching speed, more reverse recovery loss. Due to these shortcomings the conversion can not be achieved in a bidirectional converter [11][12]. The simplest topology is buck/boost, however the input is not isolated electrically from output, and therefore soft switching can not be achieved easily. Also, during the turn-on period the reverse recovery effect of diode reduces the switching speed of the switch and hence it cannot be neglected in the boost mode. This paper describes, design modelling and control of bidirectional converter. Organization of paper is as follows: Section II, describes circuit. Section III, provides DC motor modelling. Section IV describes the design of converter and controller. Section V explains all the Simulation results, finally at the end paper is concluded in Section VI.

II. HALF BRIDGE TOPOLOGY

Half bridge non-isolated topology is considered for converter and PMDC motor is used as load. It is understood from the Fig 1 that in forward motoring, it is operated in boost mode and in regeneration it is operated in buck mode . Battery is taken as low voltage source and PMDC motor is considered as the high voltage load whose speed has to be controlled . At the motor side a high-frequency capacitor is connected that works like an energy buffer and a smoothening capacitor along the

978-1-4673-9563-2/15/$31.00 ©2015 IEEE

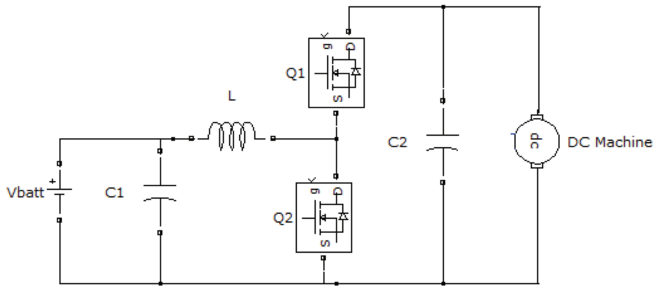

Fig. 1. Half Bridge Topology

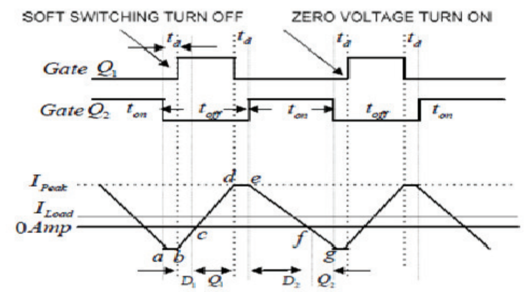

Fig. 2. ZVRT soft switching technique [6]

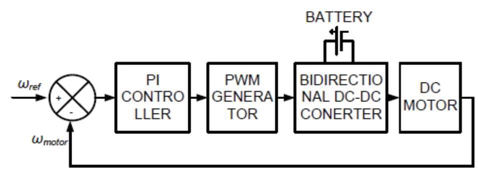

Fig. 3. Closed Loop Operation of Drive

battery side. When bidirectional dc-dc converter operates in continuous conduction mode (CCM) requires a larger valued filter inductor , the inductor size increases and it results in slow transient response and the mode transition. The inductor value can be considerably reduced with the circuit operating in the discontinuous conduction mode(DCM), and this results in faster response, therefore power density increases. DCM operation also offers zero-turn on losses and there by result in low reverse recovery loss in diode. Assuming that the main switch Q_1 is conducting initially. It can be seen that when all the devices gets turned off, the inductor current rises, and therefore the inductor current will charge the capacitor C_{Q1}. C_{Q2} will discharge to C_{Q1} as well. Due to the presence of the snubber capacitors C_{Q1} and C_{Q2} the charging and discharging rates are reduced. The turn on and turn off losses of switches are reduced as voltage across the capacitor cannot change abruptly . Now the inductor current flows through the diode D_2 and as the voltage across capacitor C_2 opposes it, inductor current decreases and finally it becomes zero. Then its polarity is reversed through Q_2, thus the the freewheeling current will flow through D_2 switch and at zero voltage Q_2 is switched on. As diode gets switched off at zero voltage, the reverse recovery losses are reduced. The negative inductor current flows through switch Q_2 during the dead time which helps in charging C_{Q2} and discharging C_{Q1} and thus the switch Q_1 turns on as the negative current is bypassed through diode D_1 till it becomes zero . Thus Zero Voltage condition is achieved.

III. Modelling

The DC motor is mathematically modelled by taking into consideration the torque and rotor angle relationship. The relation between steady state motor torque T, armature current I and torque constant K is given as,

$$T_m = KI_a. \tag{1}$$

The back emf E_b, is given as

$$E_b = K\omega_m = K\frac{d\theta}{dt} \tag{2}$$

$$j\frac{d^2\theta}{dt^2} + b\frac{d\theta}{dt} = KI_a \tag{3}$$

$$L\frac{dI_a}{dt} + RI_a = V - K\frac{d\theta}{dt} \tag{4}$$

Taking Laplace transform of equations (3) and (4),

$$Js^2\theta(s) + bs(\theta) = kI_a(s) \tag{5}$$

$$LsI(s) + RI(s) = V(s) - Ks\theta(s) \tag{6}$$

From equation (6), the current can be expressed as

$$I(s) = \frac{V(s) - K\theta(s)}{R + Ls} \tag{7}$$

$$Js^2\theta = bs\theta(s) = \frac{KV(s) - Ks\theta(s)}{R + Ls} \tag{8}$$

From equation (8), the transfer function can be written as

$$G_a(s) = \frac{\theta(s)}{V(s)} = \frac{K}{\{s[(R + Ls)(Js + b) + K^2]\}} \tag{9}$$

Also,

$$G_v(s) = \frac{\omega(s)}{V(s)} = \frac{K}{[(R + Ls)(Js + b) + K^2]} \tag{10}$$

IV. Design Of Converter and Controller

The bi-directional converter is designed with taking in consideration the input and output requirement to drive the electric vehicle at desired speed. The half bridge power converter topology is selected to control the dc motor. The inductor current has a constant peak to peak swing at a given input battery voltage and reference speed command . Equations (11)-(13) can be used to obtain the required parameters.

$$\Delta I = \frac{1}{2}\frac{V_2 - V_1}{L_c}\frac{V_1}{V_2}T_s \tag{11}$$

$$I_a = \frac{P}{V_2} \tag{12}$$

$$I_rms = \sqrt{I_L^2 oad + \frac{\Delta I^2}{3}} \tag{13}$$

The controlled speed of the dc drive can be achieved by controlling the output voltage. And to control the output voltage, a PI controller is used. It shows satisfactory result for running the vehicle at desired speed. In this control technique

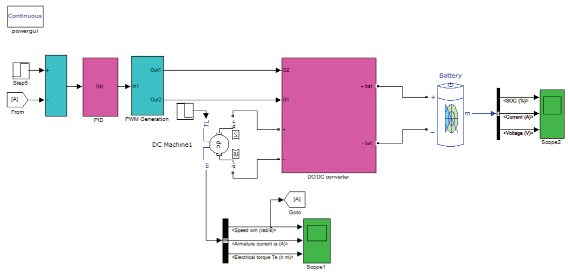

Fig. 4. Simulink model.

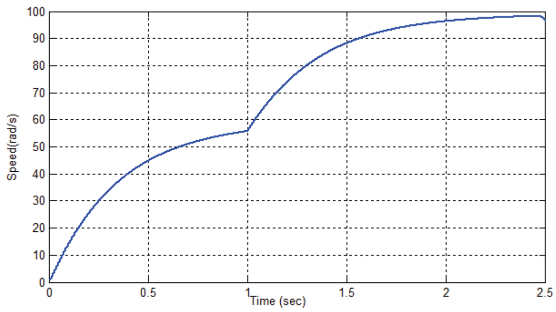

Fig. 5. Speed.

the error signal is obtained by comparing motor speed ω_m with reference speed ω_{ref}. Then it is processed through the PI controller. The PWM control signals are generated by comparing the obtained signal with a high frequency saw tooth signal.

As shown in block diagram of PI controller in fig 2, PI controller is used to reduce the steady state error between the measured speed (ω_{motor}) and reference speed (ω_{ref}) . The transfer function for PI controller is given by following equation,

$$G_c(s) = K_p + \frac{K_i}{s} \tag{14}$$

Zeigler Nichols tuning method is used to obtain the values of K_P and K_i.

V. Simulation and Results

The converter system model and the implemented control strategy has been simulated in the Simulink. The simulink model is given in Fig 4. The various waveforms corresponding to the motor speed, armature current, SOC, battery voltage and the battery current during simulation can be seen in Fig5 to Fig10. The simulation has been done for a total time of 2 sec with the converter working in the motoring mode for the initial 1 sec. After 1 sec motor operates in regenerative mode and a negative torque has been applied on the motor for next 1 sec so as to realize the vehicles downhill motion. Thus as seen in Fig 5 and Fig 7 the speed increases and the current goes negative as seen in Fig 6. The converter operates in buck mode during regeneration thus transferring the electrical energy from the motor to the battery. The various waveforms corresponding to the battery has been shown in Fig 8- Fig10. During motoring, the battery SOC (state of charge) decreases as the battery is providing the power to the motor. During regeneration, as the converter is operating in the buck mode the battery current goes negative and hence the SOC of the battery starts increasing (after 1s) as seen from Fig 8.

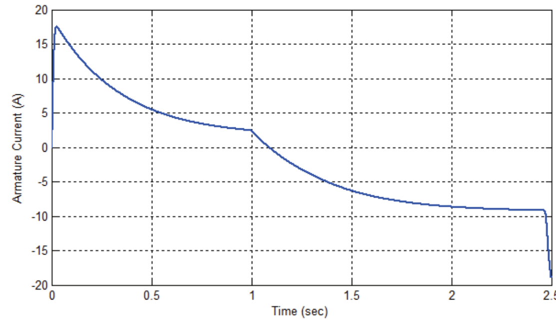

Fig. 6. Armature Current.

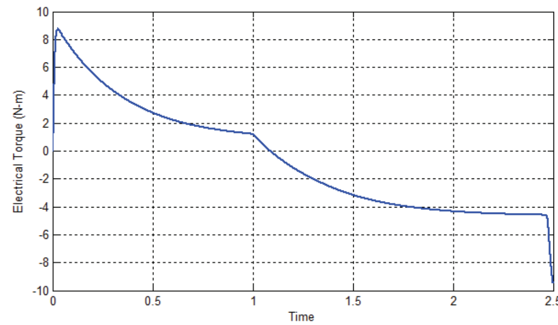

Fig. 7. Electrical Torque.

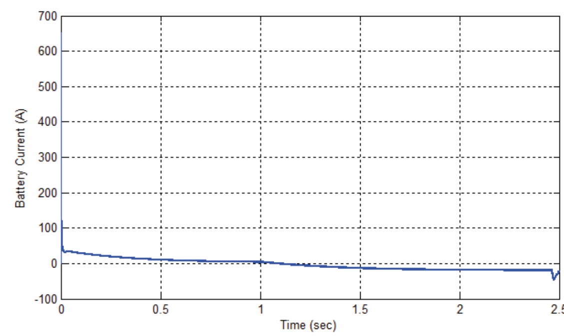

Fig. 8. Battery Current.

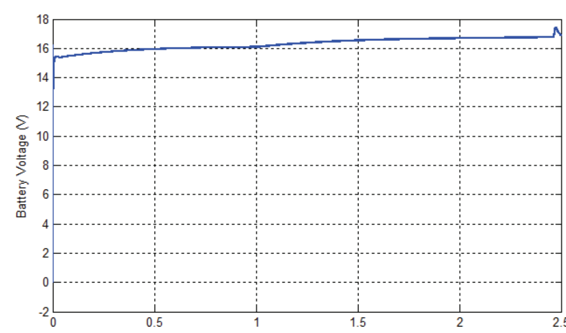

Fig. 9. Battery Voltage.

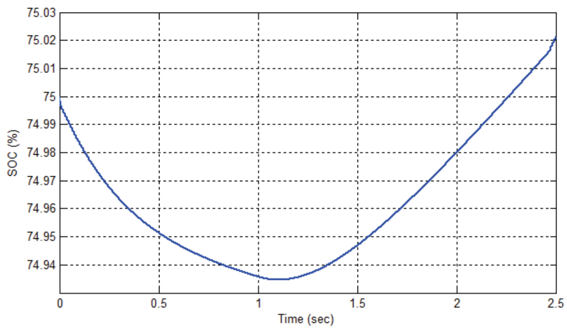

Fig. 10. SOC.

VI. Conclusion

This paper concerns with analysis, design, and realization of DC/DC converter operating in buck and boost mode for EV/HEV system. This converter can be operated in all three possible ways i.e buck, boost and buck-boost simply by selecting different combinations of the switches. The performance of the circuit is verified in simulink using MATLAB. The use of zero voltage switching technique makes the system operation more efficient.

References

[1] Zhang J., Lai J.-S., Kim R.-Y., Wensong Yu, High power density design of a soft-switching high-power bidirectional dc-dc converter. Power Electronics, IEEE Transactions Vol 22,No. 4 (2007): 1145-1153.

[2] Zhang Y., Sen P.C., 2003. A new soft switching technique for buck, boost, and buck-boost converters, IEEE transactions on Industry Applications, Vol. 39. No.6, November/December, pp. 1775-1782.

[3] Jain P.K., Kang W., Soin H., Xi Y., 2002 Analysis and design consideration of a load and line independent Zero voltage switching Full bridge DC/DC Converter topology, IEEE Transaction on Power Electronics, Vol.17, No.5, September. pp 649-657.

[4] Yu W., Lai J.-S., 2008. Ultra High Efficiency Bidirectional DC-DC Converter With multi frequency pulse width modulation APEC 2008,pp 1079-1084.

[5] Zhang J., Lai J.-S., Yu W., 2008. bidirectional dc-dc converter modeling and unified controller with digital implementation, Applied Power Electronics Conference and Exposition, APEC 2008, pp.1747-1753, Feb.

[6] Zhang, Junhong. Bidirectional DC-DC Power Converter Design Optimization, Modeling and Control. Diss. Virginia Polytechnic Institute and State University, 2008.

[7] M Hasaneen , Adel A. Elbaset Mohammed DESIGN AND SIMULATION OF DC/DC BOOST CONVERTERB. Faculty of Eng., Al-Azhar University, Kena, Egypt, IEEE Journal, 1933,03 ,2008 , page03.

[8] MARIAN K. KAZIMIERCZUK Pulse-width Modulated DCDC Power ConvertersA John Wiley and Sons, Ltd, Publication, Wright State University Dayton, Ohio, USA,2008 ,page56.

[9] M. D. Jain and P. Jain, A bidirectional DCDC converter topology for low power application, IEEE Trans. Power Electron., vol. 15, no. 4, pp. 595606, Jul. 2000.

[10] P. Jose and N. Mohan, A novel ZVS bidirectional Cuk converter for dual voltage systems in automobiles, in Proc. 29th Annu. IEEE IECON, Nov. 26, 2003, vol. 1, pp. 117122.

[11] H. Li, F. Z. Peng, and J. Lawler, Modeling, simulation, and experimental verification of soft-switched bi-directional dcdc converters, in Conf. Rec. IEEE APEC, 2001, vol. 2, pp. 736742.

[12] M. Gang, Q. Wenlong, L. Yuanyuan, and L. Bin, A novel soft switching bidirectional DC/DC converter, in Proc. ICEMS, 2005, vol. 2,pp.10751079.