Design of Electric Vehicle Drive Train with Regenerative Braking

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Abstract- *The inclusion of bidirectional DC-DC converter between the electric source and traction motor in Electric Vehicles facilitates the energy regeneration during braking and during motion along downhill slope. This inclusion can improve traction drive efficiency as much as by 25%, which improves the whole driving range. Now to reduce the weight, size and the cost of system, proper bidirectional DC-DC converter topology should be selected so as to optimize the design performance. This paper reviews and the study of the basic bidirectional DC-DC converter topology and presents the comparative advantages and disadvantages for arriving at the proper design decision for Electric Vehicle traction application.*

Keywords- Regenerative braking, traction energy, Electric Vehicle etc…

I. INTRODUCTION

Petroleum resources are getting depleted at an alarming rate because of transportation system whole dependency on it as a primary fuel. Also with use of petroleum at large extant causes greenhouse gases emission which leads to threat to surrounding and environment by deteriorating the air quality. To solve this problem there is need to design vehicle which has little or no dependency on petroleum as a fuel. Therefore automobile industries follow alternate propulsion technique to solve this problem which leads to development of Electric Vehicle (EV) from past one decade. But because of development in ICE technology and cheap price of petrol has pause the development in Electric vehicle technology and left the ICE run vehicle only choice to be used. But with recent increase in petroleum price, large consumption and degrading environment condition due to emission of hydrocarbons from ICE run vehicles had made to think again towards EV technology development. An EV unlike ICE run vehicle depends only on electrical energy storage for required traction power. Thus it increases the efficiency, drivability without any harmful emission and also facilitates improvement in energy conversion of vehicle. Furthermore there is an overall increase in efficiency by using regeneration during braking

Circuit Description Converter operation: figure shows the circuit diagram of bidirectional DC-DC converter fed PMDC motor. Bidirectional DC-DC converter operates in buck mode for regenerative braking and boost mode for forward motoring of PMDC motor. On low voltage side battery is placed and PMDC motor on the other side, also high frequency capacitor as energy buffer on motor side and a smoothing capacitor on the battery side.

II. CIRCUIT SPECIFICATION

The design specifications are as follows:

Parameter	Notaion	Values
Maximum converter power	P	$500W$
Battery output voltage range	$V_{BATT,OUT}$	$15V - 17V$
Battery input voltage range	$V_{BATT,IN}$	$13V - 16V$
DC Bus voltage	V_A	$17V - 40V$
Swtiching frequency	f_S	$10kHz$
Percentage Battery discharge current ripple	$\Delta I_{BATT,OUT}$	5%
Percentage Battery charging current ripple	$\Delta I_{BATT,IN}$	20%

III. CONVERTER OPERATION

Let assume that converter is operating in boost mode with fixed load torque and constant speed so that inductor current and armature current is at steady state. Let initially switch Q1 is conducting so inductor current rises until it not reaches the dead time when each device is getting switched off, then inductor current will discharge the capacitor C2 and charges the C1.

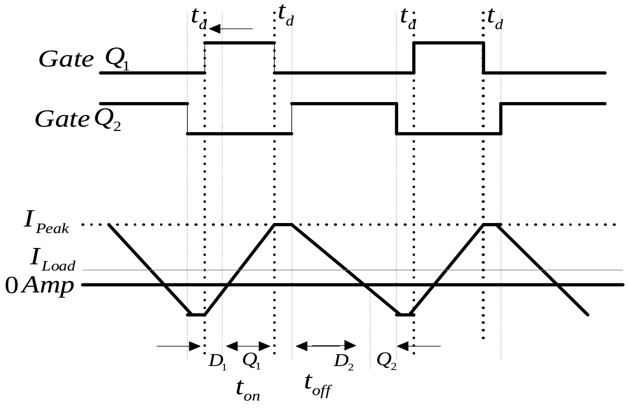


FIG: Complimentary Switching

Because of snubber capacitors C1 and C2, Charging and discharging rates reduced. Since voltage across capacitor doesn't change abruptly so switching on and switching off losses are reduced. Through diode D2 inductor current flows and reduced because of voltage across C_H until not it becomes zero and reverses its polarity through Q2, Now Q2 gets on by current through freewheeling diode D2 at zero voltage. Reverse recovery loss are reduced as diode gets switched off at zero voltage. Now again the negative current of inductor passes through switch Q2 which helps in charging C2 and discharging C1 in dead time and after that again the negative current passes through diode D1 until it not reaches zero and switch Q1 gets turn on. So at zero voltage condition switch Q1 gets turn on.

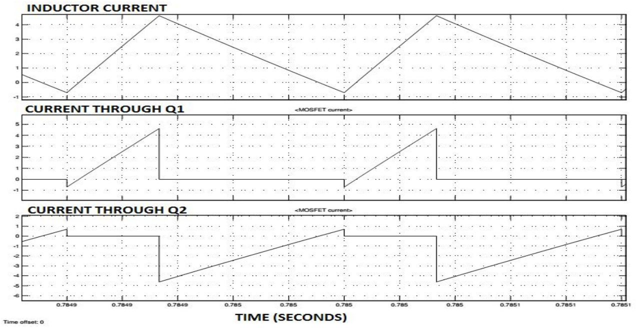


FIG: Inductor current, MOSFET Q1 current and the MOSFET Q2 current during motoring operation.

Converter's Parameters Designing Bidirectional DC-DC converter operates in three modes namely continuous conduction mode, discontinuous conduction mode and at the edge of continuous and discontinuous conduction mode. The operation of converter in these conduction modes affects its efficiency and performance in many ways. So it is necessary to have an eye on converter operation in these modes before designing circuit parameter.

Converter operating in the motoring mode in continuous conduction mode Converter operates in continuous conduction mode during motoring shown in fig below. The converter operates in boost mode to step up the voltage because it has to provide proper drive to motor. In this mode I_L is always positive i.e. $I_L > 0$.

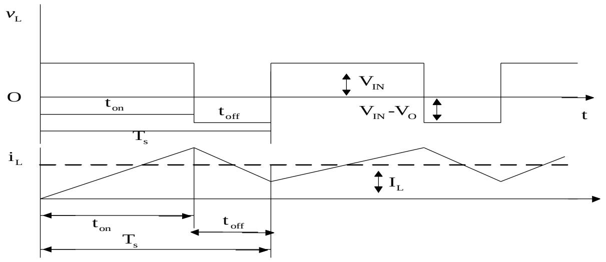


FIG: Inductor current waveform during motoring operation in continuous conduction mode

In this mode the basic equations for circuit operation are as follows:

$$V_{IN}t_{ON} + (V_2 - V_{IN})t_{OFF} = 0$$

Dividing both sides by the switching time period T_s and then rearranging we get

$$\frac{V_2}{V_{IN}} = \frac{1}{1-D}$$

By assuming lossless converter the power input equals to the power output

$$\therefore P_O = P_{IN}$$

$$V_2 I_A = V_{IN} I_L$$

$$\therefore I_A = I_L(1-D)$$

Boundary between continuous and discontinuous conduction during motoring mode

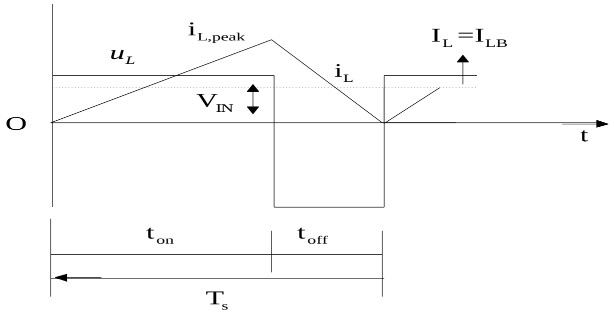


FIG: The waveforms of inductor current during motoring mode at the edge of continuous and discontinuous mode of conduction

Fig above shows the inductor waveform during motoring operation at the edge of continuous and discontinuous mode of conduction. The inductor current just reaches zero at the end of switching period. The average value of inductor current at the boundary is given by:

$$I_{LB} = \frac{1}{2}I_{L,PEAK} = \frac{1}{2}\frac{V_{IN}}{L}t_{ON} = \frac{T_S V_2}{2L}D(1-D)$$

Where I_{LB} is the average value of the inductor current at the edge of continuous and discontinuous mode of conduction.
During boost mode (motoring mode), inductor and input current are same (I_1=I_L), we find that the average output current during motoring mode at the edge of continuous conduction mode is:

$$I_A = I_L(1-D)$$

$$I_{A,AVG} = \frac{T_S V_2}{2L} D(1-D)^2$$

From the above equation we find that the I_{LB} reaches the maximum value at $D = 0.5$,

$$I_{LB,MAX} = \frac{T_S V_2}{8L}$$

Also I_A has its maximum value at $D = 0.33$,

$$I_{AB,MAX} = \frac{2}{27}\frac{T_S V_2}{L} = 0.74\frac{T_S V_2}{L}$$

Where I_{AB} is the average value of the armature current when the converter is operating at the edge of conduction and disconduction mode.

In terms of their maximum values, $I_{LB,MAX}$ and $I_{AB,MAX}$ can be expressed as:

$$I_{LB} = 4D(1-D)I_{LB,MAX}$$

$$I_{AB} = \frac{27}{4}D(1-D)^2 I_{AB,MAX}$$

Discontinuous Conduction Mode

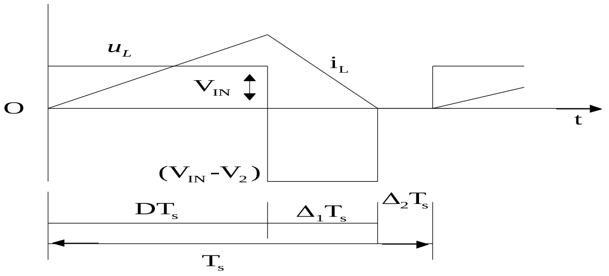


FIG: Inductor current waveform during discontinuous conduction mode

Since over one time period inductor voltage is zero,

$$\therefore V_{IN} D T_S + (V_{IN} - V_2)\Delta_1 T_S = 0$$

Thus, $$\frac{V_2}{V_{IN}} = \frac{\Delta_1 + D}{\Delta_1}$$

And $$\frac{I_A}{I_{IN}} = \frac{\Delta_1}{\Delta_1 + D}$$

From the above Fig 3.6, average battery current(input current) , which is also equal to the average inductor current therefore,

$$I_1 = \frac{V_{IN}}{2L} D T_S (D + \Delta_1)$$

$$I_A = \frac{T_S V_{IN}}{2L} D \Delta_1$$

If V_2 is regulated so as to run the motor at the constant speed and the load is varying, then the motor current is going to vary so as to so provide the required torque. We can get the expression of motor current in terms of the duty cycle with the armature voltage constant as:

$$D = \left[\frac{4}{27}\frac{V_2}{V_{IN}}\left(\frac{V_2}{V_{IN}} - 1\right)\frac{I_A}{I_{A,MAX}}\right]^{\frac{1}{2}}$$

State-Space Averaged Model: No matter whether circuit is operating in any of the modes (motoring or regenerative) its time interval is divided into two sub interval t_{on} and t_{off} shown in figure. So it is not necessary to analyze both modes separately but instead have eye on any of the time interval (t_{on} or t_{off}).

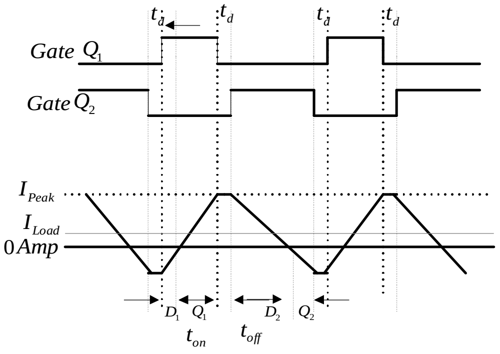


FIG: Complimentary Gating Signal Control

In both the sub intervals t_{on} and t_{off} both the switches Q1 and Q2 were on respectively. As shown in figure below.

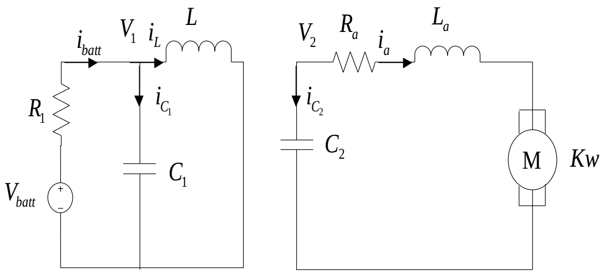


FIG: Equivalent circuit with Q1-on, Q2-off

Inductor currents I_L, I_A and battery side capacitor and motor side capacitor voltages V_1 and V_2 are four energy storage components.

Voltage across in inductor L is given by

$$V_1 = L\frac{di_L}{dt}$$

$$\therefore \frac{di_L}{dt} = \frac{V_1}{L}$$

Similarly voltage drop across armature inductance is given by

$$V_2 = i_A R_A + L_A \frac{di_A}{dt} + Kw$$

$$\therefore \frac{di_a}{dt} = -\frac{R_a}{L_a} i_a + \frac{V_2}{L_a} - \frac{K}{L_a} w$$

Capacitor current i_{c1} and i_{c2} are given by

$$V_{BATT} = R_1 i_{batt} + V_1$$

$$i_{C_1} = C_1 \frac{dV_1}{dt}$$

$$i_{batt} = i_L + i_{C_1}$$

$$\therefore \frac{dV_1}{dt} = \frac{V_{batt}}{R_1 C_1} - \frac{i_L}{C_1} - \frac{V_1}{R_1 C_1}$$

$$\frac{dV_2}{dt} = -\frac{i_a}{C_2}$$

Motor torque is given by

$$\frac{dw}{dt} = \frac{K}{J} i_a - \frac{B_m}{J} w - \frac{T_L}{J}$$

State space equations for first sub interval is given by

$$\dot{X} = A_{ON} X + B_{ON} U$$

$$Y = C_{ON} X + E_{ON} U$$

Where,

$$X = \begin{bmatrix} i_L \\ i_a \\ V_1 \\ V_2 \\ w \end{bmatrix}, \quad U = \begin{bmatrix} V_{batt} \\ T_L \end{bmatrix}, \quad Y = \begin{bmatrix} i_L \\ i_a \\ V_1 \\ V_2 \\ w \end{bmatrix} ,$$

$$A_{ON} = \begin{bmatrix} 0 & 0 & 1/L & 0 & 0 \\ 0 & -R_a/L_a & 0 & 1/L_a & -K/L_a \\ -1/C_1 & 0 & -1/R_1C_1 & 0 & 0 \\ 0 & -1/C_2 & 0 & 0 & 0 \\ 0 & K/J & 0 & 0 & -B_m/J \end{bmatrix}$$

$$B_{ON} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1/R_1C_1 & 0 \\ 0 & 0 \\ 0 & -1/J \end{bmatrix}, \quad C_{ON} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \quad E_{ON} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix},$$

In second sub interval t_{off} when Q2 is on and Q1 is off, converter equivalent circuit is given below

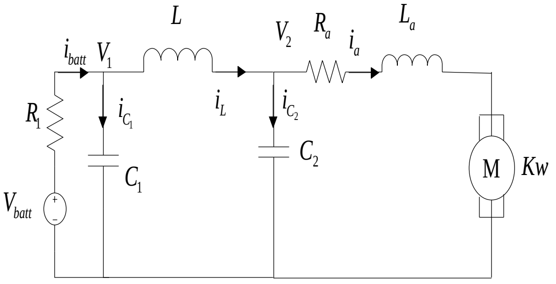


FIG: Equivalent circuit with Q1-off, Q2-on

Voltage drop across inductor L is given by

$$V_1 - V_2 = L\frac{di_L}{dt}$$

$$\therefore \frac{di_L}{dt} = \frac{V_1 - V_2}{L}$$

Voltage drop across armature inductance is given by

$$V_2 = i_A R_A + L_A \frac{di_A}{dt} + Kw$$

$$\therefore \frac{di_a}{dt} = -\frac{R_a}{L_a} i_a + \frac{V_2}{L_a} - \frac{K}{L_a} w$$

Capacitor current i_{c1} and i_{c2} is given by

$$V_{BATT} = R_1 i_{batt} + V_1$$

$$i_{C_1} = C_1 \frac{dV_1}{dt}$$

$$i_{batt} = i_L + i_{C_1}$$

$$\therefore \frac{dV_1}{dt} = \frac{V_{batt}}{R_1 C_1} - \frac{i_L}{C_1} - \frac{V_1}{R_1 C_1}$$

$$\frac{dV_2}{dt} = \frac{i_L}{C_2} - \frac{i_a}{C_2}$$

Motor torque equation is given by

$$\frac{dw}{dt} = \frac{K}{J} i_a - \frac{B_m}{J} w - \frac{T_L}{J}$$

State space equation for second sub interval is given by

$$\dot{X} = A_{OFF}X + B_{OFF}U$$

$$Y = C_{OFF}X + E_{OFF}U$$

Where,

$$A_{OFF} = \begin{bmatrix} 0 & 0 & 1/L & -1/L & 0 \\ 0 & -R_a/L_a & 0 & 1/L_a & -K/L_a \\ -1/C_1 & 0 & -1/R_1C_1 & 0 & 0 \\ 1/C_2 & -1/C_2 & 0 & 0 & 0 \\ 0 & K/J & 0 & 0 & -B_m/J \end{bmatrix}, \quad B_{OFF} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1/R_1C_1 & 0 \\ 0 & 0 \\ 0 & -1/J \end{bmatrix}$$

$$C_{OFF} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \quad E_{OFF} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

Extracting the Transfer functions All the transfer function is extracted from above equations but we require only control to output function only.

Therefore, control to output transfer functions is:

$$\frac{\hat{w}}{\hat{d}} = \frac{-s^2 + \left(\frac{V_2(1-D)}{I_L L} - \frac{1}{R_1C_1}\right)s + \left(\frac{V_2(1-D)}{I_L R_1 C_1 L} - \frac{1}{C_1 L}\right)}{s^5 + a_4s^4 + a_3s^3 + a_2s^2 + a_1s + a_0}$$

PID Controller Proportional-integral-derivative (PID) controllers has only three parameters that has to be tuned for processes control makes it to be widely used in industrial control system. An error signal is given as an input to the PID controller which is difference between the measured process variable and a desired reference signal. By adjusting the control inputs controller minimizes the error. It involves three constant parameters that has to be tuned namely Kp the proportional term, Ki the integral term and Kd the differential term. Where Kp depends on present value of error, Ki depends on the error accumulated in past and Kd depends on the rate of change of error in the present. It can be denoted as:

$$K(s) = K_P\left[1 + \frac{1}{T_I(s)} + T_D(s)\right]$$

Because of its simple structure and design PID controller is extensive control method that is used in industry. The important traits of PID controllers are:

- They can eliminate steady-state error of the step response (due the presence of the integral action)
- They can reduce the peak overshoot i.e. they can provide damping (due to derivative action)

Ziegler-Nichols tuning This method is employed when plants exhibit the step response as shown in fig below:

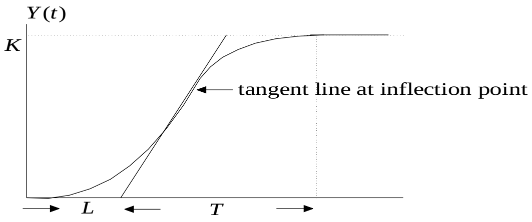


FIG: Step response curve for Zeigler Nichols parameters

This response is the characteristic of first order system with transportation delay. The response can be identified by two parameters, delay time L and time constant T. These are determined when a tangent is drawn at the point of inflection of step response and noting its intersection with steady state value and time axis. The plant model is given by:

$$G(s) = \frac{Ke^{-sL}}{Ts + L}$$

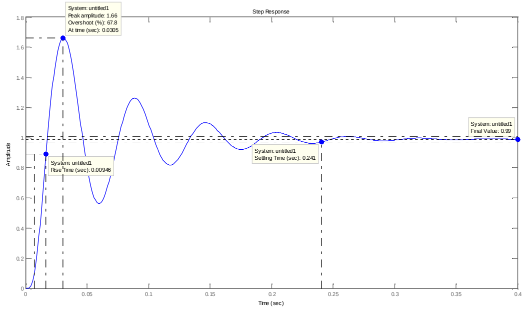
Following control parameter can be derived from this model based on Zeigler-Nichols method. The above model can be used to approximately modeled a large variety of plants in a real time process control system, By experiments parameter of approximate model is found if parameter of the system cannot be derived mathematically. For example if the step response of the system is experimentally found out as shown in the fig …then

$K_P = 1.2T/L$, $T_I = 2L$ and $T_D = 0.5L$

Also the parameters K_I and K_D can be found out as:

With $K_I = \dfrac{K_P}{T_I}$, $K_D = K_P \times T_I$

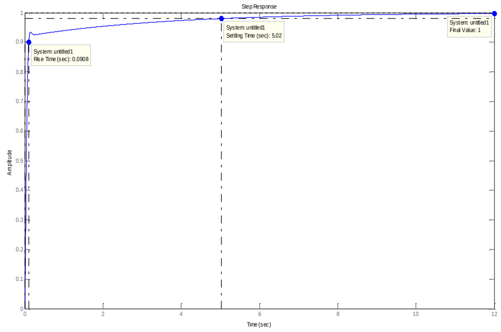
Based on the above method, the step response of the w/d was obtained as follows:



Based on the above response, the PID parameters are found as follows:

$$K_P = .1, K_I = .03, K_D = .0006$$

With the designed PID controller, the compensated system step response was obtained as follows:



The closed loop simulation of bidirectional DC-DC converter fed PMDC motor was done with designed values in Matlab Simulink. The simulation was found satisfactory and as expected. The various waveforms are as follows:

1. Without complimentary gate switching, parasitic ringing in DCM mode in bidirectional DC-DC converters.

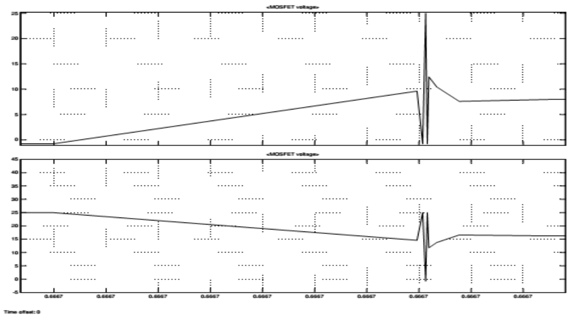


Fig 1: Mosfet Voltage Ringing at the zero inductor current without Soft Turn OFF switching

2. Motor’s Armature Voltage

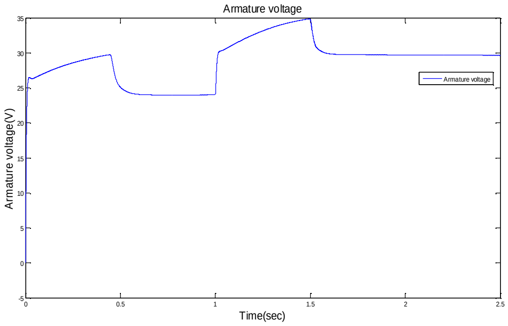


Fig 2: Motor’s Armature Voltage

Bidirectional DC-DC converter works in motoring mode and hence steady state value is near about 25V before 1 sec. After 1 sec converter works in regeneration mode as motor is suppose to be in downhill motion. Therefore speed increases due to increase in voltage.

1. Motor Current

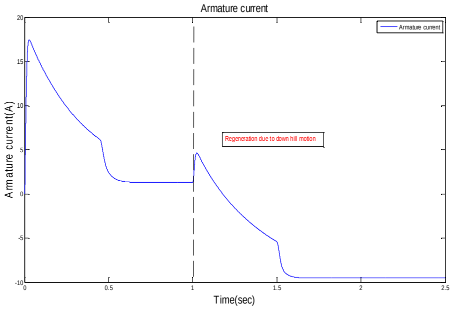
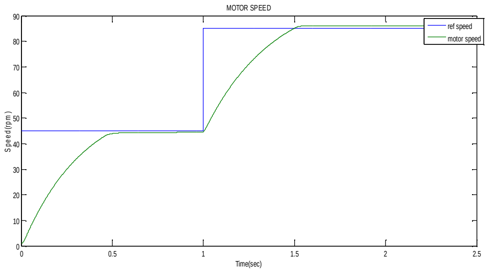


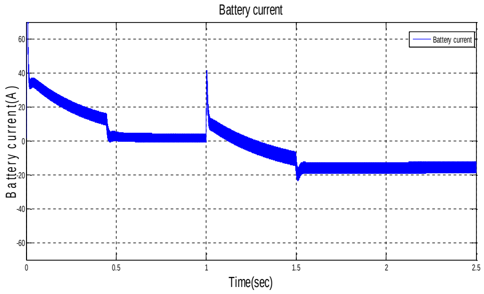
Fig 3: Motor current during motoring and regeneration

The negative current after 1 sec shows the regenerative mode; hence converter operates in the buck mode.

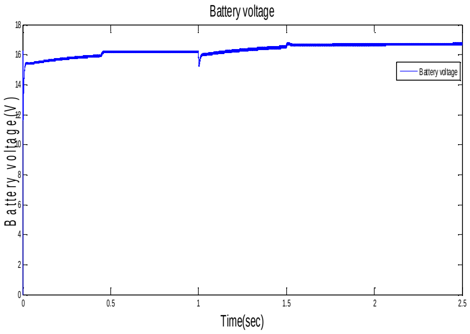
2. Motor Speed Tracking



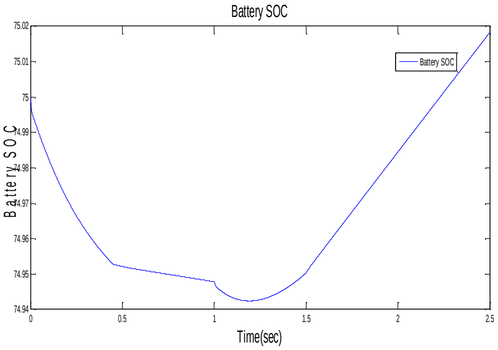
3. Battery Current



4. Battery Voltage



5. Battery SOC



IV. CONCLUSION

Designed bidirectional DC-DC converter has been successfully achieved the speed control of DC motor. Bidirectional DC-DC converter operating without complementary switching has been simulated and various current and voltage waveform are compared with the converter operating with complementary ZVRT switching, which shows that the designed converter operates in soft switching mode which in turn reduces the unnecessary switching loss causes the overall efficiency to increases.

PID controller is also designed on the basis of Zeigler-Nichols method and works with bidirectional converter which significantly reduces the overshoot and found to be work satisfactorily. Also regenerative braking during downhill motion of PMDC motor is realized thus achieving the design target.

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