Designing and Implementation of Bidirectional DC-DC Converter for Battery Based Electric Drives System

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Abstract:

Actually batteries are the primary energy-storage devices in ground vehicles. Now days battery based electric drives systems are commonly being used for electric vehicles applications, because of several advantages, like as: zero emission, good abnormal operation and energy recovery during braking operation etc. To perform these requirements converters with bidirectional power flow capabilities are required to connect the battery to the dc link of the motor drives system. Battery based electric vehicles (BFEVs) has been required to function in three different modes namely: acceleration mode, normal mode and braking or regenerative mode. During acceleration and normal modes the power flow has been from battery to motor where as during braking or regenerative mode the kinetic energy of the motor has been converted into electrical energy and supply back to battery. The DC-DC converter has been required to perform basically two functions:-

1. To match the battery voltage to the motor rated voltage.
2. To control the power flow under normal abnormal conditions. To get the drives system result has been as per the requirement. It presents the work closed loop operation of bi-directional dc-dc converter feeding a dc motor and its energy recovery because of regenerative braking has been used. The main features of battery operated electric vehicle under different drives system condition are also presented. The effectiveness of the system has been verified through the simulations using Simulink/ MATLAB.

Keywords: Bi-directional dc-dc converter, separately excited dc motor, Battery and Matlab etc.

I. INTRODUCTION

Now a days bi-directional dc-dc converters are mostly used for several applications like as battery charger, electric vehicles and UPS systems drives system systems etc. In case of the battery based electric vehicles (BFEVs), electric energy flows between motor and battery side. For achieving zero emission, the vehicle can be powered only by batteries or other electrical energy sources. Batteries are adopted in ground vehicles because of their main features of high energy density, compact size, and reliability etc. That can be applied in Hybrid Electric Vehicle (HEVs) with a battery as an energy storage element to provide desired management of the power flows. In hybrid electric vehicle energy storage devices act as a main source to provide energy boost. But due to the high initial cost of BFEVs as well as its short driving range has limited applications. Bidirectional dc-dc converters are the key components of the traction systems in Hybrid Electric Vehicles. The use of a Bi-directional dc-dc converter based dc motor drives system devoted to electric vehicles (EVs) application allows a suitable control of both motoring and regenerative braking operations, and it can contribute to rise the overall efficiency. Now a days many Bi-directional dc-dc converter topologies have been developed with soft switching technique to increase the transfer efficiency, zero-voltage-switched (ZVS) technique and zero-current-switched (ZCS) technique were introduced for Bi-directional converter. A multi-phase Bi-directional converter has been suitable for high power application. To find high voltage rating or current rating more number of converters can be connected in series or parallel with low switching frequency. A unified current controller was introduced for Bi-directional dc-dc converter which employs complementary switching between upper and lower switches.

That paper presents the use of a Bi-directional dc-dc converter for a battery based electric vehicle drives. A closed loop speed control technique of the proposed battery based electric vehicle with bidirectional dc-dc converter has been designed and implemented for dc drives system.

Figure 1. Bidirectional dc-dc converter with battery and dc motor

Figure1 represents the proposed Bi-directional dc-dc converter based DC motor drives system. In that research, boost converter operation has been find by modulating \( Q_2 \) with the anti-parallel diode \( D_1 \) acts as the boost-mode diode.
With the direction of power flow reversed, the topology functions as a buck converter through the modulation of \( Q_1 \), with the anti-parallel diode \( D_2 \) acts as the buck-mode diode. It must be noted that the two modes have opposite inductor current directions. A new control model has been developed using PI OR PID controller to find both motoring and regenerative braking of the motor. This controller represents the satisfactory result in different driving speed modes.

### II. CIRCUIT DESCRIPTION

#### 2.1 Converter operation

The bidirectional dc-dc converter shown in Figure 1 has been operated in continuous conduction mode for forward motoring and regenerative braking of the dc motor. The MOSFETs \( Q_1 \) and \( Q_2 \) are switched in such a way that the converter operates in normal with four sub intervals namely interval \( I(t_0-t_1) \), interval \( 2(t_1-t_2) \), interval \( 3(t_2-t_3) \) and interval \( 4(t_3-t_4) \). It must be noted that the low voltage battery side voltage has been taken as \( V_1 \) and high voltage output side has been taken as \( V_2 \). The gate drives systems of switches \( Q_1 \) and \( Q_2 \) are shown in Figure 3.

![Figure 2: Converter different operating modes.](image)

#### 2.1.1 Interval \( I(t_0-t_1) \): At time \( t_0 \), the lower switch \( Q_2 \) has been turned ON and the upper switch \( Q_1 \) has been turned OFF with diode \( D_1 \), \( D_2 \) reverse biased as shown in Figure 2(a). During that time interval the converter operates in boost mode and the inductor has been charged and current of the inductor increases.

\[
L_\text{c} \frac{dL_\text{c}}{dt} = V_2
\]

(1)

#### 2.1.2 Interval \( 2(t_1-t_2) \): During that interval both switches \( Q_1 \) and \( Q_2 \) has been turned OFF. The body diode \( D_1 \) of switch \( Q_1 \) starts conducting as shown in Figure 2(b). The converter output voltage has been applied across the motor. As converter operates in boost mode has been capable of increasing the battery voltage to run the motor in forward direction.

\[
\frac{dV_\text{c}}{dt} = \frac{V_\text{c}}{R_\text{c}C_\text{i}} - \frac{V_\text{c}}{R_\text{c}C_\text{i}} - \frac{I_\text{v}}{C_\text{i}}
\]

(2)

#### 2.1.3 Interval \( 3(t_2-t_3) \): At time \( t_3 \), switch \( Q_1 \) has been turned ON and switch \( Q_2 \) has been turned OFF with diode \( D_1 \) and \( D_2 \) reverse biased as shown in Figure 2(c). During this time interval the converter operates in buck mode.

\[
\frac{dV_\text{c}}{dt} = \frac{V_\text{c}}{R_\text{c}C_\text{i}} - \frac{V_\text{c}}{R_\text{c}C_\text{i}} - \frac{I_\text{v}}{C_\text{i}}
\]

(3)

#### 2.1.4 Interval \( 4(t_3-t_4) \): During that interval both switches \( Q_1 \) and \( Q_2 \) has been turned OFF. The body diode \( D_2 \) of lower switch \( Q_2 \) starts conducting as shown in Fig.

The state space average model has been shown in (4) and (5).

\[
0 = A \begin{bmatrix} I_z \\ i_\text{c} \\ i_\text{r} \\ V_1 \\ V_2 \end{bmatrix} + B \begin{bmatrix} E_\text{c} \\ E_\text{r} \end{bmatrix}
\]

(4)
\[ A = \begin{bmatrix} 0 & 0 & \frac{(1-D)}{L_c} & \frac{1}{r} & 0 \\ 0 & -\frac{R}{L_c} & \frac{1}{L_c} & 0 & 0 \\ \frac{1}{C_2} & 0 & 0 & \frac{1}{L_s} & 0 \\ \frac{1}{C_1} & 0 & 0 & 0 & \frac{1}{C_2} \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \]

\[ B = \begin{bmatrix} 0 & 0 \\ -\frac{1}{r} & \frac{1}{L_s} \\ \frac{1}{r} & 0 \\ 0 & \frac{1}{C_2} \\ 0 & 0 \end{bmatrix} \]

Figure 3. Complementary Gate Pulses

Figure 3 represents the gate pulses of the upper and lower switches of the Bi-directional converter and has been switched alternatively without any dead time in between. The control signals are obtained by comparing the modulating signal \( V_{triangular} \) with the carrier signal \( V_{control} \).

2.2 Designing of Converter: bi-directional converter has been designed based on the input supply voltage and output voltage to drives system the electric vehicle at desired speed. The converter power topology has been based on a half bridge circuit to control the dc motor. The inductor has been designed with a specified current ripple of 16A and 21A. Equations (4)-(5) are used to design the converter.

\[ \Delta I = \frac{1}{2} \frac{V_v - V_i}{L_c} - \frac{1}{V_2} I_2 \]

\[ I_m = \frac{P}{V_2} \]  \hspace{1cm} (7)

\[ I_m = \sqrt{\frac{1}{2} I^2 + \frac{\Delta I^2}{3}} \]  \hspace{1cm} (8)

2.3 Modeling of dc motor: The modeling of the DC motor has been carried out with torque and rotor angle. The normal motor torque \( T \) has been related to armature current \( I \) and a torque constant \( K \)

\[ T_m = K I_a \]  \hspace{1cm} (9)

The back emf \( E_b \), has been related to angular velocity by

\[ E_s = K \omega_m = K \frac{d\theta}{dt} \]  \hspace{1cm} (10)

\[ \dot{\theta}^2 + b \frac{d\theta}{dt} = K \thinspace I_a \]  \hspace{1cm} (11)

\[ L \frac{dI}{dt} + R I_a = V - K \frac{d\theta}{dt} \]  \hspace{1cm} (12)

Transfer function using Laplace transformation, equations (11) and (12) can be written as

\[ s^2 \theta(s) + b s \theta(s) = k \theta(s) \]  \hspace{1cm} (13)

\[ L \hat{s} I(s) + R I(s) - V(s) - K \theta(s) \]  \hspace{1cm} (14)

where, \( s \) denotes the Laplace operator.

From equation (14), the current can be written as:

\[ I(s) = \frac{V(s) - K \theta(s)}{R + L_s} \]  \hspace{1cm} (15)

\[ s \theta = \hat{s} \theta(s) = \frac{K(V(s) - K \theta(s))}{R + L_s} \]  \hspace{1cm} (16)
From equation (16), the transfer function from the input voltage $V(s)$ to the output angle $\theta$ can be written as

$$G_{\theta}(s) = \frac{\theta(s)}{V(s)} = \frac{K}{\{(R+Ls)(Js + b) + K^2\}}$$  \hspace{1cm} (17)

The transfer function from the input voltage $V(s)$ to the angular velocity $\omega(s)$ has been,

$$G_{\omega}(s) = \frac{\omega(s)}{V(s)} = \frac{K}{\{(R+Ls)(Js + b) + K^2\}}$$  \hspace{1cm} (18)

### III. CONTROL METHODOLOGY

The control circuit of the bidirectional converter has been shown in Figure 4. To control the speed of the dc drives system; one possible control option has been to control the output voltage of the bidirectional converter. To control the output voltage of the bidirectional converter for driving the vehicle at desired speed and to provide fast response without oscillations to rapid speed changes a PI OR PID controller has been used and it represents the good result. In that control technique the motor speed $\omega_m$ has been sensed and compared with a reference speed $\omega_{ref}$. The error signal has been processed through the PI OR PID controller. The signal thus obtained has been compared with a high frequency saw tooth signal equal to switching frequency to generate pulse width modulated (PWM) control signals.

![Figure 4. Control of the bidirectional dc-dc converter.](image)

The block diagram of feedback speed control system for DC motor drives system has been shown in Figure 5, the control objective has been to make the motor speed follow the reference input speed change by designing an appropriate controller. The proportional-integral (PI) controller has been used to reduce the normal error between the measured motor speed ($\omega_{motor}$) and the reference speed ($\omega_{ref}$) to be tracked. The transfer function of PI OR PID controller has been given by

$$G_{\omega}(s) = K_p + \frac{K_i}{s}$$  \hspace{1cm} (19)

Where, $K_p$ and $K_i$ are the proportional and integral gains. Simulink model of the system has been shown in figure 5.

![Figure 5. Simulink model of dc drive system with bidirectional dc – dc converter](image)
IV. BATTERY REQUIREMENT FOR HEAVY ELECTRIC DRIVE APPLICATIONS

Basically Nickel-Metal hydride (NiMH) and Lithium-ion batteries are used in these application because of their main features in terms of high energy density, compact size and reliability etc. The battery has been recharged by the regenerative capabilities of the electric motors which are providing during braking. The lithium-ion battery has been used to have excellent result in portable electronics and medical devices. The lithium-ion battery has high energy density, has good high temperature result, and has been recyclable. The aspects of the Li-ion batteries include low memory effect, high specific power of 301 W/kg, high specific energy of 101 Wh/kg, and long battery life of 1000 cycles. These main features give the lithium-ion battery a high possibility of replacing NiMH as next-generation batteries for vehicles. Equation (20) has been used for the battery.

\[ V_{\text{dcl}}(t) = V_{\text{dcl}}(0) - \frac{1}{C_{\text{dcl}}} \int e(t) dt. \]  

(20)

V. SIMULATION RESULTS

Result of the dc motor drives system with the above battery model and bidirectional converter has been simulated under different speed command. The simulations are carried out using MATLAB/SIMULINK. For the test condition of the proposed drives system topology the following values of the different components of the converter are considered. A separately excited DC motor model has been used as load to the bidirectional dc-dc converter. The motor rated at 6 hp, 240 V, and 1750 rpm.

Principal parameters of the bidirectional converter are: \( L = 1600 \ \mu H, \ C_H = 470 \ \mu F, \ C_L = 470 \ \mu F, \ \text{fSW} = 20 \ \text{kHz} \)

Battery voltage=49V, Battery capacity=17 Ah, SOC=89%.
Figure 6. Simulation result under normal condition (motoring mode), speed reference 120 rad/sec, simulation time of 10sec, at constant torque of 10Nm.

Figure 7(a). Motor speed

Figure 7(b). Motor torque

Figure 7(c). Motor current

Figure 7(d). Battery State of charge (SOC)

Figure 7(e). Battery voltage

Figure 7(f). Battery current

Figure 7(g). Motor and Battery power

Figure 7(h). Battery and motor energy
VI. CONCLUSION

In this paper the result of a battery operated electric vehicle system is presented and it gives the satisfactory result at different driving condition. The proposed control technique with PI OR PID controller find suitable for that electric drives system. The result of the BFEO has been verified in forward motoring mode, regenerative mode. The overall cost and volume of the battery operated electric vehicle has been less with the least number of components used in the system.

REFERENCES