**BIDIRECTIONAL DC TO DC CONVERTER BASED DRIVE**

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*Abstract* - This work deals with simulation of Bidirectional DC to DC converter fed PMDC motor drive. This converter can operate with steep conversion ratio, a soft-switching, a continuous inductor current, and fixed switching frequency and low switch stresses. Drive output taken for various input voltages during boost and buck mode of operation.

*Keywords* – DC-DC power conversion, energy conversion, power electronics, Switched Mode Power Supplies and Permanent magnet DC motor.

**I. INTRODUCTION**

In recent years, HEV (Hybrid Electric Vehicles) has attracted more and more attentions of many countries vehicle industry. Automobiles powered by internal combustion engines represent a huge infrastructure investment, and about one third oil consumption. So the transition to an all-electric mobile fleet appears to be very attractive and desirable, but has been limited by several key technology and business issues. So the transition of researching on Hybrid Vehicles appears to be desirable [1].

Hybrid Vehicles have several advantages over conventional cars and there are some models available in the market. From the point of view of the power electronics field, in the power chain there are two circuits that have to be developed (shown in fig. 1).

The inverter to drive the motor and the DC/DC converter placed between the battery and the high voltage bus. This DC/DC converter should be bi-directional since the energy can flow from the battery to the DC link or in the opposite direction. This can integrate with the existing gasoline and electricity infrastructure is through the use of plug-in HEV (in fig. 1). By providing sufficient energy storage for a 40 mile range, by using the existing electricity infrastructure to recharge the battery at night, and by maintaining gasoline powered operation when sufficient charge is not available, one is able to realize most of the benefits at a societal level. In Fig.1 we can see the whole circuit, but the most important part is the bi-directional DC/DC converter, and its operation principle is controlled by current $I_1$ and $I_2$ (see fig. 2), and used between the direct voltage source $V_1$ and $V_2$. Both $I_1$ and $I_2$ are respectively the average current of $V_1$ and $V_2$. We use them to control the energy transfer direction. According to the need in practice, the direction of energy transfer is changed by bi-directional DC/DC converter, in other words, the energy can transfer from $V_1$ to $V_2$ (when $I_1$ is negative and $I_2$ is positive) or in the opposite direction. In hybrid electric vehicle, the voltage of energy storage devices, such as battery or super capacitor, varies with the change in load. So we have to utilize the bi-directional converter to optimize the drive characteristic of motor, and recycle the energy when the motor is braking, thereby increase the efficiency of the energy utilization. Furthermore, in order to make complete the instantaneous power output of battery, we utilize bi-directional converter to work with super capacitor to increase instantaneous power output, and improve the acceleration and deceleration of hybrid vehicle.

Hybrid Electric Vehicle (HEV) uses an electric energy source (battery, ultra-capacitor) to assist the propulsion of the vehicle in addition to the primary energy source (Internal Combustion Engine (ICE), fuel cell), and to absorb the kinetic energy during braking. With the ever increasing gas price, the need for zero
emission vehicles and much more matured electric drive technologies available, HEV becomes more attractive and possible for commercialization [2].

Non isolated Buck-Boost Cascade Bidirectional DC-DC Converter Topology for EVs application is discussed in [3]. A four-quadrant bi-directional drive system based on non isolated bidirectional converter with reduced number of switches is given in [4]. Bidirectional DC – DC converter application in HEV with reduced switches and ZVS is discussed in [5]. A novel PWM ZVS bidirectional DC/DC converter with coupled inductor is given in [6].

For the traction drive inverter in ICE HEVs, isolation is usually not required [7]. There are two basic configurations for this inverter: one is a traditional PWM inverter powered by a battery as shown in Fig1, the other is a bidirectional DC - DC converter as shown in Fig.2.

**Figure 1** Block diagram of drive system of a hybrid vehicle

**Figure 2(a) Basic Bidirectional DC to DC converter**

**Figure 2(b) Coupled Inductor PWM DC to DC Converter**

**II. BI-DIRECTIONAL CONVERTER OPERATION**

**A. Operation in Boost Mode**

Fig.3 shows the coupled inductor PWM ZVS DC – DC converter. During boost mode of operation switch $S_1$ act as main switch and switch $S_2$ acts as body diode. The equivalent circuit diagram for each mode of operation in a single switching cycle shown in
Fig. 4 and ideal waveform for buck mode is shown in Fig. 6.

Mode 0 (t < t0): At t = t0, the switch S1 is on, the current through LC1 is raised and at the same time LC2 get energized because both the inductor shares the same core and current flows through it due to excess flux added to core. Now the converter works as standard coupled inductor PWM boost converter. There is no current flowing into the high voltage source Vhi during this mode.

Mode 1 (t0 < t < t1): At t = t1, Switch S1 is turned off by ZVS and excess voltage is diverted to capacitor across S1, Cs1. The current through inductor is used to charges the Cs1.

Mode 2 (t1 < t < t2): During this mode, current through Lr1 is diverted to Lr2 at the same time D becomes forward biased, then in turn charges the capacitor Cs2. At the end of this mode, the current in Lr1 is completely diverted to Lr2 and no current flows through Lr1, D, Cr and Lr2 makes the Cs2 to discharge.

The equations are:

\[ V_{C_r}(t) = I_{in,lo} Z_1 \sin \omega_1 (t-t_1) \]  
\[ i_{Lr1}(t) = I_{in,lo} \cos \omega_1 (t-t_1) \]  
\[ i_{Lr2}(t) = I_{in,lo} [1 - \cos \omega_1 (t-t_1)] \]  

Where \( V_{C_r} \) is the voltage across the auxiliary circuit capacitor \( C_r \), and

\[ Z_s = \sqrt{\frac{L_{r1} + L_{r2}}{C_r}} \]  
\[ \omega_s = \sqrt{\frac{1}{(L_{r1} + L_{r2}) C_r}} \]  

and \( I_{in,lo} \) is the input current from the low side source. The initial values of \( V_{C_r} \) and \( i_{C_r} \) (the voltage across auxiliary circuit capacitor \( C_r \) and the current through it) at the beginning of Mode 1 are \( V_{C_r}(t_1) = 0 \) and \( i_{C_r}(t_1) = I_{in,lo} \). At the end of this mode, \( V_{C_r} \) reaches a maximum value of

\[ V_{C_r,max} \approx I_{in,lo} Z_1 \]  

Mode 3 (t2 < t < t3): At t = t2, during this mode capacitor Cs2 is fully discharged and diode D2 begins conduction, now converter operator standard coupled inductor boost converter and energy transfer from low voltage side to high voltage side through magnetic coupling between LC1, LC2. The current through LC1 is decreased due to negative voltage applied across it.

Mode 4 (t3 < t < t4): At t = t3, switch Sa is turned ON, the capacitor Cr get discharged through the path Cr-Lr1-Lr2 so that energy is stored in Lr1 and Lr2, because of this Sa is turned on at ZCS.

\[ i_{Lr1}(t) = -\frac{(V_{C_r}(t_3)/Z_a) \sin \omega_1 (t-t_3)}{V_{C_r}(t_3) \cos \omega_1 (t-t_3)} \]  
\[ V_{C_r}(t) = V_{C_r}(t_3) \cos \omega_1 (t-t_3) \]  
\[ V_{S1}(t) = (V_{lo}/1-D_1) + V_{C_r,max} \cos \omega_1 (t-t_3) \]  

Where

\[ \omega_a = \sqrt{\frac{1}{(L_{r1} + L_{r2}) C_r}} \]  
\[ Z_a = \sqrt{\frac{L_{r1} + L_{r2}}{C_r}} \]  

The initial conditions for eqns. (6)-(8) are \( i_{Lr1}(t_3) = 0 \), \( i_{C_r}(t_3) = 0 \), and

\[ V_{C_r}(t_3) = I_{in,lo} Z_1 \]  
\[ V_{S1}(t_3) = (V_{lo}/1-D_1) + V_{C_r}(t_3) \]  

Mode 5 (t4 < t < t5): In this mode switch Sa is turned OFF Lr1, Lr2 starts resonating Cs1, Cs2 and thus Cs1 is discharged and charges the Cs2. At the end of this mode Cs1 is completely discharged and Cs2 is charged fully and excess current is flows through Lr1 to the LC1

\[ i_{Lr1}(t) = \frac{(-V_{C_r}(t_3)/Z_a) \cos \omega_1 (t-t_4)}{V_{S1}(t_4)-(V_{C_r}(0)/Z_a) Z_{S1} \sin \omega_1 (t-t_4)} \]  

Where
Where initial conditions $i_{Lr1}(t) = 0$, $i_{Lr1}(t) = (-V_{Cr}(t_4)/Z_a)$  

$$V_{S1}(t) = V_{S1}(0) = V_{lo}/(1-D_1)$$  

Mode 0 ($t < t_0$): before time $t_0$ the converter operates as standard coupled buck converter. Switch $S_1$ is on and current through the $L_{c2}$ rises. $L_{c1}$ gets energized through $L_{r2}$.

Mode 1 ($t_0 < t < t_1$): Here $S_2$ is turned OFF and the voltage is limited by capacitor $C_{s2}$, $C_{s1}$ is charged through the $L_{r2}$ and then current flows through the $D_a$, $C_r$, input current is diverted to $L_{r1}$ and $C_{s1}$ and $C_{s2}$ get discharges.

$$V_{Cr}(t) = I_{in,lo} Z_2 \sin w_1 (t-t_1)$$  

$$\omega_{s1} = \frac{1}{\sqrt{(L_{r1} + L_{r2})(C_{s1}\|C_s)}}$$  

$$Z_{s1} = \frac{L_{r1} + L_{r2}}{\sqrt{(C_{s1}\|C_s)}}$$  

$$N_{r1} = \frac{1}{L_{r2} C_r}$$  

$$\omega_{s1} = \sqrt{\frac{1}{L_{r2} C_r}}$$  

The initial value of $V_{Cr}$ at the beginning of Mode 1 is $V_{Cr}(t_1) = 0$, and $i_{Cr}(t_1) = I_{in,lo}$.

$$i_{Lr2}(t) = (-V_{Cr}(t_3)/Z_a) \sin w_a (t-t_3)$$  

$$V_{Cr}(t) = V_{Cr}(t_3) \cos w_a (t-t_3)$$  

$$i_{Lr2} = (-V_{Cr}(t_3)/Z_a) \cos w_a (t-t_4)$$  

$$V_{s2}(t) = V_{s2} - (V_{Cr}(t_3)/Z_a) Z_{s2} \sin w_{s2} (t-t_4)$$  

$$\omega_{s2} = \sqrt{\frac{1}{L_{r1} + L_{r2} (C_{s1}\|C_s)}}$$  

Where $V_{Cr}$ is the voltage across the auxiliary circuit capacitor $C_{r}$, $I_{in,lo}$ is the input current flowing to the low-side voltage source, and
The initial conditions for eqns. (23)-(24) are
\[ i_{L1}(t3) = 0, \quad i_{Cr}(t3) = 0, \quad \text{And} \]
\[ V_{Cr}(t3) = i_{in,io}Z_1 \quad (26) \]

Mode 5 (\( t_4 < t < t_5 \)): In this mode the switch \( S_a \) is turned OFF. The current in \( L_{r1} \) and \( L_{r2} \) is used to discharges \( C_{s2} \) and charges up \( C_{sa} \).

The initial conditions of eqns. (25)-(26) are
\[ i_{Lr2}(t) = (-V_{Cr}(t3)/Z_a) \quad (31) \]
\[ V_{s2}(t) = V_{s2}(0) = V_{hi} + (nV_{lo}/1-D) \quad (32) \]

\[ Z_{st} = \sqrt{\frac{L_{r1} + L_{r2}}{C_{st}/C_{st}}} \quad (30) \]

The initial conditions for eqns. (23)-(24) are
\[ i_{L1}(t3) = 0, \quad i_{Cr}(t3) = 0, \quad \text{And} \]
\[ V_{Cr}(t3) = i_{in,io}Z_1 \quad (26) \]

Mode 6 (\( t_5 < t < t_6 \)): At \( t = t_5 \), the capacitor \( C_{s2} \) is completely discharged and the body diode \( D_2 \) conducts so that across the switch \( S_2 \) is short circuited so that switch \( S_2 \) is turned ON at ZVS.

Mode 7 (\( t_6 < t < t_7 \)): The current through the \( L_{r2} \) is reversed and current starts to flows from \( L_{r1} \) to \( S_2 \). This mode continues until current is completely transferred to \( S_2 \), now converter operation is similiar to mode 0. Where \( t_{c2} \) is the time in which the current in inductor \( L_{r1} \) is completely transferred to \( L_{r2} \). By symmetry
\[ t_{c1} = t_{c2} \]
\[ t_{c2} = \left[ (L_{r1} + L_{r2}) I_{in,io} \right] / \left[ (V_{in,lo} + (V_{hi}/n)) \right] \quad (33) \]
Figure 5 Equivalent Circuits of Boost Mode operation
IV. SIMULATION RESULTS

The simulation is done using MATLAB and results are presented here for boost and buck mode.

Fig. 6 (a) shows the simulation circuit for boost mode with motor load. Fig. 6 (b) shows the gate pulses for boost switch $S_1$ and auxiliary switch $S_a$. Fig. 6 (c) shows the input voltage and Fig. 6 (d) shows the armature speed output waveform. Fig. 6 (e) shows output torque waveform of input voltage of 100 V. Fig. 6 (f) shows output torque waveform of input voltage of 125 V. Fig. 6 (g) shows output torque waveform of input voltage of 150 V.
Fig. 6 (h) shows the simulation circuit for buck mode with motor load. Fig. 6(i) shows output torque waveform of input voltage of 200 V. Fig. 6(j) shows the armature speed output waveform for 200 V.
input voltage. Fig. 6(k) shows output torque waveform of input voltage of 150 V. Fig. 7(l) shows output torque waveform of input voltage of 150 V. Fig. 6 (m) Shows output torque waveform of input voltage of 100 V, and Fig. 7(n) shows output torque waveform of input voltage of 100 V.

Figure. 6(h) Simulation circuit for buck mode

Figure. 7(i) Output torque waveform for input voltage of 200 V

Figure. 6 (j) Armature speed output waveform for input voltage of 200 V

Figure. 6(k) Output torque waveform for input voltage of 150 V

Figure. 6(l) Armature speed output waveform for input voltage of 150 V

Figure. 6(m) Output torque waveform for input voltage of 100 V

Figure. 6(j) Armature speed output waveform for input voltage of 100 V

Figure. 7(n) Armature speed output waveform for input voltage of 100 V
V. CONCLUSION

The Bidirectional DC-DC converter fed PMDC motor is modelled and simulated using MATLAB simulink. The results are presented for boost mode and buck mode. This converter can operate with steep conversion ratio, a soft-switching, a continuous inductor current, and fixed switching frequency and low switch stresses. Drive is simulated for various value of input voltages during boost and buck mode of operation.

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