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Bidirectional Positive Buck-Boost Converter

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***Abstract* - In a positive buck-boost converter, inductor current and capacitor voltage can be decoupled which may improve system stability. In fact for a specific level of capacitor voltage, the inductor current can be adjusted at different levels and can be utilized to increase the robustness of the converter against input voltage and load disturbances. But when demand is a fast response with respect to step change in reference voltage, this topology needs to be modified. In this paper, a family of topologies based on a positive buck boost converter are presented which have a fast response and bidirectional power flow capability. This feature leads to some applications in hybrid vehicle systems and telecommunications.**

Simulations have been carried out to validate the robustness and stability of the proposed converters.

Keywords— **Bidirectional, DC-DC converters, Fast response**

I. INTRODUCTION

Non inverting Buck Boost converter is a known DC-DC power electronic converter which has characteristics of both buck and boost converter and can be applied in both step up and step down applications (Fig.1).

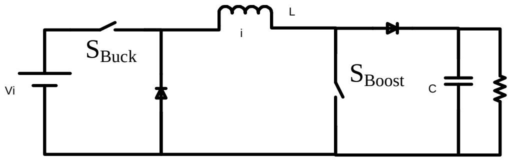

Figure 1: Positive Buck-Boost Converter

In addition it has advantage of a capacity for extra current storage in the inductor. Comparing the inductor current in Buck, Boost, inverting Buck Boost and positive Buck Boost, we have:

$$I_l = \frac{I_o}{D'} = \frac{V_o}{RD'} = \frac{V_i}{RD'^2} \qquad \text{Boost} \tag{1}$$

$$I_l = \frac{I_o}{D'} = \frac{V_o}{RD'} = \frac{DV_i}{RD'^2} \qquad \text{Inverting Buck Boost} \tag{2}$$

$$I_l = I_o = \frac{V_o}{R} = \frac{DV_i}{R} \qquad \text{Buck} \tag{3}$$

Equation (4) is same relationship for PBB.

$$I_l = \frac{1}{D'_{Boost}} I_o = \frac{1}{D'_{Boost}} \frac{V_o}{R} = \frac{D_{Buck}}{D'^2_{Boost}} \frac{V_i}{R} \tag{4}$$

The output voltage is:

$$V_o = \frac{D_{Buck}}{D'_{Boost}} V_i \tag{5}$$

So we have two controlling parameters (D_{Buck} and D_{Boost}) and two controlled quantities (i_L and v_C) which can be decoupled according to (4) and (5).

In this way the inductor of PBB can be used as an energy storage as well as energy deliverer while the amount of stored energy is independent from the level of delivered energy by D'_{Boost} in (4).

This capacity is utilized for improving the dynamic response of PBB to disturbances due to an increase in load or decrease in input voltage [8]. There are some DC-DC applications like hybrid vehicles [1-3] and hybrid power sources [4] which require bidirectional power flow. When there is a requirement for step up and step down voltage conversions or a higher degree of dynamic response to either disturbance or control reference signal a bidirectional converter topology (Fig. 1) may be promising. This converter is based on positive buck-boost converter. The other application is such as broader bandwidth where the switching frequency is restricted. For example envelop tracking in RF power amplifiers [5-7]. In this application, signal which should be amplified is divided into high and low frequency spectrums. The high frequency spectrum is amplified by a linear amplifier and the low frequency spectrum is converted by a switching circuit which reduces the size of the linear amplifier. The optimization between switching converter's band width and switching loss should be conducted to have the appropriate switching frequency. In the case of proposed converter owing to extra current capacity of positive buck-boost converter it can increase the dynamic response band width without increasing the switching frequency.

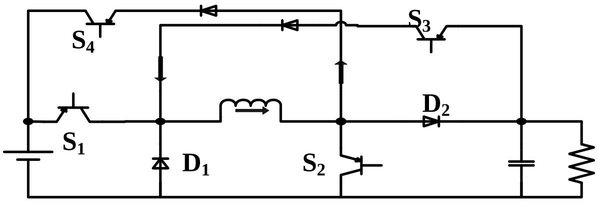

Figure 2: Bidirectional Positive Buck Boost (step up)

Using this degree of freedom of this converter another parameter is applied to decrease response time which may lead to a broader band width with lower switching frequency in communication systems [5-7]. In these low power applications there is no need to transfer small quantity capacitor energy back to input source thus the switch S_4 will be eliminated shown in Fig. 3.

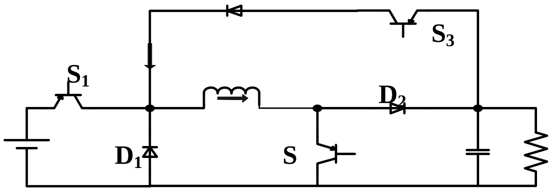

Figure 3: Topology of unidirectional Positive Buck-Boost converter with increased bandwidth.

In this paper we consider that for Inductor current control we need to recuperate the capacitor's energy in case of falling step change in reference voltage or load.

In this paper a current hysteresis, voltage hysteresis control strategy has been developed for proposed converters. The main focus is on the control strategy to increase the bandwidth of the system without increasing the switching frequency on one side and its ability to conduct bidirectional power flow on the other side.

If the bidirectional power flow be required in step down case D2 and S4 should be substituted. (Fig 4)

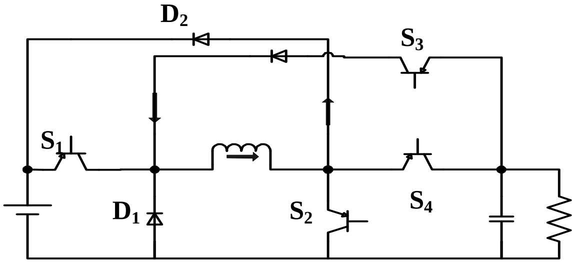

Figure 4: Bidirectional positive buck boost (step down)

Both topologies shown in Fig. 4 and Fig. 2 can perform step up and step down operations. The difference is that Fig. 2 topology can reverse the direction of energy only in step up operation and Fig. 5 topology can reverse the direction of energy only in step down operation.

The conventional way to develop a bidirectional converter is to anti parallel a diode with each switch and a switch with each diode in the unidirectional topology. Applying this method to positive buck boost converter is shown in Fig. 5.

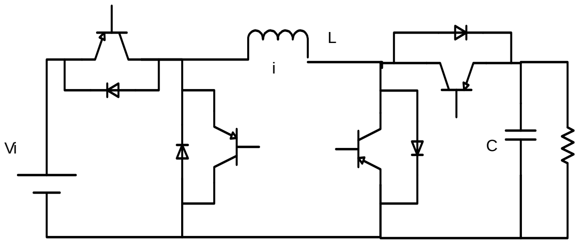

Figure5: Positive Buck-Boost Converter

Comparing this topology and the new topologies presented in this paper we can see that the number of switches and diodes are same or less.

The main difference between the new topology and the conventional bidirectional topology is that the capacitor energy can be transferred to the inductor faster in the new topology because it can direct the inductor current through the capacitor in negative way.

So the change in output voltage of the topologies presented in this paper can be performed faster.

This is more remarkable when we consider that PBB can store a level of extra current in its inductor. In the other words adding S_3 can improve the dynamic response of PBB and the dynamic response can be even more improved by storing more current in the inductor. Details of controlling PBB with a level of extra current are presented in [8] which include the effect of extra current storage on the switching frequency and switching loss of this converter.

The advantage of conventional topology is that the bidirectional energy delivery in this topology (Fig. 5) can be performed in both step down and step up cases.

In this paper we present the topologies based on PBB which are developed to be wideband and unidirectional (Fig. 3) or wideband and bidirectional (Fig. 2 and 4). All of these topologies are controlled to utilize the current storage advantage of PBB [8].

The following sections of this paper cover switching states, steady state and dynamic equations, control strategy and simulation results for proposed topologies.

II. SWITCHING STATES

To explain a general control strategy of the proposed DC-DC converter (Fig. 2) all switching states are presented in Fig.6. There are 9 switching states, 3 of which freewheels the inductor current and are called "zero states". Looking at the voltage imposed on the inductor in the other 6 states, the states can be divided into three groups with two states in each. The groups are named A, B, and C. and their states are shown in Fig.6. Because of this symmetrical availability of switching states there are options to transfer the inductor energy to the load (*A*, *C*) or to the voltage source (*B*`, *C*`), as well as options to transfer capacitor's energy to the inductor (*A*`, *C*`) and voltage source's energy to the inductor (*B*, *C*). In zero states the inductor and capacitor are disconnected and capacitor energy supplies the load while inductor keeps its current constant.

To reduce the switching loss the controller tries to decrease the switching frequency of each switch by switching from one state to the next one by changing the on or off state of only one switch. The states which can be transferred to each other by only one switching are called adjacent states. Fig. 7 shows the adjacent states.

To familiarize this converter we can see that switching between *A* and *C* states is a Buck converter and switching between *B* and *C* is a Boost converter. To discharge capacitor quickly we can apply states which direct the inductor current to the capacitor in the reverse way (*A*`, *C*`). In case of step up S_4 switch can be used to direct the energy of capacitor and inductor to the voltage source in switching states of (*B*` and *C*`).

There are three Zero states which are called so because inductor voltage is 0 when the state is *0*, *0(-)*, or *0(+)*. And capacitor is discharging by load current. Because of these states we can store some extra current in the inductor while we are controlling output voltage independently.

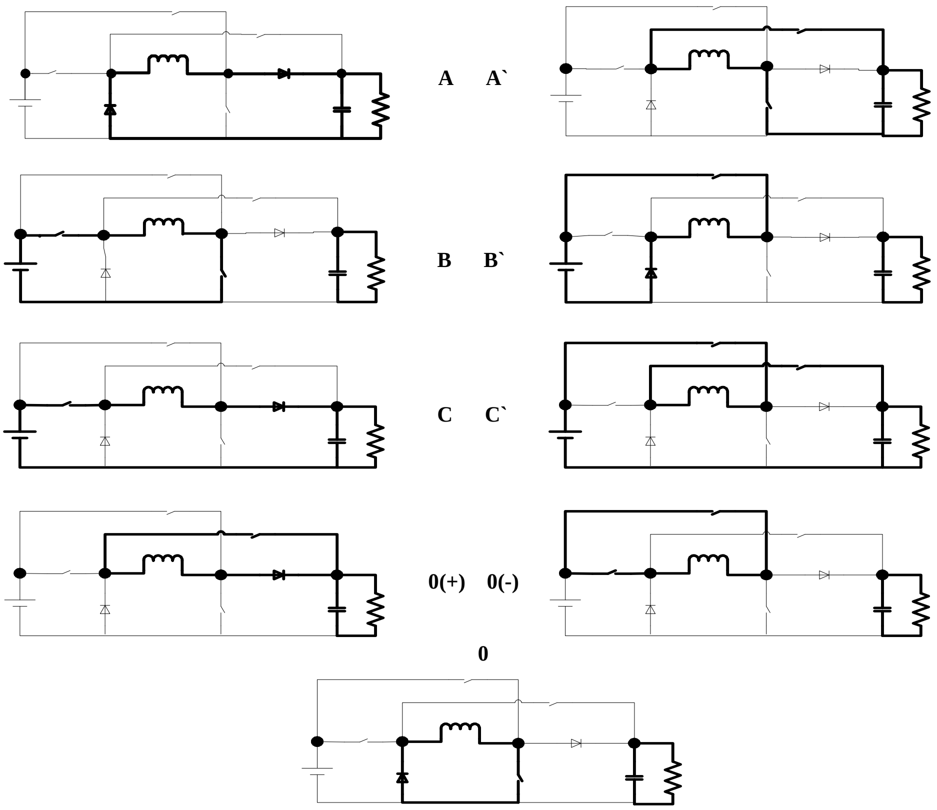

Figure 6: Switching states of Fig. 1 topology

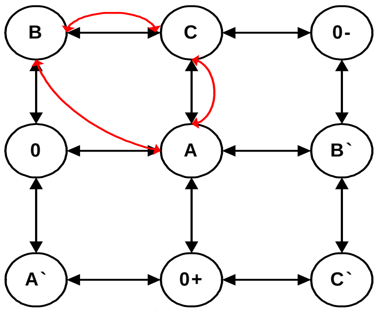

Figure 7 adjacency of switching states in bidirectional positive buck boost converter
The states in box are the states of Fig. 3 topology

Table I: Switching states and charging condition of Capacitor and Inductor in each switching state.

($S_1S_2S_3S_4$)	**C**	**L**	
A (0000)	**Charge**	**Discharge**	
B (1100)	**Discharge**	**Charge**	
C (1000)	**Charge**	**Charge** $V_o<V_i$	**Discharge** $V_o>V_i$
0 (0100)	**Discharge**	**No Change**	
A’ (0110)	**Discharge**	**Charge**	
B’ (1001)	**Discharge**	**Discharge**	
C’ (0011)	**Discharge**	**Charge** $V_o<V_i$	**Discharge** $V_o>V_i$
0+ (0010)	**Discharge**	**No Change**	
0- (1001)	**Discharge**	**No Change**	

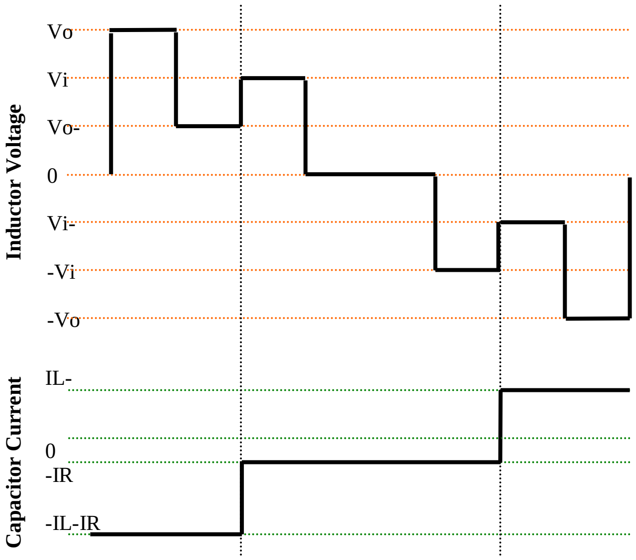

Figure 8: the effect of each switching state on Inductor and Capacitor

Fig. 8 shows the capacitor voltage and inductor current on each switching state. There are seven levels for inductor voltage and three levels for capacitor current. In capacitor current the level of $-I_L-I_R$ is identical in this topology and allows reducing the capacitor voltage faster than conventional bidirectional positive Buck Boost converter.

In drawing Fig. 8 input voltage has been considered to be less than output voltage and more than V_o-V_i.

Of course Fig 8 has been drawn simply. The detailed version should include fluctuations of output voltage and inductor current.

III. STEADY STATE AND DYNAMIC EQUATIONS

Writing dynamic equations of the inductor current we have:

$$i = inductor\ current \qquad \& \qquad v = capacitor\ voltage \tag{6}$$
$$(T_A - T_A')(-v) + (T_B - T_B')V_{in} + (T_C - T_C')(V_{in} - v) = L\varDelta i$$

Defining:

$$\begin{aligned} T_A - T_A' &= \Delta T_A \\ T_B - T_B' &= \Delta T_B \\ T_C - T_C' &= \Delta T_C \end{aligned} \tag{7}$$

We have:

$$\begin{aligned} &\Delta T_A(-v) + \Delta T_B V_{in} + \Delta T_C (V_{in} - v) = L\Delta i \\ &-(\Delta T_A + \Delta T_C)v + (\Delta T_B + \Delta T_C)V_{in} = L\Delta i \end{aligned} \tag{8}$$

And writing dynamic equations for the capacitors voltage we have:

$$((T_A - T_A') + (T_C - T_C'))i - T\left(-\frac{v}{R}\right) = C\Delta v \tag{9}$$

With same definition:

$$(\Delta T_A + \Delta T_C)i - T\left(-\frac{v}{R}\right) = C\Delta v \tag{10}$$

Writing these equations in a state space form with some simplifications leads to:

$$\begin{bmatrix} L & 0 \\ 0 & C \end{bmatrix}\begin{bmatrix} \dot{i} \\ v \end{bmatrix} = \tag{11}$$
$$\left(\frac{\varDelta T_A + \varDelta T_C}{T}\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & -1/R \end{bmatrix}\right)\begin{bmatrix} i \\ v \end{bmatrix} + \frac{\varDelta T_B + \varDelta T_C}{T}\begin{bmatrix} 1 \\ 0 \end{bmatrix}V_{in}$$

Calculating transfer functions for inductor current and capacitor voltage results in:

$$i = \frac{(RCs+1)\left(\dfrac{\varDelta T_B + \varDelta T_C}{T}\right)}{RLCs^2 + Ls + \left(\dfrac{\varDelta T_A + \varDelta T_C}{T}\right)^2 R}V_{in} \tag{12}$$

$$v = \frac{R\left(\dfrac{\varDelta T_B + \varDelta T_C}{T}\right)\left(\dfrac{\varDelta T_A + \varDelta T_C}{T}\right)}{RLCs^2 + Ls + \left(\dfrac{\varDelta T_A + \varDelta T_C}{T}\right)^2 R}V_{in} \tag{13}$$

Steady state equation can be driven by putting s = *0* in transfer functions:

$$i = \frac{T(\varDelta T_B + \varDelta T_C)}{(\varDelta T_A + \varDelta T_C)^2}\frac{V_{in}}{R} = \frac{T}{(\varDelta T_A + \varDelta T_C)}I_{Load} \tag{14}$$

$$v = \frac{(\varDelta T_B + \varDelta T_C)}{(\varDelta T_A + \varDelta T_C)}V_{in} \tag{15}$$

It is interesting to mention that equations are similar to conventional positive buck boost converter equations, which are [8]:

$$i = \frac{T(T_B + T_C)}{(T_A + T_C)^2}\frac{V_{in}}{R} = \frac{T}{(T_A + T_C)}I_{Load} \tag{16}$$

$$v = \frac{(T_B + T_C)}{(T_A + T_C)}V_{in} \tag{17}$$

But in case of bidirectional positive buck boost converter ΔT_X can have negative values unlike T_X in case of unidirectional positive buck boost converter for states of *A*, *B*, *C*, and *0*.

IV. CONTROL STRATEGY AND SIMULATION RESULTS

Hysteresis control strategy has been developed for the family of topologies presented in this paper

Hysteresis control strategy is applied to step down case for topologies shown in Fig. 1, 3, 4. This control strategy is simple but has not exact control on switching frequency and dynamic transient of the system.

This control strategy applies two bands for capacitor voltage and two bands for inductor current. Crossing these bands makes commands to change switching configurations. Fig. 9 explains hysteresis control strategy for bidirectional positive buck boost converter in step down case. The topology is shown in Fig. 4.

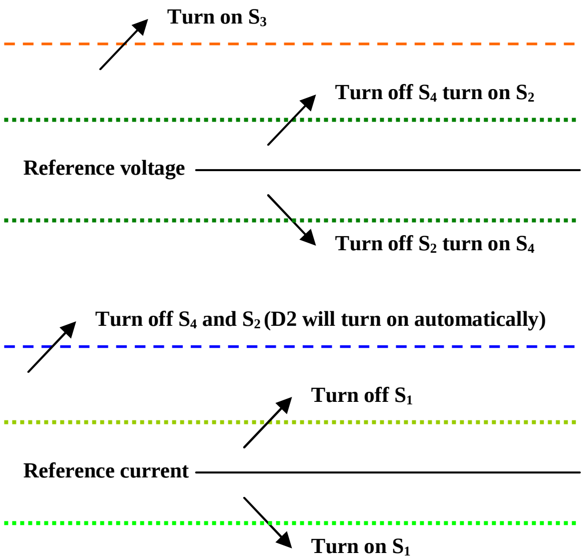

Figure 9: looking at Fig 4 the hysteresis control strategy for step down case is explained here.

Fig. 10 shows the simulation results for step conventional, wide band and bidirectional positive buck boost converters which are controlled by hysteresis strategy.

In all cases the input voltage is constantly 100V and output resistance is constantly 10 ohms.

The controller keeps the inductor current twice as minimum required current in all cases

Comparing the plots shown in Fig. 10 can be seen that the reference voltage has been changed to 80V from 20V and at 0.01sec and back to 20 from 80 at 0.03sec.

The voltage and current rise in all of the cases is same it could be quicken by increasing stored current in the inductor.

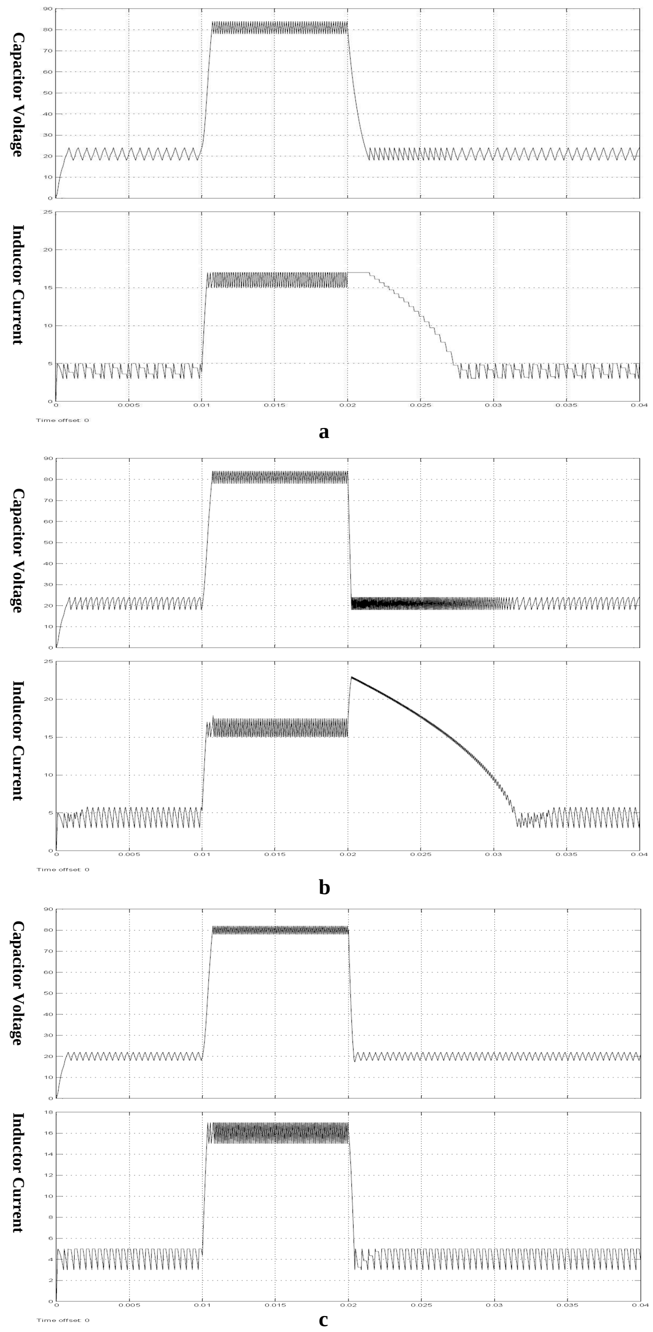

Figure 10: a) Conventional PBB (topology: Fig. 1)
b) Wide band PBB (topology: Fig. 3)
c) Bidirectional PBB (topology: Fig. 4)

Voltage drop is almost same in (a) and (b) where switch S_3 has been used. But current has risen in (b) because the topology is not bidirectional and the extra energy of the capacitor is transferred to the inductor.

In (c) the extra energy of the capacitor has been directed to the source by Diode D_2 which is included in bidirectional topology shown in Fig. 4. Looking closer at (c) the voltage drop is slightly slower than (b) the reason is transfer of energy to the source and then lower inductor current during voltage drop.

V. CONCLUSION

A family of DC-DC converter topologies based on positive Buck Boost converter are introduced. The main approach is to apply PBB's capacity for current storage to increase band width of theses converters without increasing switching frequency.

Also a bidirectional fast response topology has been derived from PBB.

These topologies have been controlled by hysteresis control strategies. Simulation results have been presented.

VI. ACKNOWLEDGMENT

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