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A New DC-DC Converter with Multi Output: Topology and Control Strategies

Arash A Boora, *Student Member, IEEE*, Firuz Zare, *Senior member, IEEE*, Gerard Ledwich, *Senior member, IEEE*,
Arindam Ghosh, *Fellow, IEEE*
School of Engineering Systems
Queensland University of Technology
arash.boora@student.qut.edu.au

***Abstract* -This paper presents a new topology based on a Positive Buck-Boost converter with multi output (MOPBB). A single output positive Buck-Boost converter consists of a Buck and Boost converters in cascade which can be controlled against input voltage fluctuation and load changes. In this paper, the steady state and dynamic analyses of the proposed topology are presented along with simulation results. A control algorithm is presented to control output voltages against input voltage fluctuation and step change in load with a purely logic control system that is based on hysteresis current and voltage control. This topology is suitable for a high power multilevel converter with diode-clamped topology where a series of capacitors are required to generate different voltage levels and capacitors voltage control is an important issue in this topology.**

***Keywords*—Multi-output, DC-DC converter, Disturbance robustness,**

I. INTRODUCTION

To clarify the advantages of proposed topology in comparison with other multi-output topologies, single output Positive Buck Boost converter (PBB) circuit is shown in (Fig. 1) [1, 2, 3].

PBB has the advantage of an extra freedom degree in comparison with basic DC-DC converters of Buck Boost and Inverting Buck Boost (IBB) [1]. This extra freedom degree can be applied to decouple the inductor current and capacitor voltage.

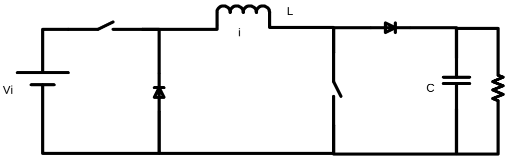

Fig. 1: Positive Buck-Boost Converter

In other words, unlike basic DC-DC converters the inductor current such as PBB is not restricted by voltage conversion ratio and load current.

The relationship between a load current (I_o) and an inductor current (I_L) in basic DC-DC converters and PBB are given in flowing equations.

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

$$I_l = \frac{I_o}{D'} = \frac{V_o}{RD'} = \frac{DV_i}{RD'^2} \qquad (2) \qquad \text{IBB}$$

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

$$I_l = \frac{1}{D'_{Boost}} I_o = \frac{1}{D'_{Boost}} \frac{V_o}{R} = \frac{D_{Buck}}{D'^2_{Boost}} \frac{V_i}{R} \qquad (4) \qquad \text{PBB}$$

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

The stored energy is utilized to increase stability of the converter and achieve robustness against input voltage fluctuation and load change.

But an extra current increase switching loss. Calculation to determine how much extra switching loss arises for any situation has been done in [1].

In this paper the Multi-Output Positive Buck Boost (MOPBB) converter is presented.

Here a multi output topology based on PBB is presented. The applications of DC-DC multi output topologies are cited in [4-7].

The main application is in diode clamp multi level inverters. [8] Has developed a multi output Boost converter for diode clamp application. The converter here can be applied for same application of inverter with the advantage of more stability, step down conversion and disturbance rejection of PBB.

The sections of this paper cover the new topology, the disturbance rejection theorization, switching frequency increase, the control method of the new topology, and simulation results

II. THE NEW MULTI-OUTPUT TOPOLOGY

A Multi Output Positive Buck Boost (MOPBB) converter is shown in Fig.2 where several output voltages are provided by putting capacitors in series. Voltages of the capacitors are controlled by the inductor current and correct switching states to share the energy stored in the inductor with each capacitor. References [4-7] are about some multi output topologies and their control strategies. The main purpose is to supply a multi level inverter.

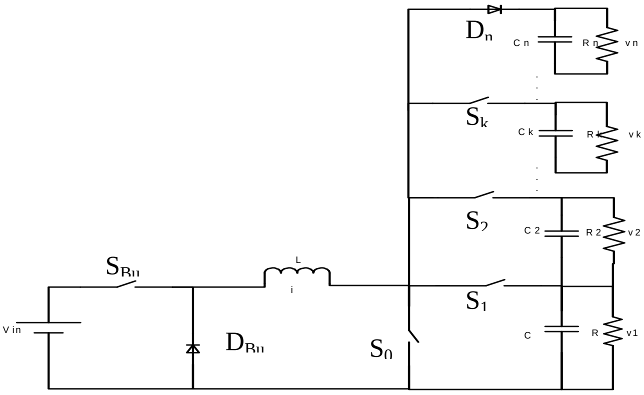

Figure 2 Multi-Output Positive Buck Boost Converter (MOPBB)

In a two output PBB converter, there are eight switching states but only 6 switching states are possible as shown in Fig.3. In this topology, when S_0 is turned on S_1 cannot be turned on as the configuration will be the same when S_1 is turned off. Thus the switching states of (011) and (111) are not allowed in this topology and the converter has six possible switching states as shown in Fig.3.

The advantage of this converter, which is achieved by input voltage switching, is that it can handle a percentage of step change in input voltage and in output current. This capability is identical to Positive Buck-Boost based converters when it comes to decrease in input voltage and increase in output load.

The above mentioned percentage of disturbance which can be dealt by the MOPBB converter without dynamics in output voltage is called disturbance margin in this paper. Disturbance margin depends on the extra current stored in inductor. The inductor current is solely dictated by load in Buck, Boost, and Inverting Buck Boost and the inductor acts only as a deliverer of energy.

Table I shows all switching states and charging and discharging states of the capacitors voltages and the inductor current. There is a switching state (010) which does not exist in the basic DC-DC converters Fig.4 and it has a significant effect on the system performance and dynamic response. Using this switching state a controller can keep the inductor current above the demand level and provide a current source in the buck converter which can charge and discharge the capacitors through the switches in the boost converter.

Table I: All possible switching states with charging and discharging states

S_{Buck}	S_0	S_1	V_{c1}	V_{c2}	I_L
0	**0**	**0**	**Charge**	**Charge**	**Discharge**
0	**0**	**1**	**Charge**	**Discharge**	**Discharge**
0	**1**	**0**	**Discharge**	**Discharge**	**No change**
1	**0**	**0**	**Charge**	**Charge**	**Discharge**
1	**0**	**1**	**Charge**	**Discharge**	**Discharge**
1	**1**	**0**	**Discharge**	**Discharge**	**Charge**

Because of 0XX switching states controller can avoid instability of inductor current easily. And because of the switching state of 010 the controller can keep some extra current in the inductor and utilize it to achieve robustness against input voltage fluctuation and load changes.

The switching configurations and states for *n* output MOPBB can be developed same as Fig. 3 and Fig. 4. The number of switching states for an *n* output MOPBB is *2(n+1)*. We calculate equations for an *n* output MOPBB.

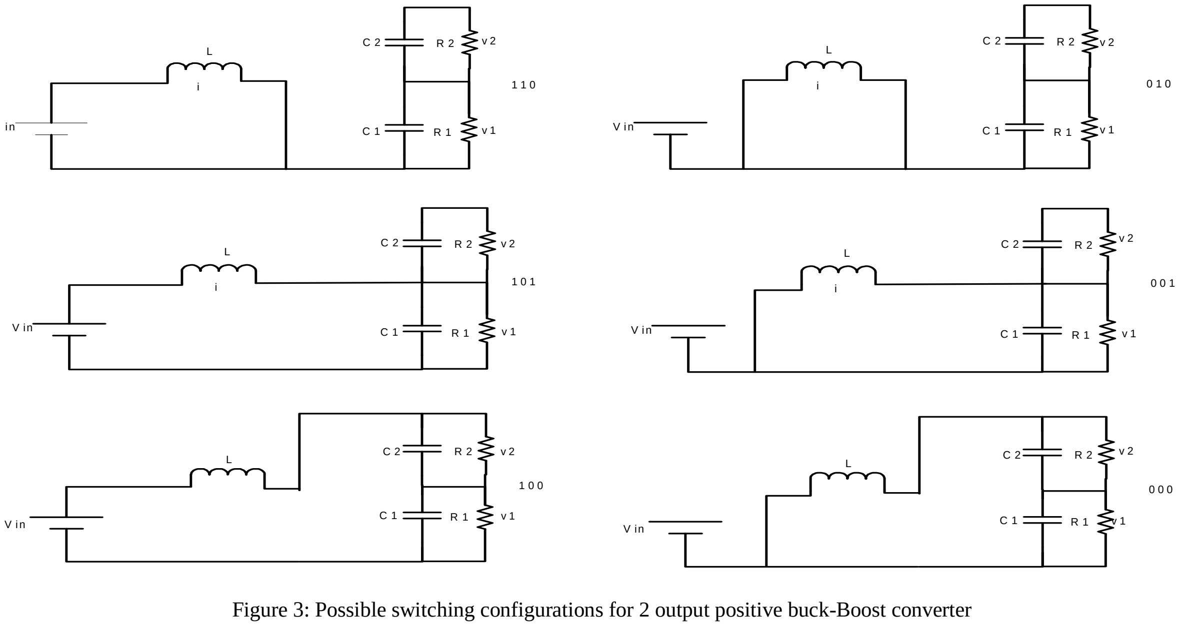

Figure 3: Possible switching configurations for 2 output positive buck-Boost converter

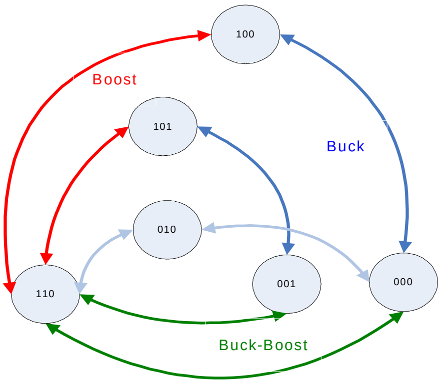

Figure 4: switching configurations and switching between them.

III. STEADY STATE AND DYNAMIC EQUATIONS

To simplify equations we use duty cycle of each switch instead of time intervals of each state. The reason is that low frequency response can be totally explained by duty cycles. D_{Bu} is the duty cycle of the Buck switch. D_0 and D_1 are the duty cycle of the switches S_0 and S_1. D_2 is the duty cycle of the output diode.

Duty cycles should satisfy:

$$\begin{array}{l} 0 \le D_j \qquad \sum_{j=0}^{n} Dj = 1 \\ 0 \le D_{Bu} \le 1 \end{array} \tag{5}$$

Using averaging technique, we can find state equations for dynamic analysis such as the inductor current and capacitors voltages in terms of the system variables.

$$L\frac{di_L}{dt} = D_{Bu} v_{in} - \left(\sum_{K=1}^{n} V_k \sum_{j=k}^{n} D_j \right) \tag{6}$$

$$C_k \frac{dv_k}{dt} = i_L \left(\sum_{j=k}^{n} D_j \right) - i_{R2} = i_L \left(\sum_{j=k}^{n} D_j \right) - \frac{v_k}{R_k} \tag{7}$$

Rewriting theses equations as state variable form:

$$\begin{pmatrix} L & 0 & 0 & 0 & 0 & 0 \\ 0 & C_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & 0 & 0 & C_k & 0 & 0 \\ 0 & 0 & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & 0 & 0 & C_n \end{pmatrix} \begin{pmatrix} \dot{i}_L \\ v_1 \\ \dots \\ v_k \\ \dots \\ v_n \end{pmatrix} = \begin{pmatrix} 0 & -\sum_{j=1}^{n} D_j & \dots & -\sum_{j=k}^{n} D_j & \dots & -D_n \\ \sum_{j=1}^{n} D_j & -1/R_1 & 0 & 0 & 0 & 0 \\ \dots & 0 & \dots & 0 & 0 & 0 \\ \sum_{j=k}^{n} D_j & 0 & 0 & -1/R_k & 0 & 0 \\ \dots & 0 & 0 & 0 & \dots & 0 \\ D_n & 0 & 0 & 0 & 0 & -1/R_n \end{pmatrix} \begin{pmatrix} i_L \\ v_1 \\ \dots \\ v_k \\ \dots \\ v_n \end{pmatrix} + \begin{pmatrix} D_{Bu} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} v_i \tag{8}$$

Extracting transfer functions from these equations:

$$v_k(s) = \frac{R_k \sum_{j=k}^{n} D_j}{R_k C_k s + 1} i \tag{9}$$

$$i_L(s) = \frac{D_{Bu}}{Ls + \sum_{k=1}^{n} \left(\frac{R_k \left(\sum_{j=k}^{n} D_j \right)^2}{R_k C_k s + 1} \right)} v_{in} \tag{10}$$

Finally, steady state equations for two output converter will be:

$$V_k = \frac{D_{Bu} R_k \sum_{j=k}^{n} D_j}{\sum_{k=1}^{n} \left(R_k \left(\sum_{j=k}^{n} D_j \right)^2 \right)} V_{in} \tag{11}$$

$$I_L = \frac{D_{Bu}}{\sum_{k=1}^{n} \left(R_k \left(\sum_{j=k}^{n} D_j \right)^2 \right)} V_{in} \tag{12}$$

According to the equations (11) and (12) we can find the effect of the switching state of (010) in dynamic response. We can chose different values for duty cycle in the buck converter, D_{Bu} to have different currents in inductor. Let us assume that we have the series of D_j and a D_{Bu} for a particular series of output voltages. By multiplying D_js and D_{Bu} by a factor of k we can change the inductor current by a factor of $1/k$ while the output voltages are unchanged. Thus, we have same output voltages for different current in inductor (13).

$$I_L = \frac{\sum_{j=1}^{n} R_j I_{Rj}^2}{D_{Bu} V_{in}} \tag{13}$$

IV. MINIMUM INDUCTOR CURRENT

There is a minimum inductor current for any case of input voltage, output voltages, and load currents. It has been shown that the controller can store some extra current in the inductor. To know how much current is stored in the inductor we need to know the minimum inductor current for each case.

The limitation of this topology is on the load current:

$$I_{R1} \ge I_{R2} \ge \dots \ge I_{Rn} \tag{14}$$

In step down case:

$$V_{in} \ge \sum_{j=1}^{n} \left(V_j \times \frac{I_{Rj}}{I_{R1}} \right) \quad \Rightarrow \quad I_{min} = I_{R1} \tag{15}$$

In step up case:

$$V_{in} < \sum_{j=1}^{n} \left(V_j \times \frac{I_{Rj}}{I_{R1}} \right) \quad \Rightarrow \quad I_{min} = \sum_{j=1}^{n} \left(\alpha_j \frac{I_{Rj}}{I_{R1}} \right) I_{R1} \tag{16}$$

The extra current stored in the inductor improves the robustness and stability of MOPBB converter against fluctuations in input voltage and load change.

On the other hand MOPBB suffers more switching frequency and switching loss as the current stored in the inductor increases.

In next section we develop the relationship between extra current stored in the inductor and the advantage of robustness (Disturbance rejection) and the disadvantage of extra switching loss. This calculation guides the user of this converter to choose how much extra current is required to be stored in the inductor according to required robustness and acceptable level of switching loss.

V. DISTURBANCE REJECTION

The extra current stored in the inductor lets MOPBB to have a margin of input voltage fluctuation and load change without “low frequency” (lower than switching frequency) effect on output voltage. In other words this extra current lets the MOPBB to block these disturbances from output voltage as far as they are inside the above mentioned margin.

The ratio of actual inductor current in any case to the minimum inductor current (γ) is important because it shows the level of robustness of this converter against input voltage fluctuations and load changes as well as level of extra switching loss arising as a consequence of extra current storage. Here we define the disturbance rejection margin as a function of γ.

$$\gamma = I_L / I_{min} \tag{17}$$

To calculate disturbance rejection margin regarding to input voltage disturbance we need to look at the relationship between D_{Bu} and γ looking at (13) and (15-16) we have:

$$\gamma = \frac{min\left\{1, \sum_{j=1}^{n}\left(\alpha_j \frac{I_{Rj}}{I_{R1}}\right)\right\}}{D_{Bu}} \tag{18}$$

The margin for input voltage rise is infinite because the controller can reduce D_{Bu} immediately without showing any dynamic at output. This way there is no limit for voltage rise disturbance rejection. When the case is input voltage drop the controller increases the D_{Bu} to let the converter has same average of voltage after Buck switch. The margin in this case depends on γ (20).

$$M^+\{V_{in}\} = \infty \tag{19}$$

$$M^- = 1 - D_{Bu} = 1 - \frac{min\left\{1, \sum_{j=1}^{n}\left(\alpha_j \frac{I_{Rj}}{I_{R1}}\right)\right\}}{\gamma} \tag{20}$$

The load disturbance rejection margin can be calculated according to equation (15, 16, and 18) we can rewrite equation (13) as:

$$I_L = \frac{\left(\sum_{j=1}^{n}\alpha_j I_{Rj}\right)}{min\left\{1, \sum_{j=1}^{n}\left(\alpha_j \frac{I_{Rj}}{I_{R1}}\right)\right\}}\gamma \tag{21}$$

Load change means the change in I_{Rj} if γ can change within one switching cycle sufficient to keep I_L, α_1, and α_2 constant the output will not experience any dynamic with frequencies lower than switching frequency. Because of stability of MOPBB the case of load drop can be handled by reducing the current conducting to load by increasing the duty cycle of boost switch. So the disturbance rejection margin in case of load drop is infinite.

$$M^-\{I_{Rj}\} = \infty \tag{22}$$

To calculate this margin for load rise we consider that load current increase by step change to full the margin of load change. To compensate this disturbance γ drops to 1.

$$\frac{\left(\sum_{j=1}^{n}\alpha_j I_{Rj}\right)}{min\left\{1, \sum_{j=1}^{n}\left(\alpha_j \frac{I_{Rj}}{I_{R1}}\right)\right\}}\gamma = \frac{\left(\sum_{j=1}^{n}\alpha_j\left(1+M^+\{I_{Rj}\}\right)I_{Rj}\right)}{min\left\{1, \sum_{j=1}^{n}\left(\alpha_j \frac{\left(1+M^+\{I_{Rj}\}\right)I_{Rj}}{\left(1+M^+\{I_{R1}\}\right)I_{R1}}\right)\right\}} \tag{23}$$

If we assume that same margin for all loads is required,

$$M^+\{I_{Rj}\} = \gamma - 1 \tag{24}$$

Of course if the loads have different sensitivity the controller can devote the stored current to the more sensitive loads or share it asymmetrically which means having wider load change margin for more sensitive loads.

Fig. 5 shows the graph or the relation ship between extra current stored in the inductor and robustness margins.

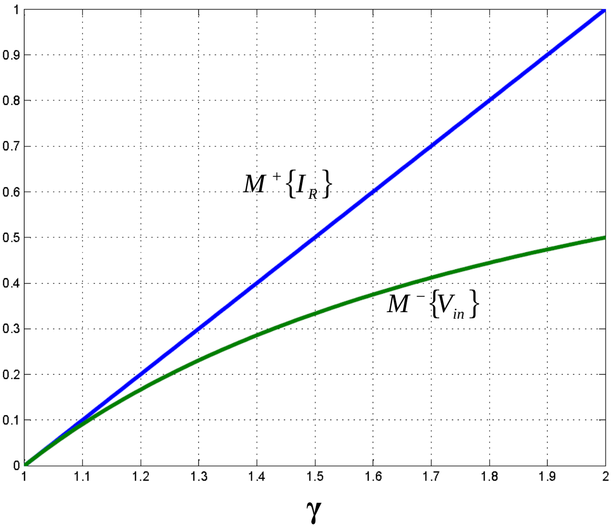

Figure 5 disturbance rejection margins as a function of γ

VI. SWITCHING FREQUENCY

The main disadvantage of extra current stored in the inductor is the increased switching frequency and loss. To have an efficient design for any particular application, the calculation of switching loss is important.

According to equations (11) and (12)

$$\sum_{j=k}^{n} D_j = I_{Rk} / I_L \tag{25}$$

Looking at the switching configuration at Fig. 3, V_2 and V_1 have their rise on the times periods of $D_2 T_{sw}$ and $(D_1+D_2).Tsw$ respectively. For n output MOPBB we have:

$$C_k \Delta V_k = T_{swBoost}\sum_{j=k}^{n} D_j (I_L - I_{Rk}) \tag{26}$$

According to (26) the ripples of Vk’s are dependent. So switching cycle of the Boost switch can be calculated as (27).

$$T_{swBoost} = min\left\{\frac{C_k \Delta V_k I_L}{I_{Rk}(I_L - I_{Rk})}\right\} \qquad k = 1,...,n \tag{27}$$

To have the switching cycle as a function of γ we apply equation (21):

$$Step\ Down: \quad T_{swBoost} = min\left\{\frac{C_k \Delta V_k \gamma I_{R1}}{I_{Rk}(\gamma I_{R1} - I_{Rk})}\right\}$$

$$stepUp: \quad T_{swBoost} = min\left\{\frac{C_k \Delta V_k \gamma\left(\sum_{j=1}^{n}\alpha_j I_{Rj}\right)}{I_{Rk}\left(\gamma\left(\sum_{j=1}^{n}\alpha_j I_{Rj}\right) - I_{Rk}\right)}\right\} \tag{28}$$

Inductor current (I_L) is defined by (21). To calculate the Buck switching frequency, the average of positive voltage exposed to the inductor end connecting to the Boost switch is:

$$V_{avgBoost} = \sum_{k=1}^{n}\left(V_k \sum_{j=k}^{n} D_j\right) \tag{29}$$

So the rise time and fall time of the inductor current will be:

$$-\frac{L\Delta I_L}{T_{fall}} = -\sum_{k=1}^{n}\left(V_k \sum_{j=k}^{n} D_j\right) \Rightarrow T_{fall} = \frac{L\Delta I_L}{\sum_{k=1}^{n}\left(V_k \sum_{j=k}^{n} D_j\right)} \tag{30}$$

$$\frac{L\Delta I_L}{T_{rise}} = V_{in} - \sum_{k=1}^{n}\left(V_k \sum_{j=k}^{n} D_j\right) \Rightarrow T_{rise} = \frac{L\Delta I_L}{V_{in} - \sum_{k=1}^{n}\left(V_k \sum_{j=k}^{n} D_j\right)}$$

The switching frequency of Buck switch will be:

$$\begin{aligned} T_{swBuck} &= T_{fall} + T_{rise} \\ &= \frac{L\Delta I_L}{\sum_{k=1}^{n}\left(\alpha_k \sum_{j=k}^{n} D_j\right)\left(1 - \sum_{k=1}^{n}\left(\alpha_k \sum_{j=k}^{n} D_j\right)\right)} \\ &= \frac{L\Delta I_L \times I_L}{\sum_{k=1}^{n}(\alpha_k I_{Rk})\left(I_L - \sum_{k=1}^{n}(\alpha_k I_{Rk})\right)} \end{aligned} \tag{31}$$

For step up and step down case the equation of Buck switch frequency will be:

$$stepDown: \quad T_{swBuck} = \frac{L\Delta I_L \gamma I_{R1}}{\sum_{k=1}^{n}(\alpha_k I_{Rk})\left(\gamma I_{R1} - \sum_{k=1}^{n}(\alpha_k I_{Rk})\right)}$$

$$stepUp: \quad T_{swBuck} = \frac{L\Delta I_L \gamma \sum_{j=1}^{n}\alpha_j I_{Rj}}{\sum_{k=1}^{n}(\alpha_k I_{Rk})\left(\gamma \sum_{j=1}^{n}\alpha_j I_{Rj} - \sum_{k=1}^{n}(\alpha_k I_{Rk})\right)} \tag{32}$$

Fig 6 shows the switching frequency of Buck and Boost switches as function of γ for cases of step up and step down.

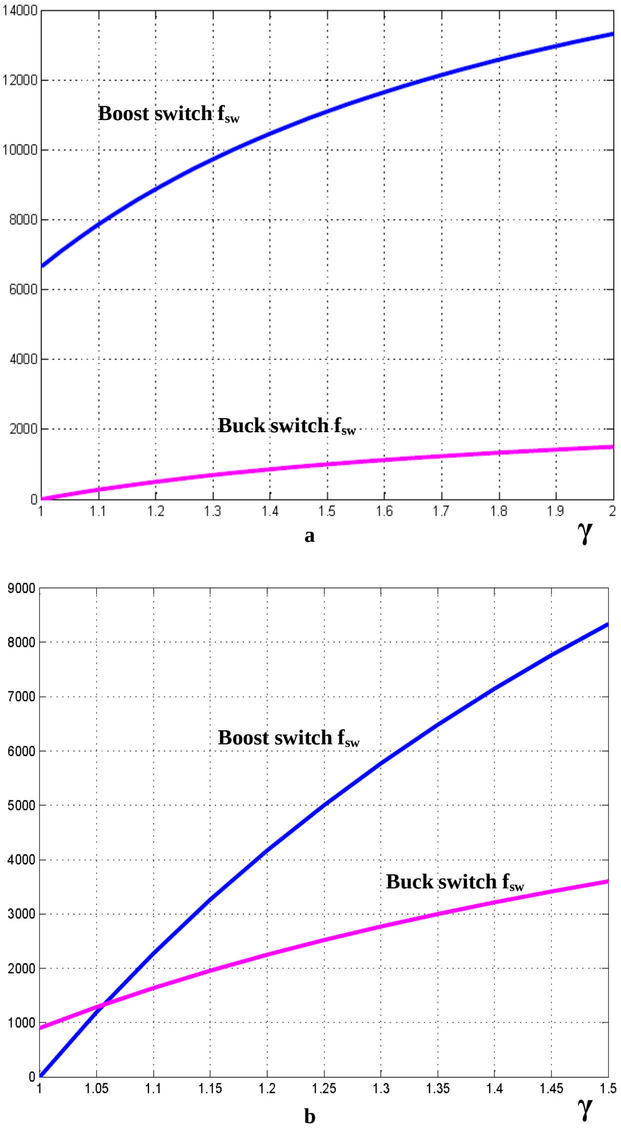

Figure 6 the relationship between switching frequency of Buck switch (purple) and Boost switches (blue) as a function of γ: a) step up b) step down ($I_{R1}=I_{R2}$)

As is shown in Fig. 6a the frequency of buck switch is 0 when γ is 1. This means that in step up case if the inductor current be equal to its minimum value the converter is working as a multi output Boost converter (eliminating S_{Bu} in Fig. 2). In Fig. 6b the switching frequency of Boost switch is 0 when γ is 1. This means that in step down case the converter is working as a multi output Buck (eliminating S_0 in Fig. 2) converter when there is no extra current stored in the inductor.

Comparing the Fig. 6a and Fig. 6b, the main switching frequency increase is happening for Boost switches. Particularly, for step up case the switching frequency of the Buck switch is negligible in comparison to the switching frequency of Boost switches.

VII. CONTROL STRATEGY AND SIMULATION RESULT

In this paper the method of Hysteresis control for inductor current and output capacitor voltage are explained.

Because PBB based topologies can decouple inductor current and capacitor voltage by storing some extra current in the capacitor, the control system will have enough freedom to use hysteresis control both for inductor current and capacitor at the same time.

However to have desirable performance the capacitor voltage hysteresis controller needs to consider the inductor as a current source with acceptable fluctuations, so the current loop controller should be faster than the voltage control loop.

The main challenge of this controller is to know the appropriate inductor current. The controller needs to detect the minimum required current to be able to keep the reference voltage at output. On the other hand controller should decide about the level of extra current needed to be stored in the inductor to achieve robustness and stability required by application. In this paper the ratio of actual inductor current to minimum required current is called γ.

Equation 14 suggests to measure I_L, V_{in}, D_{Bu} and estimate load current and extra current storage in the inductor. The controller is responsible to keep enough current stored in the inductor to achieve robustness against disturbances (Eq. 16 and 20) but not too much current should be stored because the switching frequency and loss will be increased (Eq 24 and 27).

Fig. 7 shows the control strategy for a two output MOPBB. The duty cycle of Buck switch is used to control the level of extra current stored in the inductor.

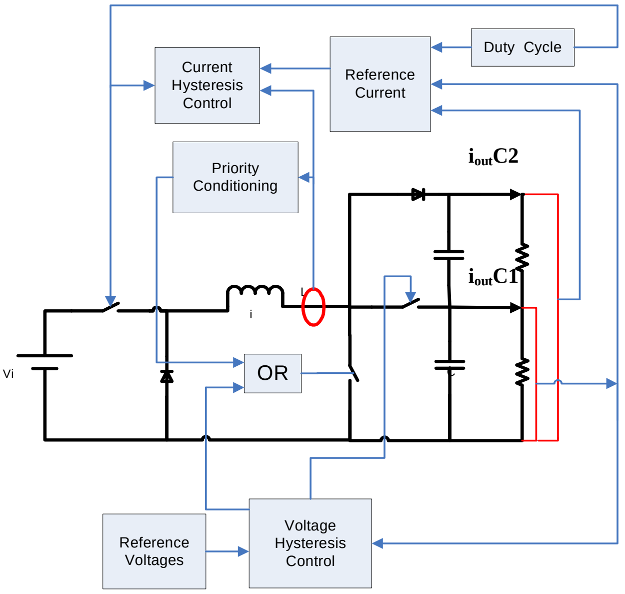

Figure 7 hysteresis control system of MOPBB

The inductor current and both output voltages are controlled by hysteresis method. Fig. 8 shows some simulation results of this control system. The aim of this simulation is to show the robustness of this topology against disturbances in input voltage and load. The level of extra current is between 25% and 40% ($1.25<\gamma<1.4$) to keep output voltages constant in spite of dramatic changes in load and input voltage.

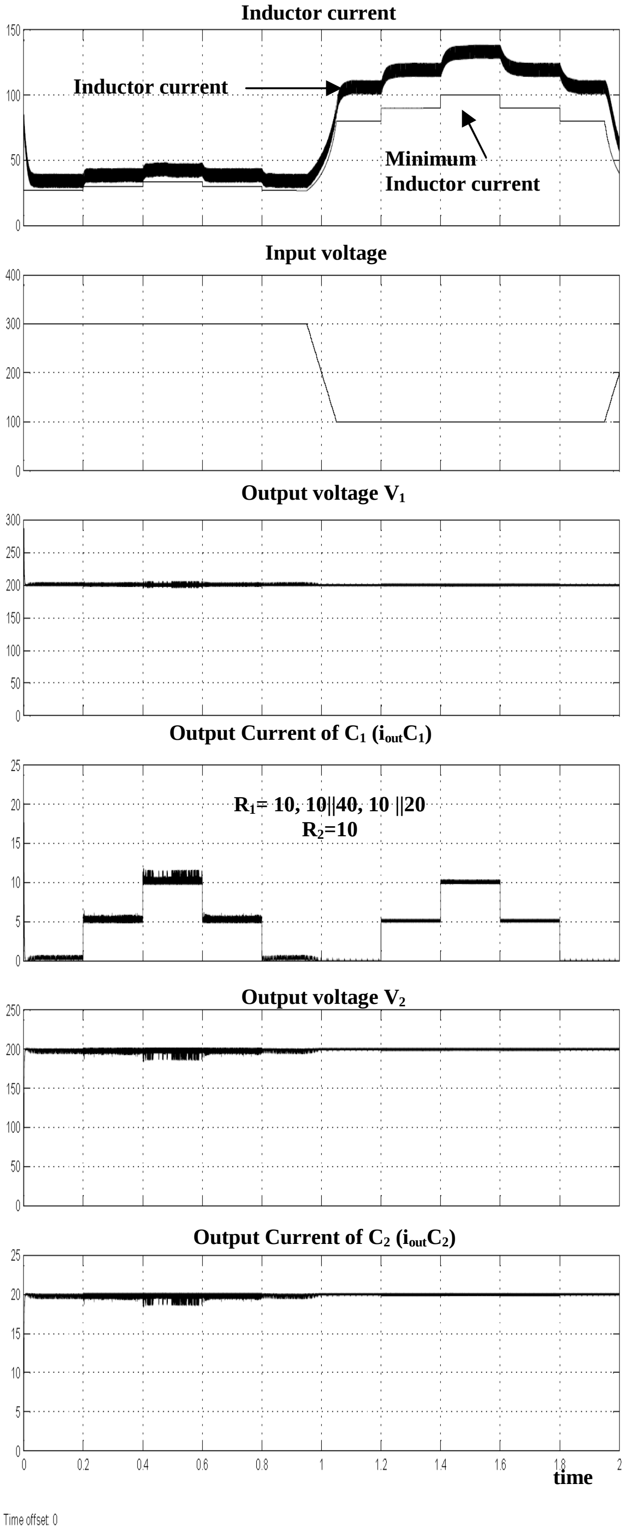

Figure 8 simulation results of the hysteresis control system for MOPBB when input voltage and R_1 change

Fig. 9 shows the same parameters in Fig 8 when input voltage and R_2 change. In both cases all the changes have been in side the disturbance rejection margins. So the output voltages do not endure low frequency dynamics.

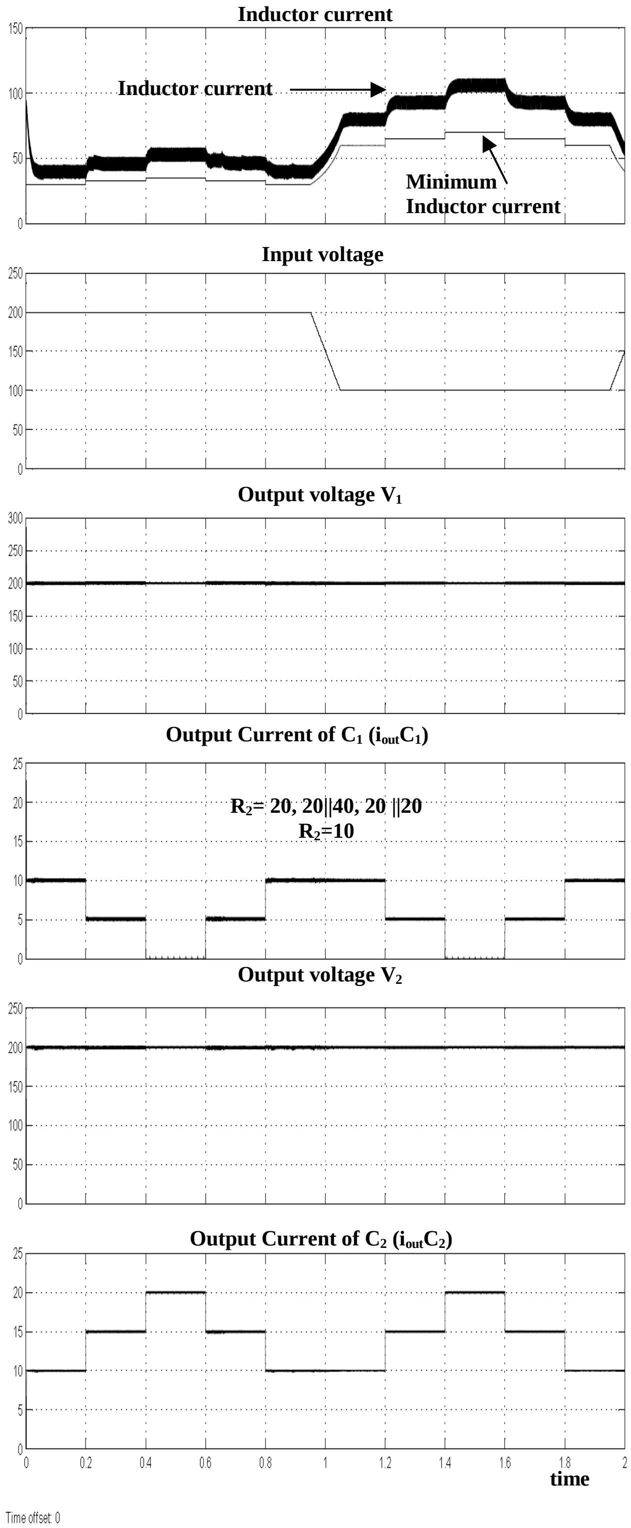

Figure 9 simulation results of the hysteresis control system for MOPBB when input voltage and R_2 change

VIII. CONCLUSION

A multi output DC-DC converter based on positive Buck Boost converter is introduce.

Positive Buck Boost converter also known as noninverting Buck Boost converter has the advantage of an extra freedom degree. This paper has shown the possibility of utilizing this freedom degree to store a level of extra current in the inductor to achieve robustness against input and output disturbances. The calculation to show the degree of robustness as the advantage of extra current stored in the inductor has been developed. The increase in switching frequency as a disadvantage of storing extra current in the inductor is theorized and formulated. A control strategy has been developed and simulated at last.

The designer of the implementation of this topology and its control strategy should consider the requirements of a particular application, level of input and Load disturbances, and allowed switching frequency and switching loss in that application to decide how much extra current should be stored in the inductor of MOPBB.

IX. ACKNOWLEDGMENT

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