A Multiple-Input DC-DC Converter Topology

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***Abstract*—A new topology for multiple energy source conversion is presented. The topology is capable of interfacing sources of different voltage-current characteristics to a common load, while achieving a low part count. A fixed frequency switching strategy is investigated and the resulting operating modes are analyzed. The analysis is verified by experimentation. The results show that the converter is an enabling technology for power diversification and optimization.**

***Index Terms*—dc-dc convertor, hybrid energy system, multiple-input-multiple-output (MIMO).**

I. Introduction

Most electrical systems are supplied by one kind of energy source, whether it is batteries, wind, solar, utility, etc. Certain special cases are powered by two sources, such as, uninterruptible power supplies. Future power systems will require interfacing of energy sources of all kinds. Renewable energy sources will be of particular interest, especially as resources are further distributed about the terrestrial power grid. In islanded power systems, interfacing of multiple sources allows for improved reliability, flexibility, and utilization of preferred energy sources. The different sources — such as photovoltaic cells, fuel cells, and batteries — will have different voltage and current characteristics. In most cases, one source may be preferential to others, or perhaps, a simultaneous combination of sources is appropriate for optimal energy/economic use. Therefore, multiple-input power converters are required to enable multiple-source technology. Such converters have received limited attention, thus far. A topology for achieving combinations of multiple dc sources is presented. The different operating modes are investigated and verified by experimentation.

With multiple inputs, the energy source is diversified to increase reliability and utilization of renewable sources. An ideal multiple-input power supply could accommodate a variety of sources and combine their advantages automatically, such that the inputs are interchangeable. Such a converter could be relocated and still take advantage of the local environment, e.g., in some areas solar power would be readily accommodated, in others, utility power may be especially reliable or inexpensive.

Many of the renewable sources have dc voltage and current characteristics. Therefore, a multiple–input dc–dc converter is of practical use. In this paper, we present a topology capable of accommodating a number of inputs. The topology is derived from the buck-boost converter. In [1], a multiple-input flyback converter was shown. However, the converter proposed here has a reduced parts count while retaining the same capability. In [2], the work in [1] is extended to include a forward-type multiple-input converter. In [3], a multiple-input converter was shown for the context of hybrid vehicles. The architecture in [3] is that of parallel two-switch phase legs. This can have higher parts count than is necessary, but does have straightforward means of bidirectional power flow. In [4], a simplified converter relative to that in [3] is proposed for a unidirectional wind/photovoltaic system. The proposed converter is directly applicable to dc–dc systems and has minimal parts count. The scope of the paper is to introduce the topology, set forth the continuous and discontinuous mode equations, and to demonstrate the capability through a few experiments. Future work will address finer points such as control, converter nonidealities, power sharing, duty cycle limits, and isolation issues.

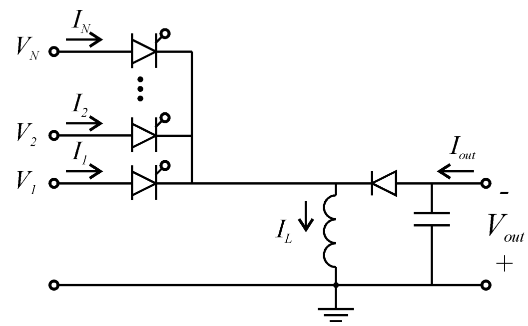

Fig. 1. Multiple-input buck-boost converter.

II. Circuit Topology and Analysis

The general circuit topology for a multiple-input buck-boost converter (MIBB) is shown in Fig. 1. There are N input voltages $V_1, V_2, \ldots V_N$ and N input currents $I_1, I_2 \ldots I_N$. The inputs are interfaced through a forward-conducting-bidirectional-blocking (FCBB) switch. The switch can be realized as a gate turn-off (GTO) thyristor, a series MOSFET and diode pair, or several other switch combinations. The inputs share a common inductance L and the output capacitance is C. The output voltage and current are V_{out} and I_{out}, respectively.

This configuration, as shown, allows for only unidirectional power flow. For sources such as primary batteries, solar cells, and fuel cells, this is sufficient. For bidirectional power flow, V_{out} serves as the input to another converter that has V_1 as the output, for example. In fact, it is not necessarily intended that V_{out} is the final output of the total converter system. It may or may not be a regulated voltage. It can feed other converters that are tightly regulated to different voltages, or it can be fed back to one of the sources. In that way, a bidirectional multiple-input multiple-output converter can be constructed. The concept is illustrated in Fig. 2, but the details are beyond the scope of this work.

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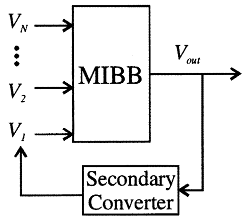

Fig. 2. Conceptual use of MIBB for bidirectional energy sources.

As shown, the converter has a negatively referenced output. This is only by the convention used here, but of course can be reversed. Many of the possible sources used, such as batteries, solar cells, and fuel cells, have naturally floating inputs that will allow reversal of their terminals with respect to the traditional ground convention. If isolation and/or voltage reversal is required, then a double-winding inductor can be substituted for the single-winding one. An advantage of this scheme is that the inductor is shared by all the inputs. By decoding of the gate signals and sampling of the inductor current, all the input currents can be monitored with only one sensor. Another advantage is that with the switching strategy proposed below, all but one of the active switches turn on with zero current.

A. Continuous Conduction Mode

If the inductor current, I_L, is greater than zero in the steady-state, continuous conduction mode results. This guarantees that at least one FCBB switch or the diode is conducting at all times. In the steady state, the average inductor voltage is zero and we will assume that the output capacitor is sufficiently large as to make the output voltage almost constant. If any active switch is on, the diode is off, but if all switches are off, then the diode is on and the inductor voltage is $v_L = -V_{out}$. If several active switches are on, then the inductor voltage is equal to the highest of the voltages for which the respective switch is on. Labeling the binary (0 or 1 value) switching signals q_i

$$v_L = \max_i (q_i V_i) - V_{out} \prod_i \bar{q}_i. \tag{1}$$

Setting the average of (1) to zero and solving

$$V_{out} = \frac{\int_0^T \max_i (q_i V_i)\, dt}{\int_0^T \prod_i \bar{q}_i dt}. \tag{2}$$

Consider a duty cycle control scheme where each switch switches at the same frequency and the leading edge of each gate signal, q_i, coincides (see Fig. 3). The trailing edges do not coincide, as each switch has a different duty cycle, D_i. Then (2) simplifies to

$$V_{out} = \frac{\sum_i D_{eff(i)} V_i}{1 - \max_i (D_i)} \tag{3}$$

where $D_{eff(i)}$ is the effective duty cycle of each switch; that is, the portion of time the switch conducts nonzero current. If the voltage indices are arbitrarily ordered such that $V_1 > V_2 > \cdots > V_N$, then

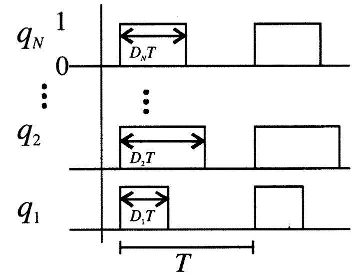

Fig. 3. Example switch strategy.

$$D_{eff(i)} = \begin{cases} 0, & D_i < \sum_{j=1}^{i-1} D_{eff(j)} \\ D_i - \sum_{j=1}^{i-1} D_{eff(j)}, & D_i \geq \sum_{j=1}^{i-1} D_{eff(j)}. \end{cases} \tag{4}$$

For example, a two-input converter, there are only two possibilities: if $D_1 > D_2$, then

$$V_{out} = \frac{D_1}{1 - D_1} V_1 \tag{5}$$

or, if $D_2 > D_1$, then

$$V_{out} = \frac{D_1 V_1 + (D_2 - D_1) V_2}{1 - D_2}. \tag{6}$$

In general, the number of possible combinations of duty cycle relationships, and therefore the number of different forms of the output voltage equation, is $K_N = N K_{N-1}$, where $K_1 = 1$. Equation (5) is that of a normal buck-boost converter- the lower voltage source, V_2 does not enter in. Equation (6) is the form that allows simultaneous contribution from both sources. Note, that if we want contribution only from source 2, then let $D_1 = 0$ and we have a standard buck-boost from source 2. If the input voltages change such that source 2 exceeds source 1, we simply renumber the sources to accommodate the equations.

The average inductor current, by KCL, is

$$I_L = \frac{I_{out}}{1 - \sum_j D_{eff(j)}} \tag{7}$$

and the peak-to-peak inductor current ripple is

$$|\Delta i_L| = \frac{V_{out}}{L} \left[1 - \max_i (D_i) \right] T. \tag{8}$$

when approximating the inductor time constant as long compared to the period, T. The output voltage ripple is approximated with the same assumption as

$$|\Delta v_C| = \frac{I_{out}}{C} \left[\max_i (D_i) \right] T. \tag{9}$$

B. Discontinuous Conduction Mode

Discontinuous mode is important to consider due to completeness and the possible advantages of a small inductor and higher output voltage. In the case of the MIBB, there is to be a

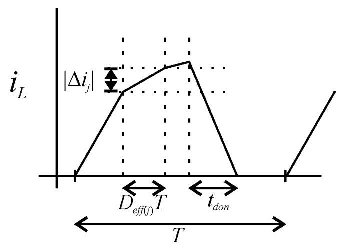

Fig. 4. Illustration of discontinuous inductor current.

lot of versatility in the input sources. It may be an unreasonable constraint to impose a minimum inductor current (in order to assure continuity) when trying to optimize the contributions from all sources connected. Therefore, discontinuous mode may be an essential aspect of multiple-input converter control.

Only one switch conducts at a time. Assuming the time constant of the inductor is slow compared to the time a given switch is on, the change in inductor current during the jth interval is

$$|\Delta i_j| = \frac{V_j}{L} D_{eff(j)} T \tag{10}$$

where T is the period. The total change in current in the positive direction is the sum of all (refer to Fig. 4). Since in discontinuous mode, the current starts from zero each cycle

$$i_p = \sum_j |\Delta i_j| = \frac{T}{L} \sum_j D_{eff(j)} V_j. \tag{11}$$

Once all switches are gated off, the diode conducts until its current (the inductor current) returns to zero. Again, assuming a time constant relatively large compared to the period

$$t_{don} = \frac{i_p L}{V_{out}} \tag{12}$$

is the time it takes for the inductor to completely discharge and the time the diode is on each cycle. The time the diode is off each cycle is then $T - t_{don} = t_{doff}$.

The voltage ripple on the capacitor can be calculated by assuming a discharge that is slow compared to the switching period. The discharge occurs while the diode is off, so

$$|\Delta v_{out}| = \frac{I_{out}}{C} t_{doff}. \tag{13}$$

The inductor energy stored at the instant the diode turns on is $0.5 L i_p^2$. All of this energy passes to the load and capacitor. The capacitor voltage increases by $|\Delta v_{out}|$ from $0.5C\left(V_{out} - \Delta v/2\right)^2$ to $0.5C\left(V_{out} + \Delta v/2\right)^2$ in the time t_{don}, for a net energy change of $C V_{out} \Delta v$. The energy passing to the load during the inductor discharge is $V_{out} I_{out} t_{don}$. This yields the energy balance

$$\frac{1}{2} L i_p^2 = C V_{out} \Delta v + V_{out} I_{out} t_{don}. \tag{14}$$

Substituting (13) and (12), assuming a resistive load, R, and solving for V_{out},

$$V_{out} = i_p \sqrt{\frac{RL}{2T}}. \tag{15}$$

Equation (15) is very similar to that of an ordinary buck-boost converter. It is very sensitive to parameters as we expect for discontinuous mode in general for dc–dc converters. It will usually be necessary to employ feedback control if a specific output voltage is required.

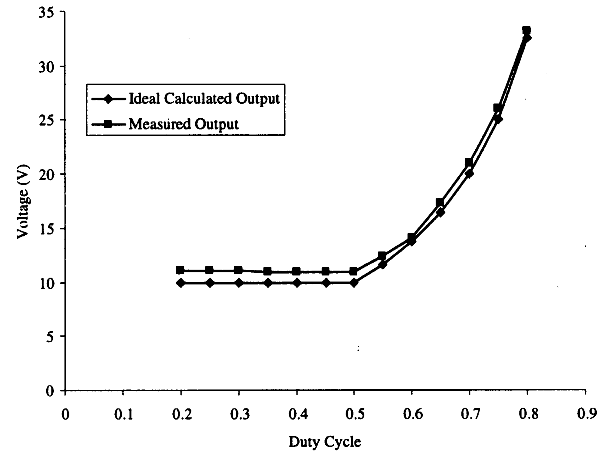

Fig. 5. Continuous mode operation with the D_2 varied and $D_1 = 0.5$.

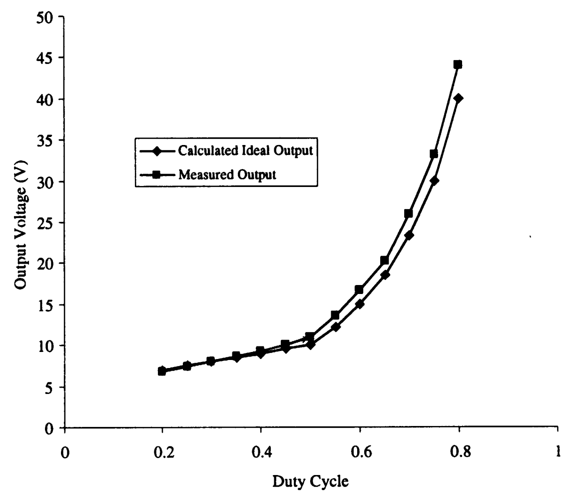

Fig. 6. Continuous mode operation with the D_1 varied and $D_2 = 0.5$.

III. Experimental Examples

In an experimental, two-input setup, the two modes are demonstrated and compared with the equations presented. For the continuous mode, the two inputs voltages are 10 V and 5 V. The inductance is 4.84 mH (series 0.25 ohm resistance). The capacitance is 1000 μF. The MOSFETs used are IRF520's and the diodes are MBR 360's. The switching frequency is 50 kHz. In Fig. 5, the average output voltage is plotted versus the idealized (no switch or parasitic loss) predictions. The duty cycle of the 10 V source input is 0.5, while the other duty cycle D_2 is varied. Once D_2 exceeds D_1, the converter no longer behaves like an ordinary buck-boost: the output voltage increases significantly as shown. In Fig. 6, the conditions are the same except D_1 is varied and $D_2 = 0.5$. In this case, the output voltage never behaves like that of a typical buck-boost converter since either $D_1 < D_2$ or if otherwise, $V_1 > V_2$. Again, the measured and predicted data are in good agreement. In both Figs. 5 and 6, the difference in results is mainly due to unmodeled switch drops.

To show the discontinuous mode operation, a similar study was conducted. The switching frequency was reduced to 5 kHz, the inductance to 1 mH (series resistance 0.1 Ω), and $D_1 = 0.2$. The MOSFET's used (MTW16N40E-I) have on-state resistance

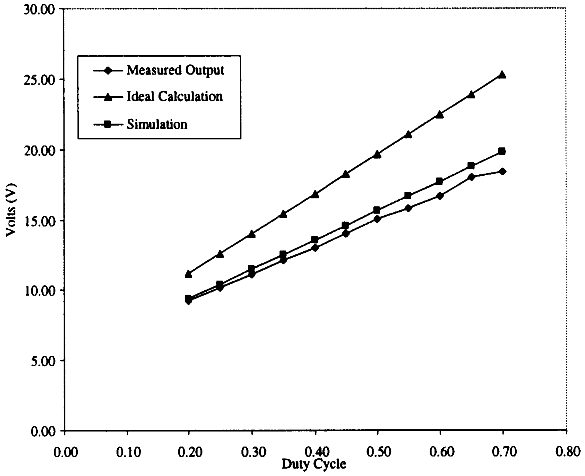

Fig. 7. Discontinous mode with D_2 varied and $D_1 = 0.2$.

of 0.24 Ω and the diodes and voltage sources are the same as before. D_2 was varied and the output voltage was recorded. In Fig. 7, the results are shown as measured, as predicted by a detailed (device level) simulation, and as calculated for the ideal case (15). The ideal case was verified separately through simulation with ideal components. Though the ideal case shows the correct trend, there is error since discontinuous mode is very sensitive to the circuit parameters and timing, as expected. The simulation shows that the experiment is predictable if parasitic aspects of the circuit are considered (switch on-state voltages, passive component resistance, timing delays, etc.). Therefore, the idealized equation is only useful in the sense of predicting a trend or an upper bound. As with the continuous mode, the equation can be improved by including the effects of the parasitics in the mathematical development.

IV. Conclusions

A new topology for dc–dc converters was presented. The topology is capable of supporting multiple inputs and shows promise for achieving diversification of multiple energy sources. Idealized equations were presented for the converter as an aid to design and a basis for control development. Some experimental results were presented for the two-input case.

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