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Synthesis of Double-Input DC-DC Converters Using a Single-Pole Triple-Throw Switch as a Building Block

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***Abstract*—Hybridizing power electronic systems using an energy storage unit has gained popularity in transportation and power system applications. This task has traditionally been performed by using several independent power electronic converters. Multi-input converters, due to their reduced part count and improved efficiency, seem to be an advantageous option to replace the conventional converters. A few multi-input converter topologies have been reported in the literature; however, there is not a systematic approach to derive them. Furthermore, all possible topologies are not completely explored and it is difficult to derive new converters from the existing topologies. Hence, in this paper, a systematic approach to derive multi-input converters by using single-pole triple-throw switches as building blocks is presented.**

I. Introduction

Double-input converters have gained popularity in power electronic application including power factor correction, photo voltaic systems, fuel cell systems, and hybrid electric vehicles. In these applications, utilizing energy storage is inevitable as the instantaneous values of input and output powers are not equal [1-6]. The energy storage unit can be comprised of batteries, capacitors, or ultracapacitors.

In order to combine the main source of power with the energy storage unit, either two independent converters or a single double-input converter can be used. The advantages of using a double-input converter are high efficiency, reduced component count, low cost, and control simplicity. In this paper a single-pole triple-throw (SPTT) switch is used as a building block to realize three new double-input dc-dc converters.

Fig. 1 shows the basic representation of an SPTT switch. At any given time, pole is connected to one and only one of the throws. An SPTT switch can be realized by using three single-pole single-throw (SPST) switches, as depicted in Fig. 2. It is worth mentioning that one and only one of the three switches is on at any time instant [7].

In this paper, SPTT switches are utilized as building blocks to create new double-input converter topologies. Three new double-input dc-dc converters are proposed in Section II. The operating modes of the new converters as well as their voltage transfer ratios are also presented. In Section III, the switch realization of the converters is discussed. The simulations results to verify the converter characteristics are presented in Section IV. Finally, Section V draws the concluding remarks.

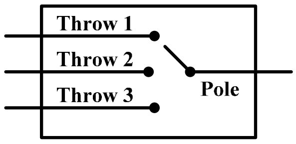

Fig. 1. Single-pole triple-throw switch (SPTT)

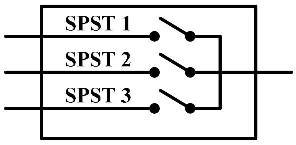

Fig. 2. SPTT switch realized using three SPST switches

II. Derivation of New Double-Input Converters Using an SPTT Switch

Figs. 3, 4, and 5 show the circuit diagram of the new double-input converters using an SPTT switch. These new converters are named double-input buck, double-input buckboost, and double-input buckboost-buck, respectively. It is worth mentioning that only one inductor is used in the structure of these converters. These converters are derived using basic power electronic converter topologies reported in the literature [8-17]. Fig. 6 shows the circuit diagram of the double-input buck converter using three SPST switches instead of a single SPTT switch. Voltage source V_1 can be made to deliver power by keeping the switch at position 1, voltage source V_2 can be made to deliver power by keeping the switch at position 2, and position 3 can be used for freewheeling purposes. Fig. 7 shows the switching patterns of three switches S_1, S_2, and S_3. The pattern is true for all the possible arrangements of the converter. Three modes of operation that occur under unidirectional power flow are explained in Table I concentrating on the voltages across the inductor. Modes of operation for the double-input buckboost and buckboost-buck converters are given in Tables II and III.

One can observe from Fig. 7 that T_1 is the on time of switch S_1, T_2 is the on time of switch S_2, and T_3 is the on time of switch S_3. Hence,

$$T_1 = d_1 * T,\ T_2 = d_2 * T,\ \text{and}\ T_3 = d_3 * T. \qquad (1)$$

Where T is the switching period and d_1, d_2, and d_3 are the duty cycles of switches S_1, S_2, and S_3, respectively. Considering the double-input buck converter, one can write the following equations based on Fig. 7, Table I, and volt-second balance equation of the inductor.

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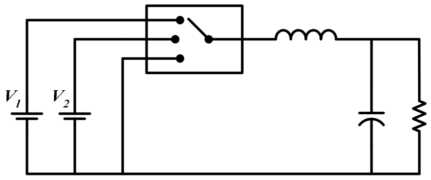

Fig. 3. Double-input buck converter using an SPTT switch.

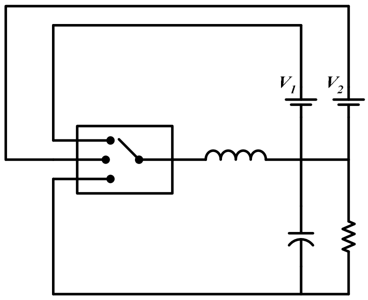

Fig. 4. Double-input buckboost converter using an SPTT switch.

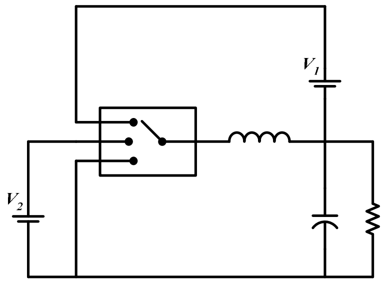

Fig. 5. Double-input buckboost-buck converter using an SPTT switch.

$$T_1 + T_2 + T_3 = T \tag{2}$$

$$T_1 * (V_1 - V_O) + T_2 * (V_2 - V_O) + T_3(-V_O) = 0 \tag{3}$$

This can be simplified as the following equation

$$V_1 * T_1 + V_2 * T_2 = V_O * (T_1 + T_2 + T_3) \tag{4}$$

Combining equations (1), (2), and (4) one can obtain the following equation which describes the relation between input and output voltages.

$$V_O = d_1 * V_1 + d_2 * V_2 \tag{5}$$

Voltage transfer ratios of the new double-input buckboost and buckboost-buck converters are given in (6) and (7), respectively.

$$V_O = \frac{d_1}{1 - d_1 - d_2} * V_1 + \frac{d_2}{1 - d_1 - d_2} * V_2 \tag{6}$$

$$V_O = \frac{d_1}{1 - d_1} * V_1 + \frac{d_2}{1 - d_1} * V_2 \tag{7}$$

III. Switch Realization for the New Double-Input Converter Topologies

In the double-input buck converter depicted in Fig. 6, SPST switches S_1, S_2, and S_3 can be realized using diodes and transistors. Switch realization depends on the input and output voltage levels as well as the power flow direction. Assuming that the power flow is from left to right (or $i_L > 0$), one can argue

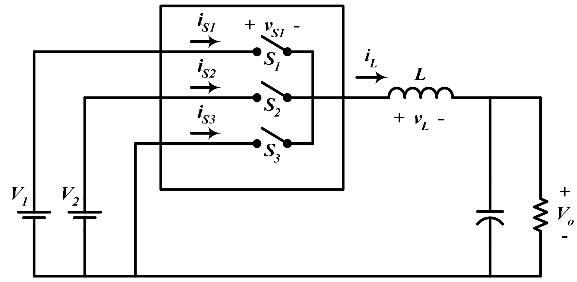

Fig. 6. Double-input buck converter using three SPST switches

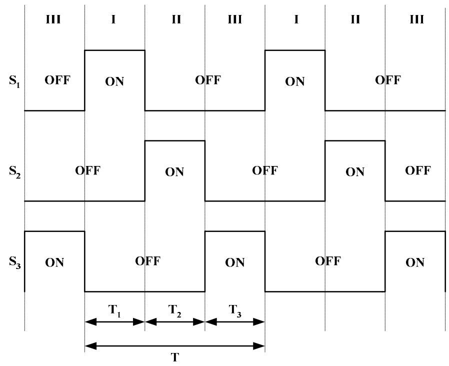

Fig. 7. Switching patterns of a double-input buck converter

TABLE I
Voltage Across the Inductor for Different Modes of Operation of the Double-Input Buck Converter

Mode	ON Switch	V_L	Note
I	S_1	$V_1 - V_o$	V_1 supplies energy
II	S_2	$V_2 - V_o$	V_2 supplies energy
III	S_3	$-V_o$	Freewheeling

TABLE II
Voltage Across the Inductor for Different Modes of Operation of the Double-Input Buckboost Converter

Mode	ON Switch	V_L	Note
I	S_1	V_1	V_1 supplies energy
II	S_2	V_2	V_2 supplies energy
III	S_3	$-V_o$	Freewheeling

TABLE III
Voltage Across the Inductor for Different Modes of Operation of the Double-Input Buckboost-Buck Converter

Mode	ON Switch	V_L	Note
I	S_1	V_1	V_1 supplies energy
II	S_2	$V_2 - V_o$	V_2 supplies energy
III	S_3	$-V_o$	Freewheeling

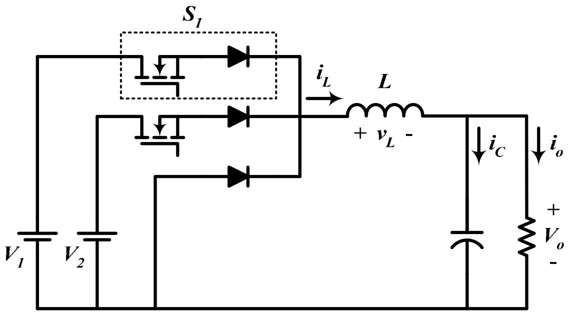

Fig. 8. Switch realization for the double-input buck converter (unidirectional power flow).

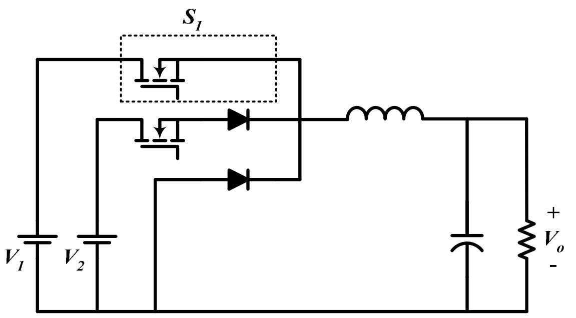

Fig. 9. Simplified double-input buck converter (if $V_1 > V_2$).

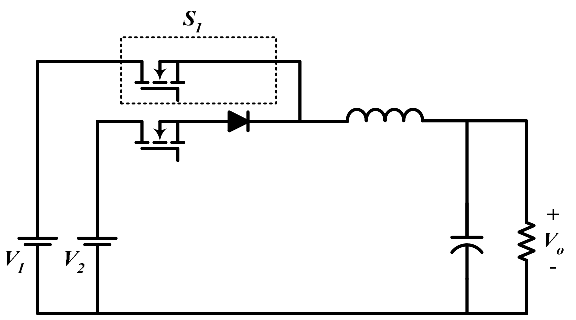

Fig. 10. Further simplified double-input buck converter with $V_1 > V_2$ and no mode III.

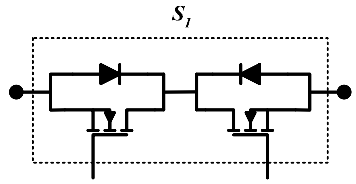

Fig. 11. Four-quadrant switch for bidirectional power flow.

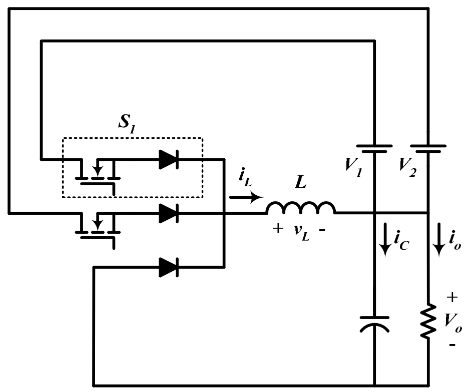

Fig. 12. Switch realization for the double-input buckboost converter (unidirectional power flow).

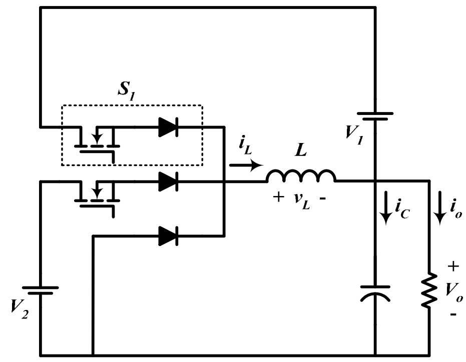

Fig. 13. Switch realization for the double-input buckboost-buck converter (unidirectional power flow).

(If S_1 is on ➔ S_2 and S_3 off) => ($i_{S1} > 0$, $V_{S2} = V_2 - V_1$, and $V_{S3} = -V_1$)

(If S_2 is on ➔ S_1 and S_3 off) => ($i_{S2} > 0$, $V_{S1} = V_1 - V_2$, and $V_{S3} = -V_2$)

(If S_3 is on ➔ S_1 and S_2 off) => ($i_{S3} > 0$, $V_{S1} = V_1$, and $V_{S2} = V_2$)

Therefore, SPST switch S_1 conducts positive currents and has to block either a positive or a negative voltage depending on the magnitude of V_1 and V_2; hence, it can be replaced by a diode in series with a transistor. Similarly switch S_2 can be replaced by a diode in series with a transistor. Switch S_3, which conducts positive current and opposes negative voltage, can be replaced by a diode. Therefore, the final circuit diagram of the double-input buck converter is shown in Fig. 8.

The structure of the double-input buck converter can be simplified to Fig. 9 if V_1 is greater than V_2 ($V_1 > V_2$). Similarly, the structure of the double-input buck converter can be further simplified if V_1 is greater than V_2 ($V_1 > V_2$) and mode III never occurs. The simplified converter in this case is shown in Fig. 10. This converter is similar to a ti-buck (two-input buck) converter [18-20].

In applications such as hybrid electric vehicles and photovoltaic systems one of the dc sources noted by V_1 or V_2 is a battery. Hence, bidirectional power flow to and from one of the sources (V_1 in this paper) is required. In this case, switch realization will be slightly different and switch S_1 in Fig. 6 needs to be replaced by a bidirectional switch realization as depicted in Fig. 11. One can obtain the switch realization of the bidirectional double-input buck converter by the following equations.

(If S_1 is on) => ($i_{S1} > 0$ or < 0)

(If S_2 is on ➔ S_1 is off) => ($V_{S1} > 0$ or <0)

As switch S_1 conducts either a positive or a negative current and also blocks either a positive or a negative voltage, it must be replaced by a four-quadrant switch (see Fig. 11).

Similarly, the unidirectional switch realization for the double-input buckboost and buckboost-buck converters results in the final circuits depicted in Figs. 12 and 13, respectively. These two topologies may also be further simplified similar to the discussion presented for the double-input buck converter.

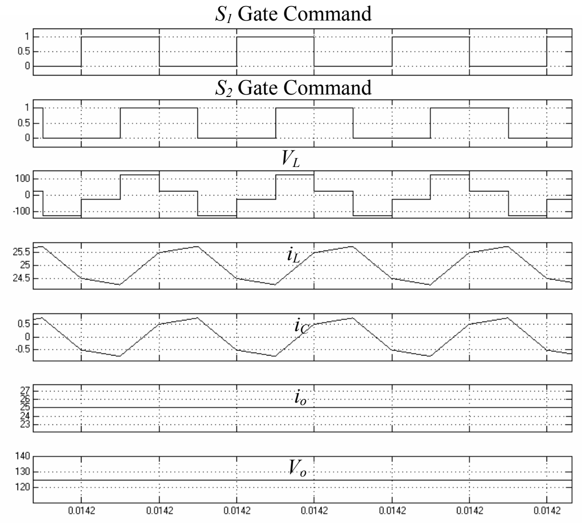

Fig. 14. Simulation results of the double-input buck converter.

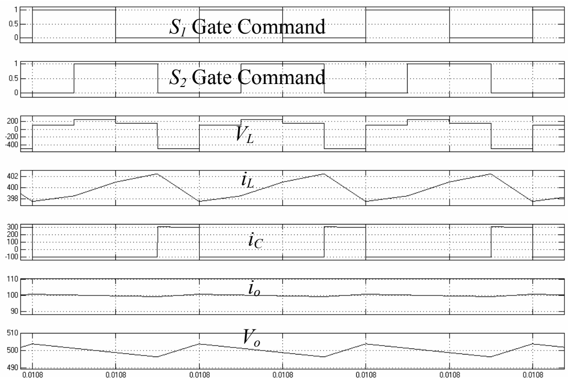

Fig. 15. Simulation results of the double-input buckboost converter.

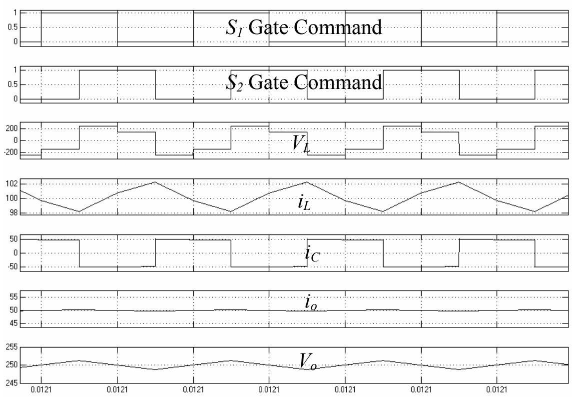

Fig. 16. Simulation results of the double input buckboost-buck converter.

IV. Simulation Results of the New Double-Input Converters

Fig. 14, 15, and 16 shows the typical simulation results of the double-input buck, buckboost, and buckboost-buck converters, respectively. Two dc voltage sources V_1 = 100V and V_2 = 150V are used as input voltage sources. The switching commands for S_1 and S_2 have fixed duty ratios of 0.5 at a switching frequency of 100 kHz. From top to bottom are the waveforms of the switching commands for S_1 and S_2, inductor voltage V_L, inductor current i_L, capacitor current i_C, output current i_o, and the output voltage. One can observe from the waveforms that the average value of the output voltage for the double-input buck converter is 125 V. This can also be obtained from the voltage transfer ratio described in (5). Similarly, the output voltages of the double-input buckboost and buckboost-buck converters are regulated at 500 V and 250 V, respectively.

V. Conclusion

Three new double-input converters are presented in this paper using a single-pole triple-throw switch as building block. All of the proposed converters use only one inductor which results in reduced size and parts count of the system. The proposed converters can be use in ultracapacitor enhancement of battery packs in automotive applications or hybridizing photovoltaic or fuel cell systems. Simulation and analytical results perfectly agree with each other.

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