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Review of Multiple Input DC-DC Converters for Electric and Hybrid Vehicles

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***Abstract*—Batteries, ultra capacitors, fuel cells, and solar arrays are widely used in electric and hybrid vehicles (EVs/HVs) as an electric power source or an energy storage unit. In the structure of the electric power system of modern EVs/HVs, more than one of these units may be employed to improve the performance and efficiency; hence utilization of a multi-input dc-dc converter is inevitable to obtain a regulated bus dc voltage. In this paper, a review of multiple input dc-dc power electronic converters (MI-PEC) devoted to combine the power flow from several on-board energy sources of an EV/HV is presented. Several multi-input dc–dc converters based on various topologies are studied and analyzed. The operating modes of each topology is presented and compared with other topologies.**

I. Introduction

EVs and HVs are gaining popularity compared to internal combustion engine (ICE) vehicles as they can save energy which is lost during various acceleration and deceleration cycles of the conventional ICE vehicles. In order to achieve this, different power sources or energy storage systems are employed in the EVs/HVs. Several power sources are required so that one input can run at the optimal rating with maximum efficiency, say the ICE for example and then any additional acceleration requirement can be fulfilled by another input source; say the ultra capacitor or battery unit. During deceleration reverse regenerative braking can be employed and the energy can be stored in batteries and ultra capacitors. Customer demands for greater acceleration performance and vehicle range in EVs and HVs increase the appeal for combined on-board energy storage systems.

In conventional approaches for two/multiple voltage sources connected in series, a control switch has to be provided for each dc voltage source to act as by-pass short-circuit for input current of other supply. However for a parallel connection, because of the difference between two dc voltage amplitudes, only one of the two sources can be connected at a time. Multiple-input dc–dc converters, as shown in Fig. 1, are the unique solution to combine several input power sources whose voltage levels and/or power capacity are different and to get regulated output voltage for the load from them.

Various multiple-input power electronic converter topologies have been proposed in the literature to interface traction drive requirements with on-board energy sources [1-4]. The proposed techniques are mainly based on (i) pulse width modulation (PWM) dc-dc converter for high/low voltage sources, (ii) the concept of flux additivity, and (iii) converters for energy storage units including advanced batteries and ultra capacitor banks. In this paper, without loss of generality, only two or three input voltage sources are considered. The concept can further be extended to various numbers of input sources.

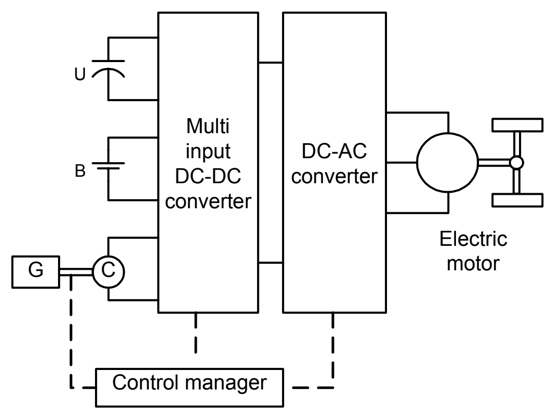

Fig. 1. MI-PEC topology

Chen in [1] proposed a converter circuit topology with two input voltages and a regulated output voltage. In order to implement the double-input PWM dc-dc converter for high/low voltage sources two dc sources are put in parallel by using a coupled transformer. In [2], the concept of the magnetic flux additivity, where the input dc sources are combined in magnetic form by adding up the produced magnetic flux together in the magnetic core of a coupled transformer has been employed to combine two current-fed full-bridge dc/dc converters. A multiple input dc-dc power converter devoted to combine the power flow of a multi-source on board energy system is presented by Napoli in [3]. The employed energy system includes a generator, an ultra capacitor (UC) tank, and a battery system.

In this paper, three different multi-input power converters are studied and classified based on their characteristics. Furthermore, the basic circuitry and the topological arrangements of these converters are illustrated and analyzed. The various modes of operation of the converters are discussed. The advantages and disadvantages of using these arrangements to run the hybrid electric propulsion drives are studied. An attempt is made to investigate the optimal and feasible solution by utilizing the benefits of all these designs.

II. Multi-Input Converter Using High/Low Voltage Sources

The circuit diagram of this topology is depicted in Fig. 2. This topology consists of two input voltage sources, high voltage source V_H and low voltage source V_L, and an output voltage of V_O where $V_H > V_O > V_L$ [1]. When the power switches M_H and M_L are turned off, diodes D_H and D_L will provide the by-pass path for the inductor current to flow continuously. By applying the PWM control scheme to the power switches M_H and M_L, the proposed double-input dc-dc converter can draw power from two voltage sources individually or simultaneously.

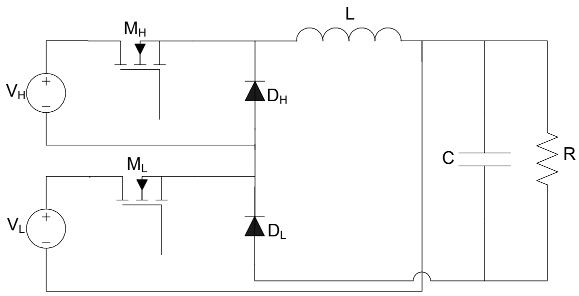

Fig. 2. High/low double-input PWM dc-dc converter

The four different modes of operation based on the status of the power switches, as depicted in Fig. 3, can be explained as follows [1]:

Mode I (M_H:on / M_L:off): Switch M_H is turned on and M_L is turned off. Because of conduction of M_H, power diode D_H is reverse biased and treated as an open circuit and diode D_L will provide a by-pass path for the inductor current as shown in Fig. 3(a). In this mode, V_H charges inductor L, capacitor C, and provides the electric energy for the load.

Mode II (M_H:off / M_L:on): Power switch M_H is turned off and M_L is turned on. This results in power diode D_{HI} to turn on as a short circuit and D_L to turn off as an open circuit as depicted in Fig. 3(b). During this operation mode, V_L will charge inductor L, while the load is supplied by output capacitor C.

Mode III (M_H:off / M_L:off): Both of switches M_H and M_L are turned off. Diodes D_H and D_L will provide the current path for the inductor current as shown in Fig. 3(c). Both of voltage sources V_H and V_L are disconnected from the double-input converter. The electric energy stored in L and C will be released into the load.

Mode IV (M_H:on / M_L:on): M_H and M_L are turned on which results in D_H and D_L to turn off with reverse biased voltages. V_H and V_L are connected in series to charge inductor L. The demanded power for the load is now provided by capacitor C as depicted in Fig. 3(d).

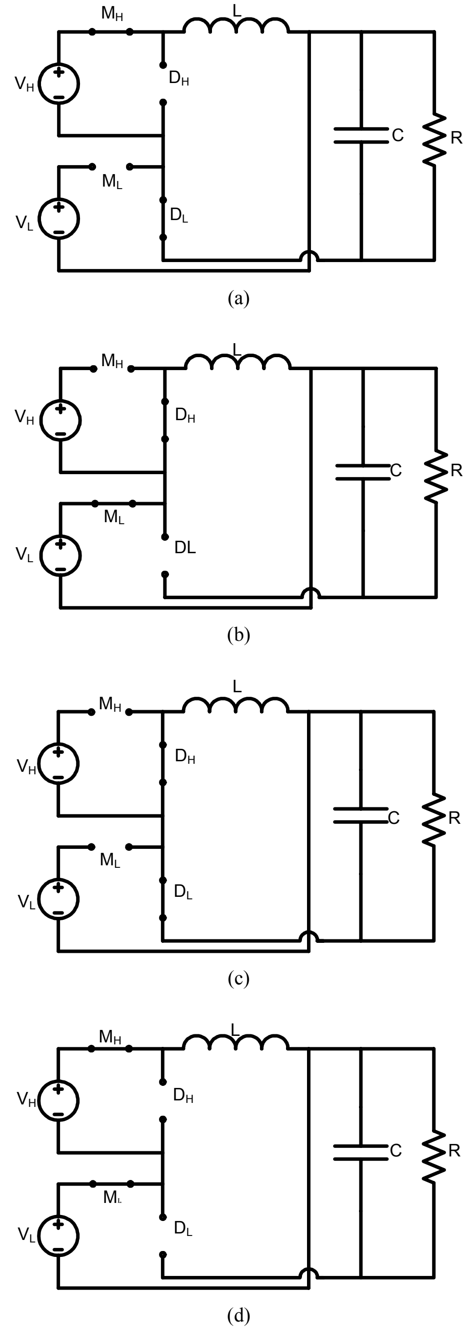

Fig. 3. Different operating modes

For the same switching frequency, the turn-off synchronization in which M_H and M_L are synchronized by the same turn-off transition with different turn-on moment is considered. Fig.4 shows typical voltage and current waveforms of this converter [1]. From top to bottom are the waveforms of high voltage source input current i_H, low voltage source input current i_L, and unfiltered output current i_o'.

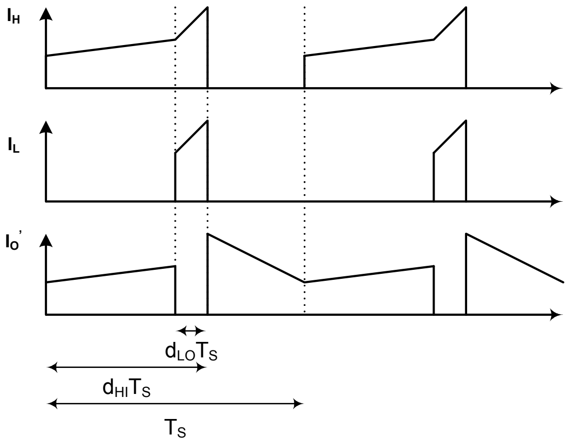

Fig. 4. Typical voltage and current waveforms of key components

III. Multi-Input Converter Based On Flux Additivity

The circuit diagram of the two-input dc-dc converter using flux additivity is shown in Fig. 5. This can further be extended to a multi-input converter by increasing the number of input sources while the coupled transformer and the output-stage circuit remain unchanged [2]. The amplitude of the dc voltage source can be different since each dc voltage source associated with a choke inductor becomes a dc current source. The switches in the input state are in series with the reverse blocking diodes since the reverse blocking diode can regulate the direction of the current flow and prevent the reverse power flow from other dc sources via the coupled transformer and switches. Without these diodes the power can not be delivered to the load simultaneously. The output-stage circuit is an ac-dc rectifier.

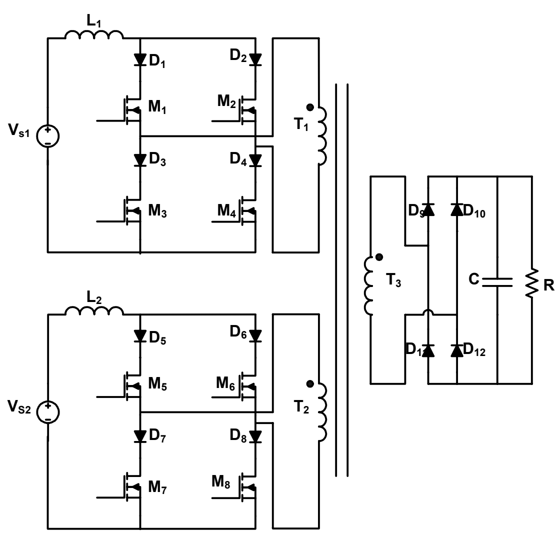

Fig. 5. The topology of the two-input current-fed full bridge dc-dc converter

The power is delivered to the load from the input source through the transformer when two switches located at the diagonal position of the converter in each input stage circuit are turned on. On the other hand, no power is transferred to the load when two switches of the same leg in each input stage circuit are turned on. This is because the input current is freewheeling through these turned on switches. The output can be regulated by controlling the time ratio of the power transferring stage to the freewheeling stage. The operation of the converter over one full switching cycle is divided into twelve different operation modes. Current waveforms of the primary side i_{P1} and i_{P2} and the secondary side of the transformer i_S are illustrated in Fig. 6 [2].

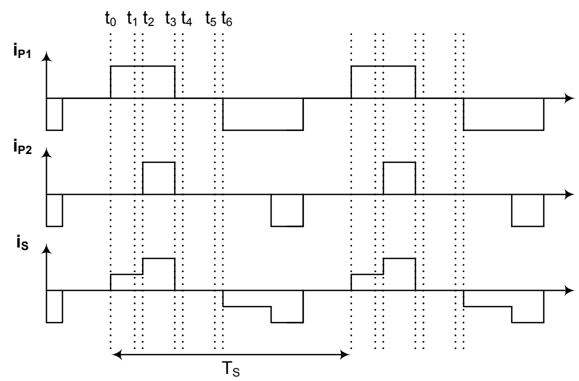

Fig. 6. Input and output current waveforms

The six operation modes within the one half of switching cycle are symmetrical to the other six operation modes. Therefore, only the first six operation modes over one half switching cycle are described below [2].

Mode 1: ($t_0 \le t < t_1$) At time instant t_0, M_3 is turned off. Power starts to flow from the first input-stage circuit through the transformer to the load. The current source, I_{S1}, in the first input-stage circuit will flow through the first transformer winding, T_1, via switches D_1, M_1, D_4, and M_4, while I_{S2} is still kept freewheeling in the second input-stage circuit. The magnetic flux produced by the first winding current, i'_{S1}, will induce voltages on other transformer windings. Induced voltages across transformer windings, T_1, T_2, and T_3, are clamped to $(n_1V_o)/n_3$, $(n_2V_o)/n_3$, and V_o, respectively. Diodes, D_9 and D_{12} in the output-stage circuit will be turned on because of the induced transformer winding voltage, V_3, which results in the conduction of the body diode of Switch M_8.

Mode 2: ($t_1 \le t < t_2$) At time instant t_1, M_8 is turned on at zero voltage due to the conduction of its body diode in the previous operation mode. During this mode, M_8 is turned on but conducts no current. The input current I_{S2} is still kept freewheeling through D_5, M_5, D_7, and M_7 in the second input-stage circuit. Operations of the first input-stage and the output-stage circuits remain unchanged.

Mode 3: ($t_2 \le t < t_3$) This mode begins when switch M_7 is turned off at t_2. The current source, I_{S2}, in the second input- stage circuit will flow through the second transformer winding, T_2, via switches D_5, M_5, D_8, and M_8 and start to transfer power to the load. During this operation mode, both of the first and the second input-stage circuits are delivering power to the load individually and simultaneously. The total magnetic flux linkage in the coupled transformer is increased because of the additional magnetic flux produced by the second winding current, i'_{S2}. The operation of the output-stage circuit and the clamped transformer winding voltages stay unchanged.

Mode 4: ($t_3 \le t < t_4$) At time instant t_3, both M_2 and M_6 are turned on. Switches M_1 and M_5 are still kept on but conduct no current. All of the diodes in the output-stage circuit will be reversed biased since all of transformer winding voltages are clamped to zero because of the freewheeling currents in the two input-stage circuits. No power is transferred from any input-stage circuit to the output- stage circuit. The power demanded by the load is provided by the output filter capacitor, C.

Mode 5: ($t_4 \le t < t_5$) Switches M_1 and M_5 are turned off with zero current at t_4.. The current sources I_{S1} and I_{S2} are kept freewheeling in the input-stage circuits, and no power is delivered to the load.

Mode 6: ($t_5 < t < t_6$) At time instant t_5, M_3 is turned on at zero voltage due to the clamped zero voltage across the first transformer winding, T_1. The rest of the circuit is the same as described in the previous operation mode. Two current sources are freewheeling in the input-stage circuits and no power is delivered to the load. Mode 7 begins when M_4 is turned off at t_6. This mode is similar to mode 1. The polarity of transformer voltages and currents are opposite to these shown in mode 1. Consequently, mode 8 through mode 12 can be found to be symmetrical to mode 2 through mode 6, too.

IV. MULTI-INPUT DC-DC CONVERTER FOR ENERGY STORAGE UNITS

The circuit topology of the multi input dc-dc converters for energy storage units like advanced batteries and ultra capacitor banks is shown in Fig. 7. This arrangement is suitable to connect high and low voltage power sources [3]-[4]. In the generator systems, UC tanks, and battery systems the numbers of elements connected in series are limited to improve the system reliability. The regulated output voltage is load and the battery system state of charge (SOC) dependent.

This topology is generally used to drive traction loads, for instance a hybrid vehicle. Therefore, a bidirectional converter is selected such that the converter acts as step up converter (boost converter) for one mode of operation and as step down converter (buck converter) for other mode of operation. Each power source is connected to the dc link by means of this bidirectional step up or step down dc-dc converter. Step up mode of operation is used in order to transfer energy from each power source to the dc-link, where as step down operation is used to charge both UC tank and battery storage system and to recover the braking energy

The converter is composed of two controlled switches, two diodes, one input inductor and output capacitor. Volume saving strategy is applied to the converter under consideration. This is prevalent by the useless presence of switch and diode concerning the step down configuration in the generator systems side of the converter, where energy can not be recovered during braking mode of operation. The control switches are controlled in order to supply the dc link following the traction power demand. The control manager shares the power flow on the basis of UC and battery SOC. The desired dc-link voltage level is accomplished in every working condition by operating on battery-side converter.

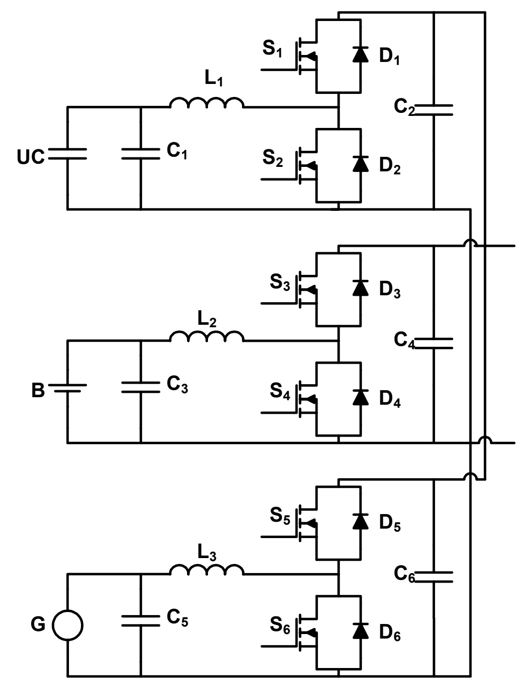

Fig. 7. Multi-input power converter for advanced batteries and capacitor banks

V. CONCLUSION

Multi-input power converters are considered and three topologies were discussed. Their characteristics were studied and comparisons were made between them. Future work will be addressed to carry on simulations on these three designs being used in an electric or hybrid vehicle. More emphasis will be given to finding the optimal and feasible designs by incorporating all the advantages of these designs.

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