



POWER SHARING ANALYSIS OF A NEW MODIFIED MULTI-INPUT INTERLEAVED BOOST CONVERTER BASED ON H-BRIDGE CELLS

W. M. Utomo, Y. M. Buswig, Z. A. Haron and A. Bakar

Electrical Power Department, Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia,

Parit Raja, Batu Pahat, Johor, Malaysia

E-Mail: ans_cold84@yahoo.com

ABSTRACT

In this paper, a new modified multi-input boost converter is proposed using H-bridge cells as building blocks and uncoupled inductors in parallel using interleaved technique as ripple reduction method. The objectives of this paper are to design a high ripple reduction and a high-performance multi-input boost converter. Different operating modes and the switch realization of the new converter are obtained. The modes of operation based on the status of the four switches. The proposed multi-input boost converter is composed of two inputs source that accommodated with some extra semiconductors, inductances and diodes to form the interleaving technique as proposed method. The proposed concept has been investigated through simulation using the MATLAB/Simulink environment. The simulation results confirm the validity of the proposed method, which can be seen as a promising new topology that ensure multi-input converter suitable for renewable energy applications.

Keywords: multi-input converter, interleaving technique, H-bridge cells.

INTRODUCTION

Nowadays, Multiple-input DC-DC converters are playing a significant role in interfacing and diversification of different energy sources. The single DC-DC converters are connected to electric sources like battery, fuel cell, wind power and other renewable energy with (V-I) features and the outputs can be combined with dc bus in both parallel or series (Valenciaga and Puleston, 2005), (Kumar and Ikkurti, 2011), (Wang and Nehrir, 2008), (Jiang and Fahimi, 2011), (Dobbs and Chapman, 2003).

Therefore, several energy sources can be consolidated either in parallel (Tao *et al.*, 2006)(Gummi and Ferdowsi 2010)(Chen *et al.* 2006) or in series(Ahmadi and Ferdowsi, 2012), (Kumar and Jain, 2012), (Nami *et al.* 2010)(Shen and Yang, 2013) with the electric connected multiple-input converter topologies. However, the main restrictions of the input source topologies connected in parallel are the compulsory of the input voltage source to be asymmetrical and at one time, only one input source can provide energy to the load to obviate energy from the conjugation effect.

Series connecting the input sources are necessary to provide energy simultaneously. Therefore, in series configurations, by using an individual diode, each input source can avoid the other input source to form a parallel connection, which increases numbers of components (Ahmadi *et al.* 2013) (Li *et al.* 2010) (Kwasinski, 2009).

Nevertheless, these configurations have weaknesses such as expensive, huge and complicated in design. It also minimizes the efficiency and accuracy of the whole system. Consequently, a single converter with multiple inputs has been introduced, replacing the multiple single input converters.

Multiple-input converters offer uncomplicated and more consolidated styling as well as reducing cost and the systems complexity. Moreover, the efficiency of power distribution reinforces reliability at the regulated output voltage (Dobbs and Chapman 2003) (Tao *et al.* 2006).

Various isolated and non-isolated topologies on multiple-input converters have been presented (Tao *et al.* 2006) (Chen *et al.* 2002) (Patra *et al.* 2012) (Liu and Chen 2009). Electric-connected circuits belong to the non-isolated topologies while the magnetic-connected circuit belongs to those isolated topologies.

In the magnetic-connected circuit, the energy conversion transformation from sources to load is executed using flux technique and the time domain multiplexing (Matsuo *et al.* 1993). Thence, the necessity of the extra Peripheral circuitry and the transformer requirement make the magnetic-connected circuit complicated, huge, and expensive as well as increasing the circuit parameters dependency (Dobbs and Chapman, 2003) (Zhao *et al.* 2008) (Khaligh *et al.* 2009) while electric-connected circuit has a modular structure, reduces cost and is not using transformer, thus making this non-isolated circuit more attractive and greatly reduces the matter associated with magnetic-connected circuit..

PROPOSED MODIFICATION FOR MULTI-INPUT BOOST DC-DC CONVERTER

The operation principle of multi-input DC-DC converter is based on the essential of DC-DC converter. The essential operation of the basic DC-DC converter is to charge the passive elements of the converter during a specific period of time and then discharge the stored energy of the passive element through load during the



remaining period of time over a single switching cycle. In the single-input DC-DC converter, power flow from input source to the load can be controlled by controlling charging and discharging of the inductor.

Similarly, in multi-input DC-DC converters, the inductors can be charged by multiple input voltage sources instead of one source depend on a suitable switching technique that connects or disconnects multiple-input sources to the inductor individually or simultaneously.

Therefore, in this paper a systematic approach to modify a new multi-input boost converter by using cascaded H-bridge cell included of two series H-bridge cells as building blocks with uncoupled inductors in parallel using interleaved technique as ripple reduction are proposed in boost operation mode in order to reduce the ripple of input current as well as output current, and increase performance of the proposed multi-input converter system.

A simple outline of the proposed modified multi-input interleaved boost DC-DC converter using H-bridge cells with interleaving technique is shown in Figure-1.

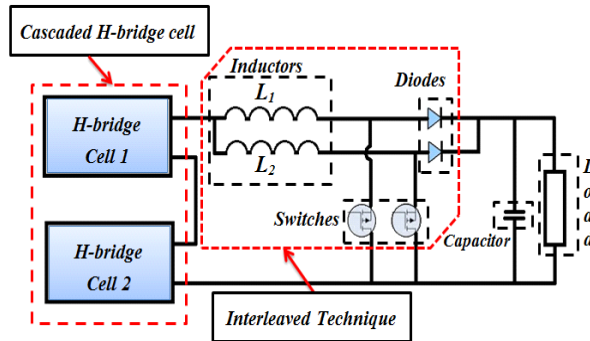


Figure-1. Outline of a proposed modified multi-input interleaved boost DC-DC converter.

DERIVATION OF THE PROPOSED MULTI-INPUT CONVERTER USING H-BRIDGE CELL

Topology introduced in Figure-1 hereafter named multi-input interleaved boost DC-DC converter, resembles the topology of an interleaved boost converter with two inputs voltage sources. By replacing H-bridge cells in proposed converter with their circuit topology, one would obtain Figure-2. Four modes of operation that occur under unidirectional power flow are depicted in Figure-3 up to Figure-6.

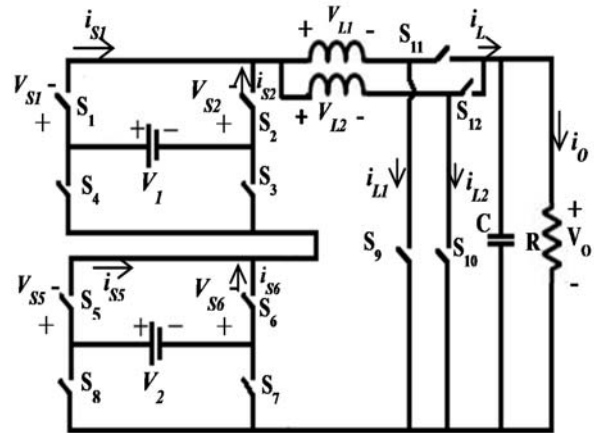


Figure-2. The schematic circuit of the proposed multi-input converter using cascaded H-bridge cells.

Mode 1- (S_1, S_3, S_6, S_7, S_9 and S_{12} : on)

In this mode, input source V_1 supplies the energy to the load and inductor L_2 while inductor L_1 starts charging. Thus, the source V_1 can operate individually as depicted in Figure-3.

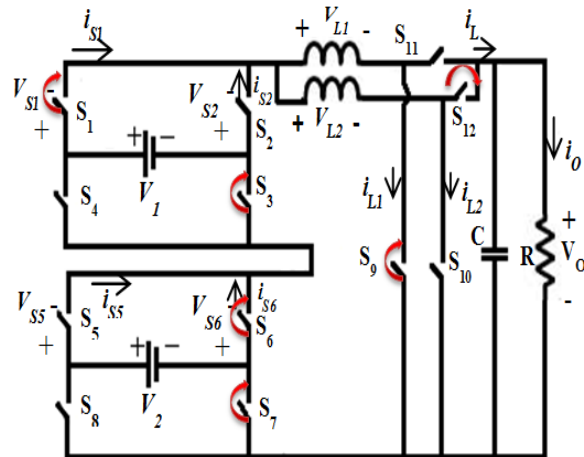


Figure-3. Derivation circuit of the mode 1.

Mode 2- ($S_1, S_3, S_5, S_7, S_{10}$ and S_{11} : on)

In this mode both of input sources (V_1 and V_2) supply the energy to the load and inductor L_1 , while inductor L_2 starts charging. Thus, both the sources can operate simultaneously as depicted in Figure-4.

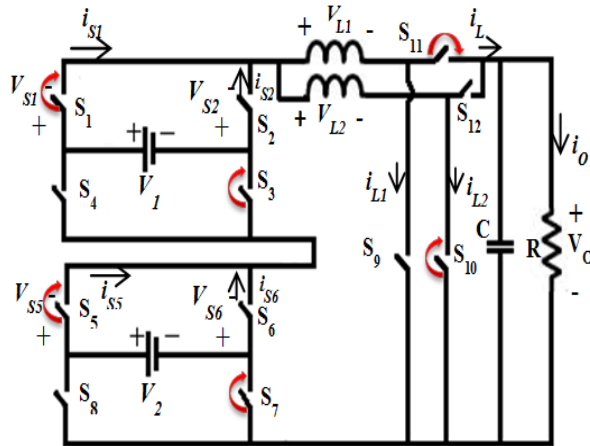


Figure-4. Derivation circuit of the mode 2.

Mode 3- (S_1, S_3, S_5, S_7, S_9 and S_{12} : on)

In this mode both of input sources (V_1 and V_2) supply the energy to the load and inductor L_2 , while inductor L_1 starts charging. Thus, both the sources can operate simultaneously as depicted in Figure-5.

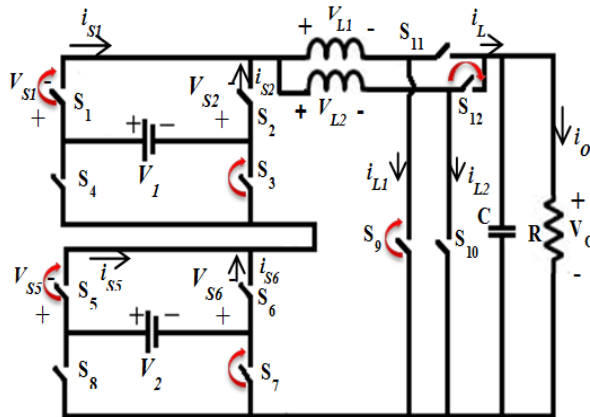


Figure-5. Derivation circuit of the mode 3.

Mode 4- ($S_2, S_3, S_5, S_7, S_{10}$ & S_{11} : on)

In this mode, input source V_2 supplies the energy to the load and inductor L_1 while inductor L_2 starts charging. Thus, the source V_2 can operate individually as depicted in Figure-6.

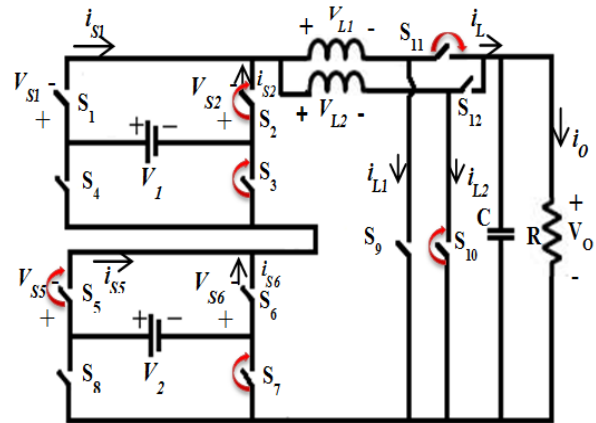


Figure-6. Derivation circuit of the mode 4.

SWITCH INVESTIGATION OF THE PROPOSED MULTI-INPUT CONVERTER

As a result of operation modes circuits of the proposed converter that in the unidirectional power flow, switches S_4 and S_8 are not used at all so they can be eliminated from the circuit. Also switches S_3 and S_7 are always on so they can be shorted. Residual switches S_1, S_2, S_5 , and S_6 can be replaced by diodes or transistors considering the following explanation. If the power flows through the inductors are considered to be unidirectional, I_{L1} and I_{L2} is always positive.

As switch S_2 conducts positive current and opposes negative voltage, it can be replaced by a diode D_1 and as switch S_1 conducts positive current and positive voltage it can be replaced by a transistor. Similarly, S_6 can be replaced by a diode D_2 , and S_5 can be replaced by a transistor. As switches S_9 and S_{10} conduct positive current and positive voltage they can be replaced by transistors.

Also, as switch S_{11} and S_{12} conduct positive current and opposes negative voltage it can be replaced by a diode D_3 and D_4 respectively. So the final circuit that is obtained is shown in Figure-7.

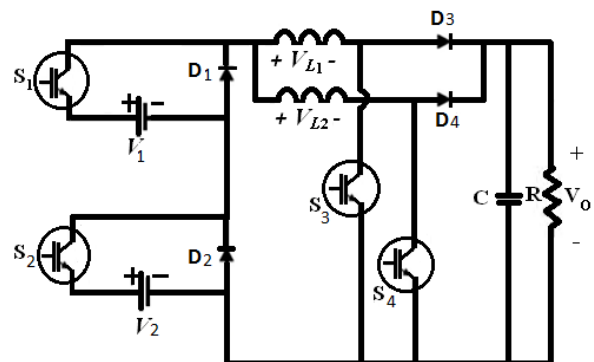


Figure-7. Final derived circuit of the proposed multi-input converter using cascaded H-bridge cells.



OPERATING PRINCIPLE OF THE PROPOSED MULTI-INPUT DC-DC CONVERTER

The gate pulses of the switches for the proposed multi-input converter have been purposely assumed that the duty cycle of S_1 , S_2 , S_3 and S_4 denoted as d_1 , d_2 , d_3 , and d_4 respectively. The pulse modulation of the switches and change in inductors current waveforms of proposed multi-input converter are shown in Figure-8. Where $T_{3,4}$ represents the switching frequency of interleaving switches S_3 and S_4 .

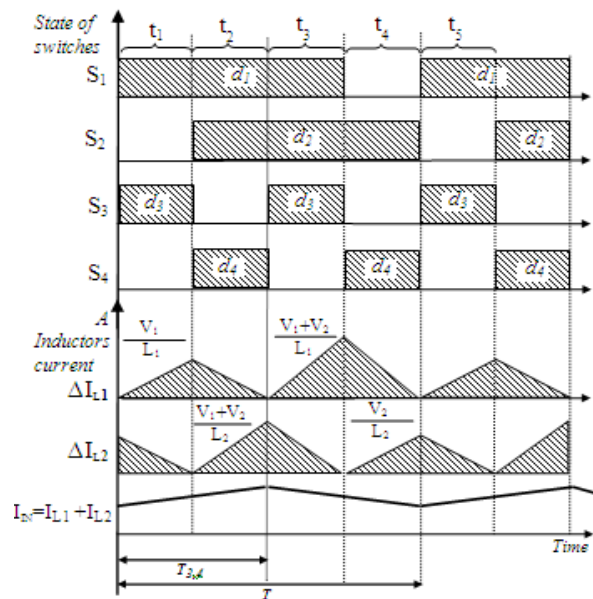


Figure-8. Pulse modulation of the switches and current waveforms of the proposed multi-input converter.

The switching conditions in different operations modes are shown in Figure-9 up to Figure-12, and described as follow:

Equivalent circuit of mode 1

Referring to the Figure-9, during T_1 , the inductor current, and the capacitor voltage during T_1 can be computed as given in equations (1), (2), and (3):

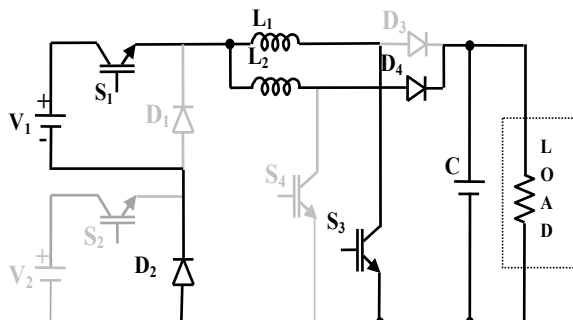


Figure-9. Operating mode-1 at time T_1 .

$$\frac{di_{L1}}{dt} = \frac{V_1}{L_1} \quad (1)$$

$$\frac{di_{L2}}{dt} = \frac{V_1}{L_2} - \frac{V_C}{L_2} \quad (2)$$

$$\frac{dV_C}{dt} = \frac{I_{L2}}{C} - \frac{V_O}{R C} \quad (3)$$

Equivalent circuit of mode 2

Referring to the Figure-10, during T_2 , the inductor current, and the capacitor voltage during T_2 can be computed as given in equations (4), (5), and (6):

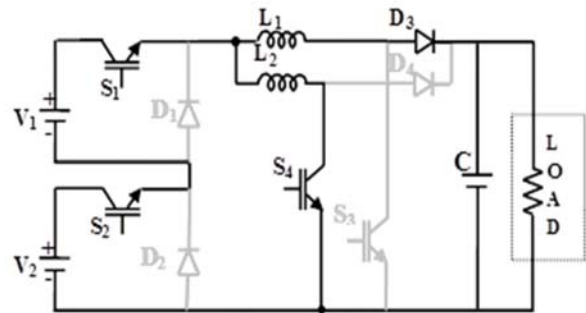


Figure-10. Operating mode-2 at time T_2 .

$$\frac{di_{L1}}{dt} = \frac{(V_1 + V_2)}{L_1} - \frac{V_C}{L_1} \quad (4)$$

$$\frac{di_{L2}}{dt} = \frac{(V_1 + V_2)}{L_2} \quad (5)$$

$$\frac{dV_C}{dt} = \frac{I_{L1}}{C} - \frac{V_O}{R C} \quad (6)$$

Equivalent circuit for mode 3

Referring to the Figure-11, during T_3 , the inductor current, and the capacitor voltage during T_3 can be computed as given in equations (7), (8), and (9):

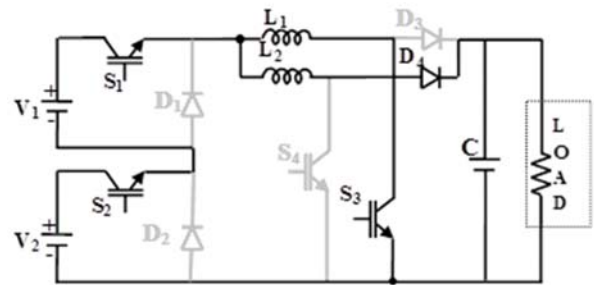


Figure-11. Operating mode-3 at time T_3 .



$$\frac{di_{L2}}{dt} = \frac{(V_1 + V_2)}{L_2} - \frac{V_C}{L_2} \quad (7)$$

$$\frac{di_{L1}}{dt} = \frac{(V_1 + V_2)}{L_1} \quad (8)$$

$$\frac{dV_C}{dt} = \frac{I_{L2}}{C} - \frac{V_O}{R C} \quad (9)$$

Equivalent circuit for mode 4

Referring to the Figure-12, during T_4 , the inductor current, and the capacitor voltage during T_4 can be computed as given in equations (10), (11), and (12):

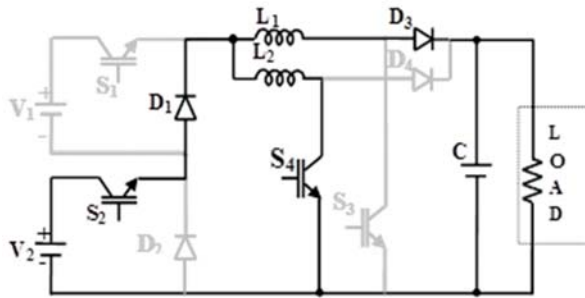


Figure-12. Operating mode-4 at time T_4 .

$$\frac{di_{L2}}{dt} = \frac{V_2}{L_2} \quad (10)$$

$$\frac{di_{L1}}{dt} = \frac{V_2}{L_1} - \frac{V_C}{L_1} \quad (11)$$

$$\frac{dV_C}{dt} = \frac{I_{L1}}{C} - \frac{V_O}{R C} \quad (12)$$

VOLTAGE TRANSFER RATIO OF THE PROPOSED MULTI-INPUT CONVERTER

Explained analysis for boost mode of operation is carried out in continuous conduction mode (CCM) under steady-state condition. In the analysis, switching loss and a resistive drop of passive components are considered to be negligible.

The switching patterns are true for all the possible arrangements of the proposed multi-input converter as it consists of all the four modes. The duration of each mode (t_1 , t_2 , t_3 , and t_4) in terms of duty cycles and switching period then can be expressed as.

$$\begin{cases} t_1 = t_3 = d_3 \\ t_2 = t_4 = d_4 \\ t_1 + t_2 + t_3 = d_1 \\ t_2 + t_3 + t_4 = d_2 \end{cases}$$

Where T represents the time period of the switching patterns as expressed in equation (13)

$$t_1 + t_2 + t_3 + t_4 = T \quad (13)$$

According to the volt-second balance theory, average inductor voltage over a single switching period should be zero:-

$$\text{Average inductor voltage} = \int_0^T V_L \frac{d_{iL}}{dt} dt = 0 \quad (14)$$

Assume that the current waveforms had reached a steady state condition. Thus, by analyzing the waveforms for I_{L1} and I_{L2} of the switching cycle for different working states based on Figure-8, can be written the following equations:-

$$\frac{d_{iL1}}{dt} = \frac{(V_1)}{L_1} t_1 + \frac{(V_1 + V_2)}{L_1} t_2 - \frac{(V_O)}{L_1} \left(\frac{1-d_3}{2} \right) + \frac{(V_1 + V_2)}{L_1} t_3 + \frac{(V_2)}{L_1} t_4 - \frac{(V_O)}{L_1} \left(\frac{1-d_3}{2} \right) = 0 \quad (15)$$

$$\frac{d_{iL2}}{dt} = \frac{(V_1)}{L_2} t_1 - \frac{(V_O)}{L_2} \left(\frac{1-d_4}{2} \right) + \frac{(V_1 + V_2)}{L_2} t_2 + \frac{(V_1 + V_2)}{L_2} t_3 - \frac{(V_O)}{L_2} \left(\frac{1-d_4}{2} \right) + \frac{(V_2)}{L_2} t_4 = 0 \quad (16)$$

$$\frac{d_{iL1}}{dt} + \frac{d_{iL2}}{dt} = \frac{d_{iLtotal}}{dt} = 0 \quad (17)$$

$$\begin{aligned} \frac{d_{iLtotal}}{dt} = & \frac{(V_1)}{L_1} t_1 + \frac{(V_1 + V_2)}{L_1} t_2 - \frac{(V_O)}{L_1} \left(\frac{1-d_3}{2} \right) + \frac{(V_1 + V_2)}{L_1} t_3 + \frac{(V_2)}{L_1} t_4 - \frac{(V_O)}{L_1} \left(\frac{1-d_3}{2} \right) \\ & + \frac{(V_1)}{L_2} t_1 - \frac{(V_O)}{L_2} \left(\frac{1-d_4}{2} \right) + \frac{(V_1 + V_2)}{L_2} t_2 + \frac{(V_1 + V_2)}{L_2} t_3 - \frac{(V_O)}{L_2} \left(\frac{1-d_4}{2} \right) + \frac{(V_2)}{L_2} t_4 = 0 \end{aligned} \quad (18)$$

In principle, equations (15)-(18) can be solved to find V_{out} . Even so, in order to simplify the calculation, it is assumed that $L_1 = L_2 = L$ and $d_3 = d_4 = d_{3,4}$. After some algebraic manipulations and solving equation derived from (18). The expression of the output voltage of the proposed multi-input converter shown as the in equation (19)

$$V_{out} = \frac{V_1 d_1 + V_2 d_2}{(1 - d_{3,4})} \quad (19)$$

SIMULATION RESULTS

A multi-input converter with double inductance interleaved scheme has been considered for the simulation study in boost operation mode. A simulation model of the proposed converter using MATLAB Simulink is shown in Figure-13. All the results have been analyzed for mismatched sources with continuous current mode under steady condition. A fixed frequency switching strategy had



been selected to present the results of the simulation study. All the simulation parameters are given in Table-1.

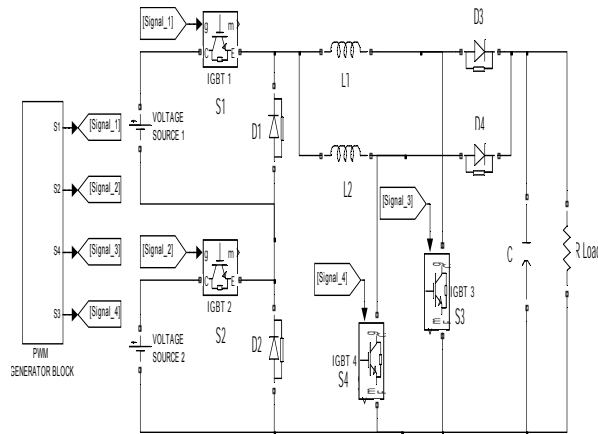


Figure-13. Simulation model circuit of proposed multi-input interleaved boost converter.

Table-1 Power stage parameters of the designed converter

Parameter (unit)	Value
V_{in1} (V)	24
V_{in2} (V)	12
d_1, d_2 (%)	75
d_3, d_4 (%)	50
f (kHz) S_1 & S_2	10
f (kHz) S_3 & S_4	20
L_1, L_2 (mH)	8
C (μ F)	680
V_{Out} (V)	54
R (Ω)	10

Simulation results of switching signals, inductors voltage, inductors currents, input voltage sources and output voltage for boost mode of operation in case mismatched sources when voltage sources $V_{in1}=24V$ and $V_{in2}=12V$ are shown in Figure-14 up to Figure-17.

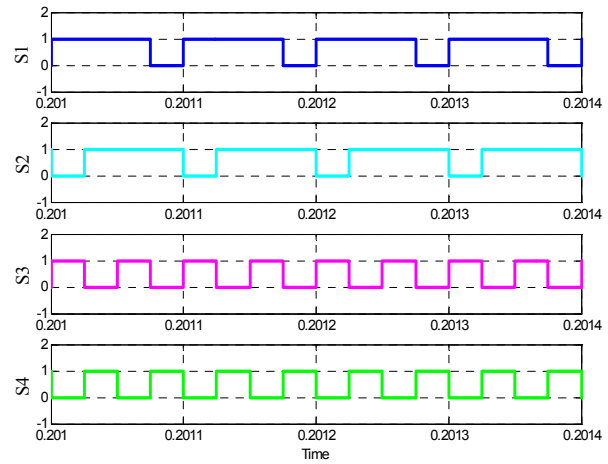


Figure-14. Switching signals of switches S_1, S_2, S_3 and S_4 ; [$d_1 = d_2 = 0.75$; $d_3 = d_4 = 0.5$].

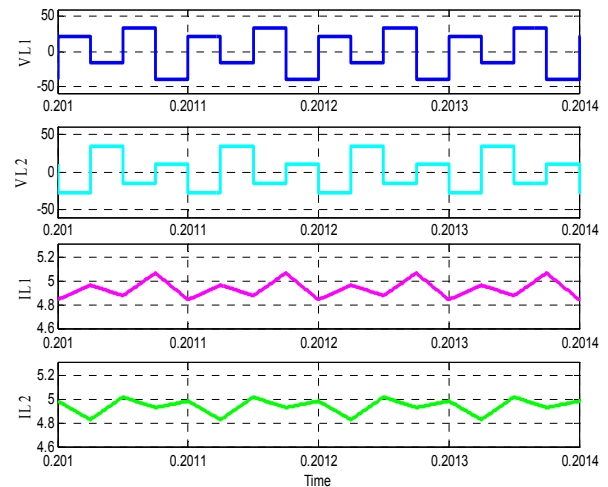


Figure-15. Inductors voltage (V_{L1} and V_{L2}); Switching signals of switches S_3 and S_4 ; [$d_3 = d_4 = 0.5$]

As shown in Figure-15, the simulation results when the input voltage sources are mismatched: at time (t_1), the inductor L_1 was charged by 24V (i.e. $V_{L1}=V_1$) when the inductor L_2 was discharged (i.e. $V_{L2}=V_1-V_0$) and for time (t_2), the inductor L_2 was charged by 36 V (i.e. $V_{L2}=V_1+V_2$) when the inductor L_1 was discharged (i.e. $V_{L1}=V_1+V_2-V_0$); for time period (t_3) the inductor L_1 was charged by 36 V (i.e. $V_{L1}=V_1+V_2$) when the inductor L_2 was discharged (i.e. $V_{L2}=V_1+V_2-V_0$), and for time (t_4) the inductor L_2 was charged by 12 V (i.e. $V_{L2}=V_2$) when the inductor L_1 was discharged (i.e. $V_{L1}=V_2-V_0$) and reached its initial position.

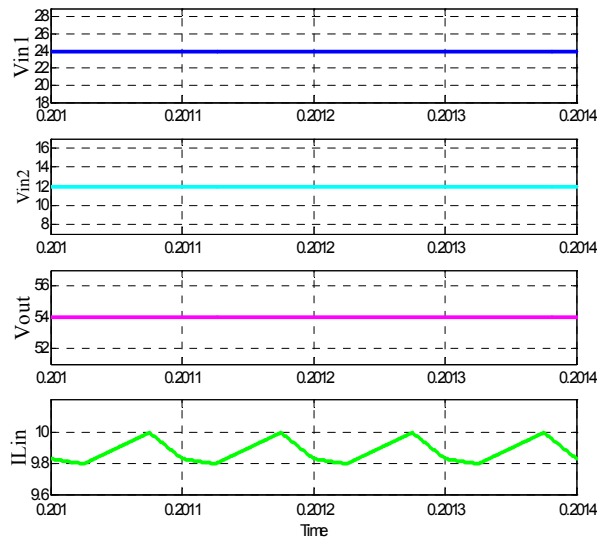


Figure-16. Voltage input source (V_{in1} and V_{in2}); output voltage (V_{out}); total input inductor current ($I_{L1} + I_{L2}$).

In Figure-16, the simulation results shown that the input current $I_{L_{in}}$ is the sum of both inductor currents I_{L1} and I_{L2} . As the inductor's ripple currents are out of phase as shown in Figure-15, they have a capability to cancel each other and decrease the input ripple current as well as output current ripple due to the interleaved boost inductors.

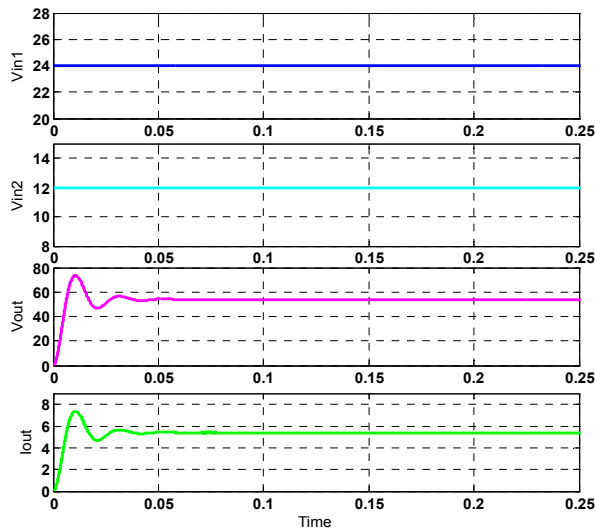


Figure-17. Voltage input sources (V_{in1} and V_{in2}); output voltage V_{out} ; output current I_{out} .

In Figure-17, simulation results proved the capability of the proposed multi-input converter to regulate output voltage when is commanded 54V based on the voltage transfer ratio equation of the proposed converter that proved previously.

CONCLUSIONS

In this paper a new modified multiple-input interleaved boost converter is proposed. Different operating modes and the switch realization of the new multi-input converter are explained. Operating principle of the proposed multi-input converter and its voltage transfer ratio are obtained.

The proposed multi-input converter is modified by suitable adjustments in duty cycles d_3 and d_4 using the interleaving technique as ripple reduction. Obviously, as shown in simulation results, the proposed multi-input converter has been simulated with uncoupled inductors interleaving topology as ripple reduction. Thus, the results shown the charging and discharging of inductors can be observed by variation in voltage across inductors and rise and fall in inductors current.

Consequently, the main feature of this topology is that the voltage stress of each switch is one-half of the voltage stresses of the switches in the single inductor implementation. Furthermore, the input currents of input voltage sources are distributed evenly through the two boost inductors so that the ripples in input current as well as the output current have been reduced greatly.

In addition, the simulation results proved that the proposed multi-input converter able to sharing different amount of power from individual sources while meeting power demand of the load at regulated output voltage. As a final point, the structure of the proposed multiple-input interleaved boost converter using the concept of double inductance interleaved technique is interesting in reducing ripple for renewable energy applications.

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