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A Modified Dual Input DC-DC Converter for Hybrid Energy Application

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ABSTRACT

Power electronic interface has reached a new level in the area of hybrid energy integration nowadays. The existence for the concept of hybrid energy integration is truly questionable without a proper power electronic interface. In this paper, a modified dual input DC-DC converter which is capable of incorporating two distinct V-I characteristic sources such as solar-PV, battery, fuel cell, etc., is proposed. The converter has the ability to operate in both unidirectional and bidirectional mode with buck, buck-boost and boost operation. The software simulation of the proposed converter has been conducted in MATLAB/Simulink platform in a detailed manner and an experimental prototype of the propsed converter has been built to validate the simulation results.

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1. INTRODUCTION

The electricity demand is drastically increasing as a result of massive increase in the population and industrial growth. Conventional energy generation based on fossil fuels and other sources are excessively used to satisfy the increasing power demand. But in the current scenario of electric power generation, the rapid depletion of fossil fuel and the critical environmental issues due to the usage of these conventional energy sources made the researchers to think about the alternatives. Hence the practice of using the non-conevntional energy sources such as solar-PV, wind and storages like the battery, fuel cell and ultra-capacitor are started since they are clean and non-polluting in nature. But the stand-alone usees of these energy sources particularly solar-PV and wind is not preferable due to their highly intermittent nature. Hence the idea of Hybrid Energy System (HES) is developed to overcome these issues.

The HES is an advanced technology which is proficient in meeting the widely changing rural electricity requirements by the proper incorporation of non-conventional energy sources with same or distinct voltage-current (V-I) characteristics [1]. The powerful realization of the concept of hybrid energy integration is incomplete without a suitable power electronic interface [2]. To accommodate multiple number of energy sources, parallel connected single input DC-DC converters are widely used in the conventional scheme. But high cost, large system complexity and lower efficiency are the major demerits of this method. To cancel out these drawbacks, the notion of multiple input DC-DC converter (MDCs) is developed. Comparatively lower component count, higher efficiency, simple and compact structure are the potential advantages of MDCs. Different MDCs are already reported in the literature [3]-[7]. Most of the MDC topologies are integrating various input energy sources parallelly [3]-[5]. These topologies have certain limitations like the input voltage should be asymmetric and only one energy source can deliver energy to the load to avoid the power coupling effect. To provide the power concurrently, the input energy sources should be connected in series

[6]-[7]. In certain parallel connected topologies, the problem of power coupling effect can be avoided by incorporating transformer with multiple primary windings [8]. But, the presence of multi-winding transformer with larger core size makes the system more bulky and complicated, even though it provides electrical isolation. A systematic and generalized approach for the development of MDCs are discussed in [9]-[11]. An MDC with a buck-boost operation is described in [12]. But the polarity of the converter is negative even though the converter has less number of components. Additional arrangements like the transformer are required to convert the polarity of the output voltage to positive that may cause a drastic reduction in system efficiency. The concept of dual input DC-DC converter which is capable for bidirectional interfacing of input energy sources is discussed in [13]. But the power losses due to the reverse recovery currents of output diodes leads to lower system efficiency, which is a major drawback of the converter. Several MDC topologies for the applications like renewable energy integration, electric vehicle, etc., are reported in [14]-[17]. The idea of a high step-up DC-DC converters for solar PV application is presented in [18]-[19]. The converter has lower voltage stress on switches, but for *n*-input mode, it requires *n* switches and *n* inductors which make the system complicated and expensive. A multi-input voltage summation converter is proposed in [20]. The converter operation is based on the switched capacitor cells present in the input side. But for *n*-input mode, the number of capacitors and switches will be *n* which increases the overall system complexity. The concept of multi-phase step up DC-DC converter topology with voltage doubler rectifier are discussed in [21]. The idea of multi level DC-DC boost converter for high voltage gain application is presented in [22]. A transformerless switched capacitor based buck-boost converter model is proposed in [23]. Higher voltage gain and good efficicency profile are the potential merits of the proposed converter compared to the conventional buck-boost converter.

So, many of the converters reported in the literature have certain drawbacks such as incapable of simultaneous power supply from the connected energy sources, complex structure, lack of bidirectional power flow capacity etc. Hence in this paper, an attempt has been made to propose a Modified Dual Input DC-DC (MDIDC) converter which has series and parallel power supply capabilities from the connected energy sources, both unidirectional and bidirectional power flow capacity etc., with higher efficiency and lower expenses. The proposed converter is well sufficient to handle two distinct V- I characteristic sources where the energy from the input sources can supply to the load either individually or concurrently. The converter is capable of operating in all the three basic types of operation of DC-DC converter (buck, buck-boost and boost type). The principle of operation and detailed analysis of the converter are illustrated in the following sections.

2. MODIFIED DUAL INPUT DC-DC CONVERTER

The modified dual input DC-DC converter proposed in the paper is derived from the standard single input DC-DC converter. Similar to the conventional converters, MDIDC converter also contains an inductor and capacitor for the power flow from source to a load. The structure of MDIDC converter is shown in Figure 1. The analysis of the proposed converter topology has been carried out by considering two input sources V_1 and V_2 respectively. The MDIDC converter has four main power switches (S_{W1}-S_{W4}) and two optional power switches (S_{D1} and S_{D2}) to make the converter capable of operating in both the unidirectional and bidirectional modes of operation. If the converter needs to be operated only in unidirectional mode, the optional power switches S_{D1} and S_{D2} can be replaced by simple fast recovery diodes D_1 and D_2. Here the power switches S_{W1}-S_{W3} determines the parallel and series operation of the converter and the operation of the power switches S_{W4}, S_{D1} and S_{D2} decide the possible operation types of the converter (buck, buck-boost, boost). All the possible working states of the converter under buck-boost operation based on the control of power switches available in the converter are shown Figure 2 (a-d) and briefily illustrated in Table 1.

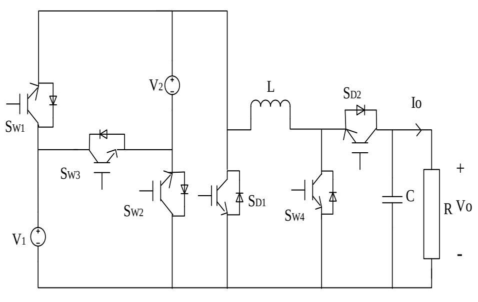


Figure 1. Basic structure of MDIDC converter

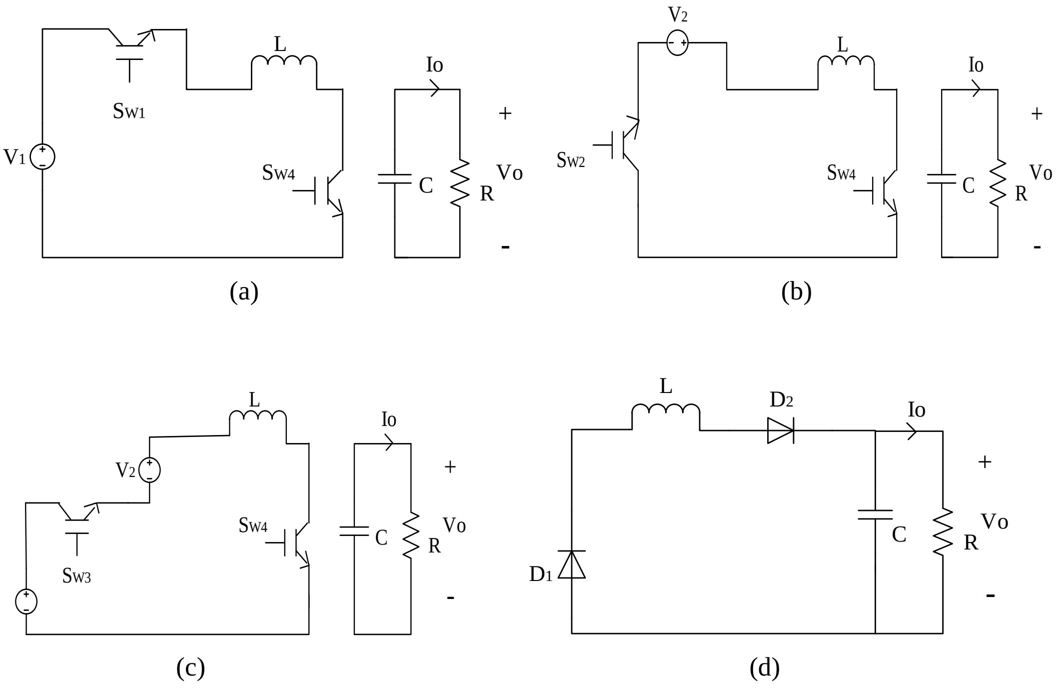


Figure 2. Working states of MDIDC converter: (a) Source V_1 delivers power, (b) source V_2 deliver power, (c) sources V_1 and V_2 together delivers power (d) freewheeling of the output current

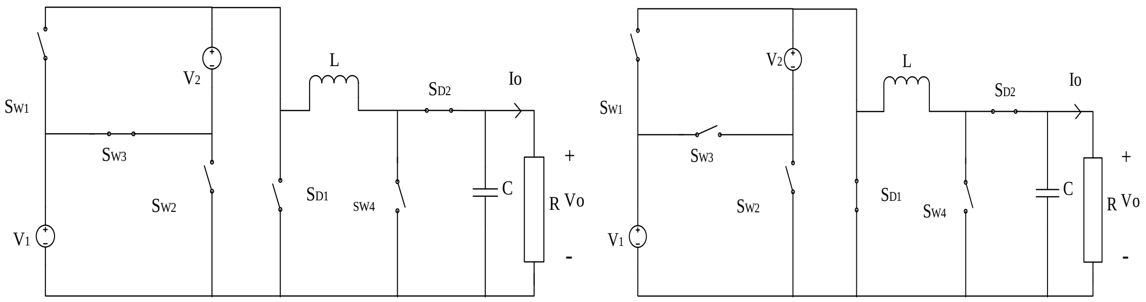
Table 1. Different working states of the MDIDC in buck-boost type operation

Working state	Sources supplying	Conducting switch	Voltage across the inductor	Status of inductor
State-1	V_1	S_{W1}, S_{W4}	V_1	Charging
State-2	V_2	S_{W2}, S_{W4}	V_2	Charging
State-3	V_1+V_2	S_{W3}, S_{W4}	V_1+V_2	Charging
State-4	None	D_1, D_2	$-V_0$	Discharging

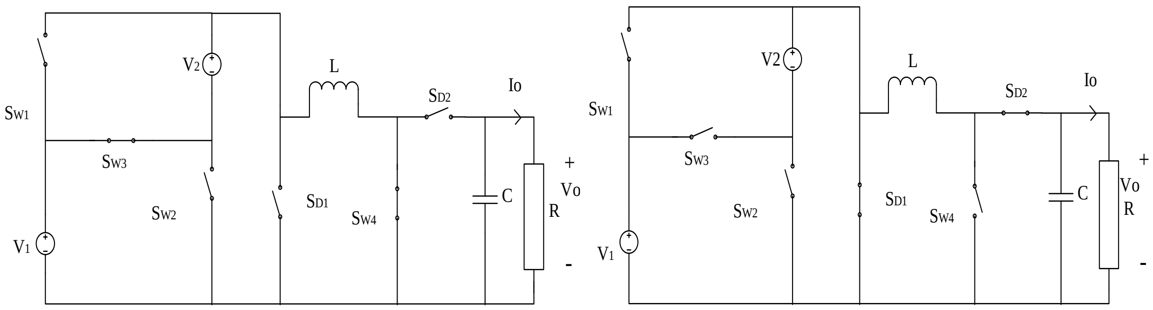
State 1: The circuit representation of state 1 is given in Figure 2a. Here, the switches S_{W1} and S_{W4} conducts, where the remaining switches are in OFF state. So, here the voltage source V_1 charges the inductor.
State 2: The equivalent circuit of state 2 is given in Figure 2b. Here, the switches S_{W2} and S_{W4} conducts, where the remaining switches are in OFF state. In this state the voltage source V_2 charges the inductor.
State 3: State 3 operation is illustrated in Figure 2c. The conducting switches in this state are S_{W3} and S_{W4} and remaining switches are in OFF state. When the switch S_{W3} is conducting, the input sources are added together (V_1+V_2) and charges the inductor.
State 4: The equivalent circuit for the state 4 operation is given in Figure 2d. In this state only the diodes D_1 and D_2 are conducting, while all other switches are in OFF state. So, the stored energy in the inductor is dissipated to the load through diode D_1 and D_2. In this case of the unidirectional mode of operation, instead of power switches S_{D1} and S_{D2}, diodes D_1 and D_2 are considered in for the better understanding of the working states.

2.1. Buck, buck-boost and boost types of operation of the MDIDC converter

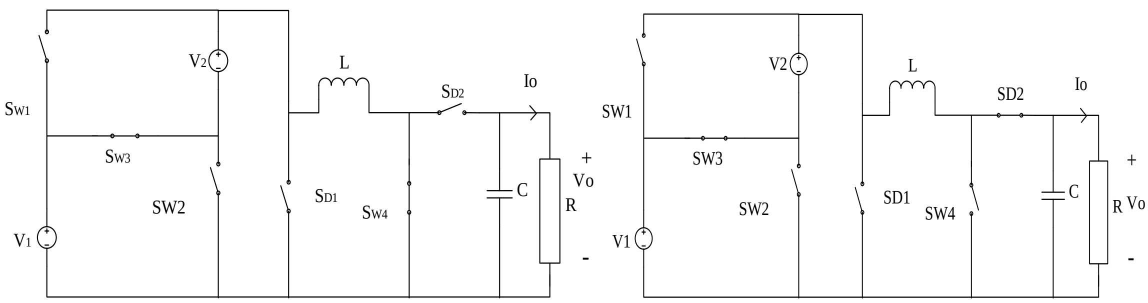
By the proper control of the power switches available in the converter, it is possible to operate the proposed MDIDC converter in all the three basic types of operation of the DC-DC converter such as buck, buck-boost and boost as shown in Figure 3(a-c). To explain the unidirectional operation of the converter, control of S_{W3} is alone considered. When the switch S_{W3} is turned ON, both voltage sources V_1 and V_2 are connected in series. Similarly, the converter can be operated in another three type by controlling S_{W1} (source V_1 alone) and three more type by controlling S_{W2} (source V_2 alone). Similarly, the converter can be operated in the bidirectional mode of operation by the proper control of the power switches, which makes the proposed MDIDC converter suitable for the applications like the electric vehicle, aerospace etc. However, in this paper, main concentration has been given to the analysis of the MDIDC converter in the unidirectional mode of operation; hence the detailed analysis of the converter in the bidirectional mode in both simulation and experimental platform can be considered as a future scope of the proposed work.



(a)



(b)



(c)

Figure 3. The MDIDC converter under different modes of operation: (a) buck operation, (b) buck-boost operation and (c) boost operation

2.2. Analysis of the MDIDC converter

The analysis of the MDIDC converter for the buck-boost type of operation has been carried out in Continuous Conduction Mode (CCM) of inductor under steady state condition. The variation of inductor voltage and current due to the change of working states in single switching cycle are illustrated in Figure 4. The necessary analytical equations that are sufficient to explain different operating states of the converter under the buck-boost mode of operation are given below. In this paper a different pulse generation scheme has been selected, where the initial switching pulse is provided to the power switch S_{W3} which ensures the contribution of both input sources together. Then the switching pulse is applied to the power switch S_{W2} which confirms the power delivery from source V_2 alone. The power delivery from source V_1 alone can be ensured by giving proper switching pulse to the power switch S_{W1}. However, in this paper, the operation of the power switch S_{W2} and S_{W3} are considered under buck-boost operation, which also ensures the contribution from all the connected energy sources. During, the operation of switch S_{W3}, the voltage across the inductor is V_1+V_2. Hence, the inductor current in this state can be derived as

$$i_L = i_{L(0)} + \frac{1}{L}\int_0^{d_3T} v_L \ dt \quad (1)$$

Here, $V_L = V_1 + V_2$, hence Eqn. (1) becomes

$$i_L = i_{L(0)} + \frac{1}{L}\ (V_1 + V_2)d_3T \quad (2)$$

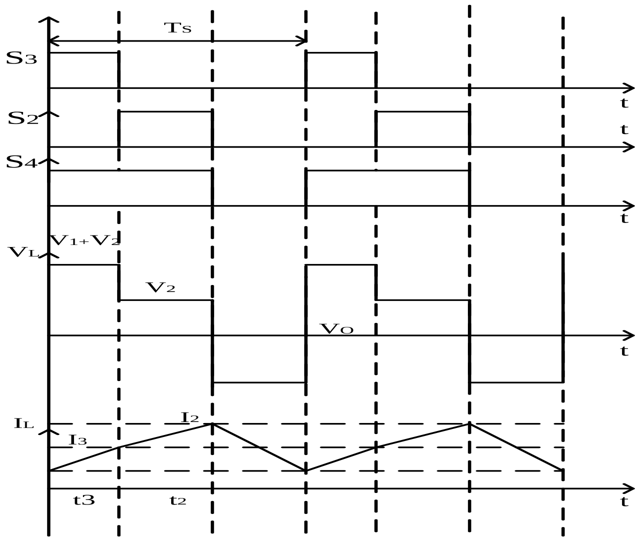


Figure 4. Analytical wave form of the MDIDC converter under buck-boost operation

During, the operation of switch S_{W2}, the voltage across the inductor is V_2. Hence the inductor current in this state cand be depicted as,

$$i_L = i_{L(1)} + \frac{1}{L}\int_{d_3T}^{(d_3+d_2)T} v_L \ dt \quad (3)$$

In this state $V_L = V_2$, hence Eqn. (3) becomes

$$i_L = i_{L(3)} + \frac{1}{L}\ (V_2)d_2T \quad (4)$$

Since $V_1 + V_2 \ \geq V_2$, the increase in slope of the inductor current in the previous interval is higher than the same value in current time interval. Finally, the stored energy in the inductor is dissipated to the load through the diodes D_1 and D_2 in the freewheeling period and the current through the inductor in this state can be extracted as

$$i_L = i_{L(2)} + \frac{1}{L}\int_{(d_3+d_2)T}^{T} V_L \ dt \quad (5)$$

In this case, $v_L = -v_c = -v_o$; so Eqn. (5) becomes

$$i_L = i_{L(2)} - \frac{1}{L}\ V_c\ [T(1-(d_3+d_2)] \quad (6)$$

Since the voltage across the inductor is negative, (ie., $-v_c < 0$) the inductor current decreases from its previous value ($i_{L(3)}$). According to the volt-second balance equation, the average value of the inductor voltage should be zero for a DC-DC converter under steady state condition and is expressed as

$$(V_1 + V_2)d_3 + V_2d_2 - V_0(1 - d_3 - d_2) = 0 \quad (7)$$

The output voltage of the converter from the above expression can be derived as

$$V_0 = \frac{(V_1+V_2)d_3+V_2d_2}{(1-d_3-d_2)} \quad (8)$$

Similar analysis can be carried out for the MDIDC converter in buck and boost operation also. The expression for the output voltage under all the three basic types of operation (buck, buck-boost, and boost) by considering the individual and simulataneous power contribution from the conneceted energy sources can be briefly concluded in Table 2.

Table 2. Theoretical analysis of the proposed converter in buck, buck-boost and boost operation

Mode	Input Voltage		Duty Ratio			Output Voltage	Conducting Switches (t_{on})	Conducting Switches (t_{off})
buck	V_1	V_2	d_1	d_2	d_3	$V_0 = V_1d_1 + V_2d_2 + (V_1 + V_2)d_3$	S_1, S_2, S_3	D_1, D_2
buck-boost	V_1	V_2	d_1	d_2	d_3	$v_0 = \frac{V_1d_1+V_2d_2+(V_1+V_2)d_3}{(1-d_1-d_2-d_3)}$	S_1, S_2, S_3, S_4	D_1, D_2
boost	V_1	V_2	d_1	d_2	d_3	$V_0 = \frac{V_1(d_1+d_3)+V_2(1+d_1)}{(1-d_1-d_3)}$	S_1, S_2, S_3, S_4	S_2, D_2

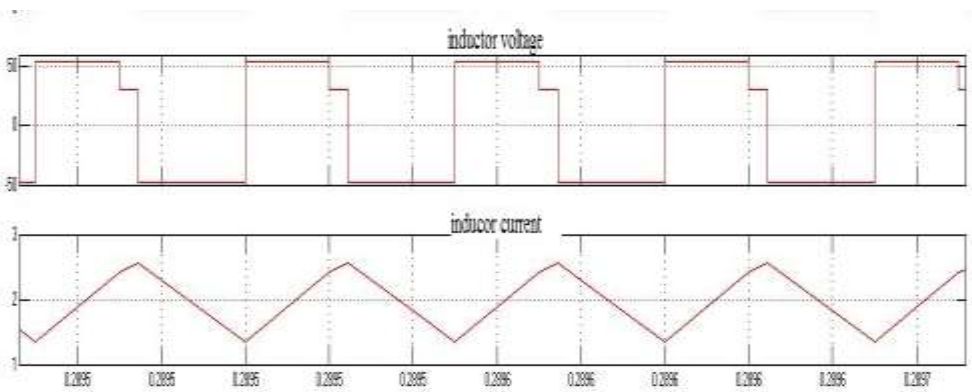
3. SIMULATION RESULTS AND ANALYSIS

The software simulation of the MDIDC converter has been carried out in MATLAB/Simulink platform. The various parameters considered for the simulation and experimental analysis are given in Table 3. Since the MDIDC converter is intended for the applications like renewable energy integration, only the buck-boost and boost operation of the converter is considered for the simulation and experimental analysis. Because the voltage profile of the renewable sources like solar-PV and wind is very low, hence it requires boost operation rather than buck operation. The simulation results of MDIDC converter for buck-boost and boost operation are shown in Figure 5 and Figure 6. From Figure 5 (a), it can be noticed that the inductor is initially charged by a voltage of 54 V (i.e., V_1+V_2) for a duty cycle of d_3 and then charged by a voltage of 30 V (i.e., V_2) for a duty cycle of d_2. Finally, the inductor is discharged with a voltage of -48 V(i.e., $-V_O$) in the freewheeling period. The variation in the slope of inductor current according to the charging voltage of the inductor can be observed from the inductor current waveform shown in Figure 5 (a). Similarly, from Figure 6 (a), it can be observed that the inductor is initially charged by a voltage of 24 V (i.e., V_1) for the conduction period of S_{W1}. Then it is charged by the voltage of 54 V (i.e., V_1+V_2), and 30 V (i,e., V_2) for duty cycle d_3 and d_2 respectively. Finally, it is discharged with a voltage of -80 V (i.e., V_2-V_O) for the remaining period. From Figure 5 and Figure 6, the process of the inductor charging and discharging can be clearly observed in terms of inductor voltage and current. Hence by adjusting the duty cycles d_1, d_2, and d_3 the inductor and load currents can be controlled.

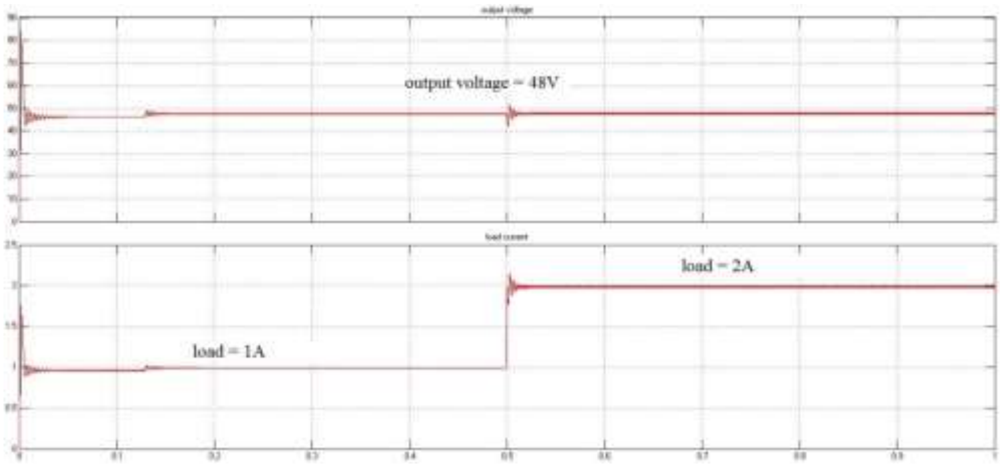
The dynamic characteristic of the MDIDC converter in buck-boost operation is analyzed to the variation in load resistance and simulation result of the same is shown in Figure 5 (b). In this paper, a control strategy based on a PI controller is selected for maintaining the output voltage at the desired value of 48 V (i.e., V_O). Here a step change in load current from 1 A to 2 A is applied at 0.5 seconds to observe the dynamic response of the converter under load variations. From Figure 5 (b), it can be noticed that the output voltage is returned to the required value of 48 V very quickly after a small dip due to the sudden rise in load current. Similarly, the dynamic response of the converter under boost operation also tested with the same PI controller. In this case, also, a sudden change in load current from 2.3 A to 4.6 A is applied at 0.5 second and corresponding output voltage response has been observed from Figure 6 (b). From the figure, it can be observed that the output voltage is recovered to the desired value of 110 V (i.e., V_O) within a short span of time after a small dip in its magnitude due to the sudden load current increment. Hence, from Figure 5 (b) and Figure 6 (b), it can be concluded that the designed controller is very effective for regulating the output voltage at their desired values under buck-boost and boost operation.

Table 3. Design parameters considered for simulation and experimental analysis

Source 1 (V)	Source 2 (V)	Inductor (mH)	Capacitor (μF)	Switching Frequency (kHz)	Output Voltage (V) Buck-boost	Output Voltage (V) Boost
24	30	3	470	20	48	110



(a)



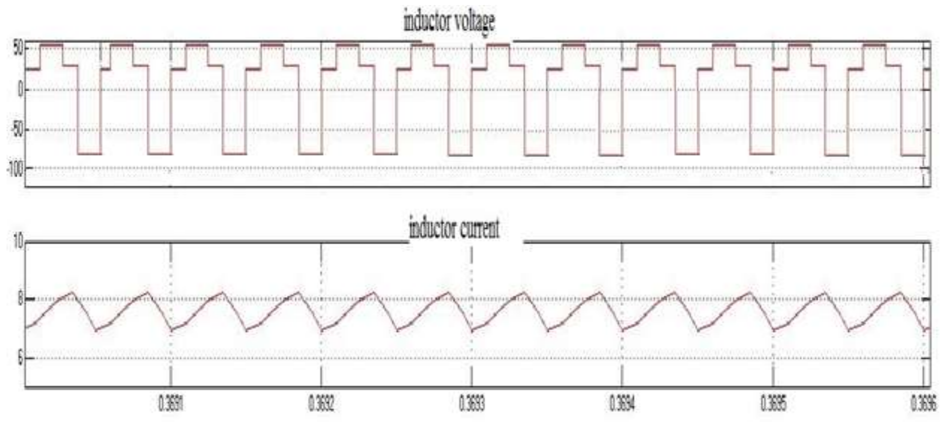
(b)

Figure 5. Simulation waveforms of the MDIDC converter under buck-boost operation (a) Inductor voltage and current (b) Output voltage and current under varying load conditions

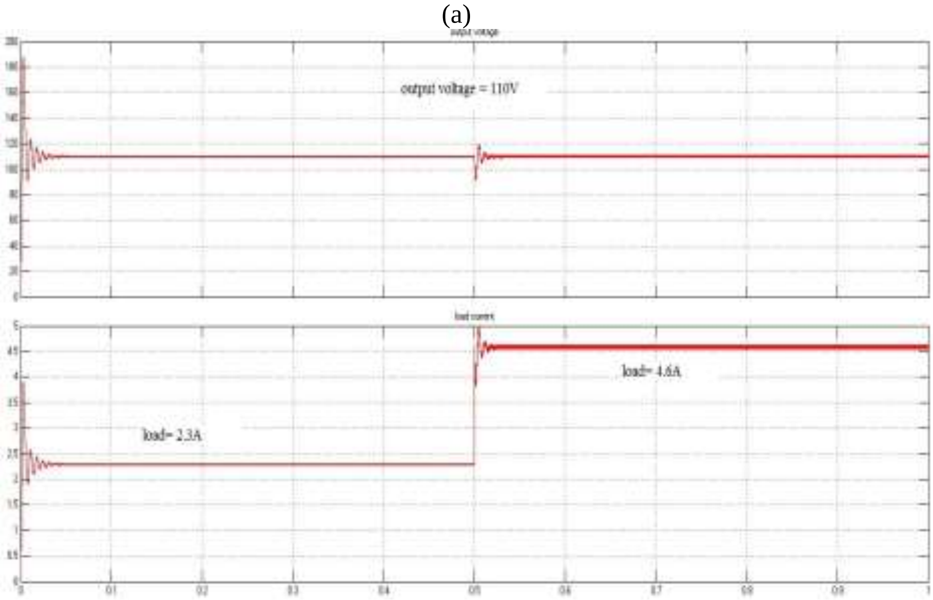
4. EXPERIMENTAL RESULTS AND DISCUSSION

To test the feasibility and performance of the MDIDC converter, a laboratory scale hardware prototype of the converter has been developed as shown in Figure 7. The testing of the prototype has been conducted by considering two input sources of the different voltage level. The switching pulses for the converter have been generated by using LabVIEW 2013 software and the real-time interfacing with the hardware has been achieved with the help of NI cRIO-9081 controller using NI 9401 digital input and output module. Here, NI 9225 and NI 9227 modules are adopted for sensing the voltage and current. The generated switching pulses are of 20 kHz frequency and IRF 460 MOSFET and MUR 860 respectively realize the power switches and diodes. The experimental analysis of the converter has been carried out for CCM of inductor under steady state condition. The converter performance under buck-boost and boost operation has been verifeied and the experimental waveforms of the inductor voltage, inductor current, output voltage and output current for buck-boost and boost operation are shown in Figures 8 and Figure 9 respectively.

The charging and discharging phenomena of inductor under buck-boost and boost operation have been observed from the inductor voltage and current waveforms shown in Figure 8 (a) and Figure 9 (a) respectively. The output voltage of the MDIDC converter is obtained as 48 V (Figure. 8 (b)) in buck-boost operation and 110 V (Figure 9 (b)) in boost operation. Hence, from the analysis of the experimental results, it can be clearly noticed that the results obtained from the experimental prototype and MATLAB simulation are well matched. A transient analysis of the converter is carried out in buck-boost operation to observe the dynamic behaviour of the MDIDC converter under varying load condition. The response of the output voltage and current due to the load variation are shown in Figure 8 (b) and Figure 8 (c). From Figure 8 (b) it can be noticed that the output voltage of the converter is maintained at the required value of 48 V under sudden variation of load current from 1 A to 2 A. Similarly, when the load current falls from 2 A to 1 A, the output voltage is returned to 48 V very quickly after a small spike as shown in Figure 8 (c). So, the transient analysis of the converter in the experimental platform shows the effectiveness of the controller designed.



(a)



(b)

Figure 6. Simulation waveforms of the MDIDC converter under boost operation (a) Inductor voltage and current (b) Output voltage and current under varying load conditions

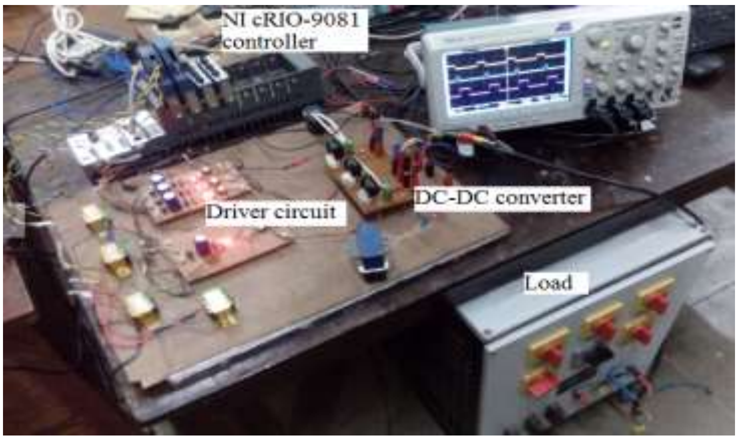


Figure 7. Experimental setup of MDIDC converter with controller

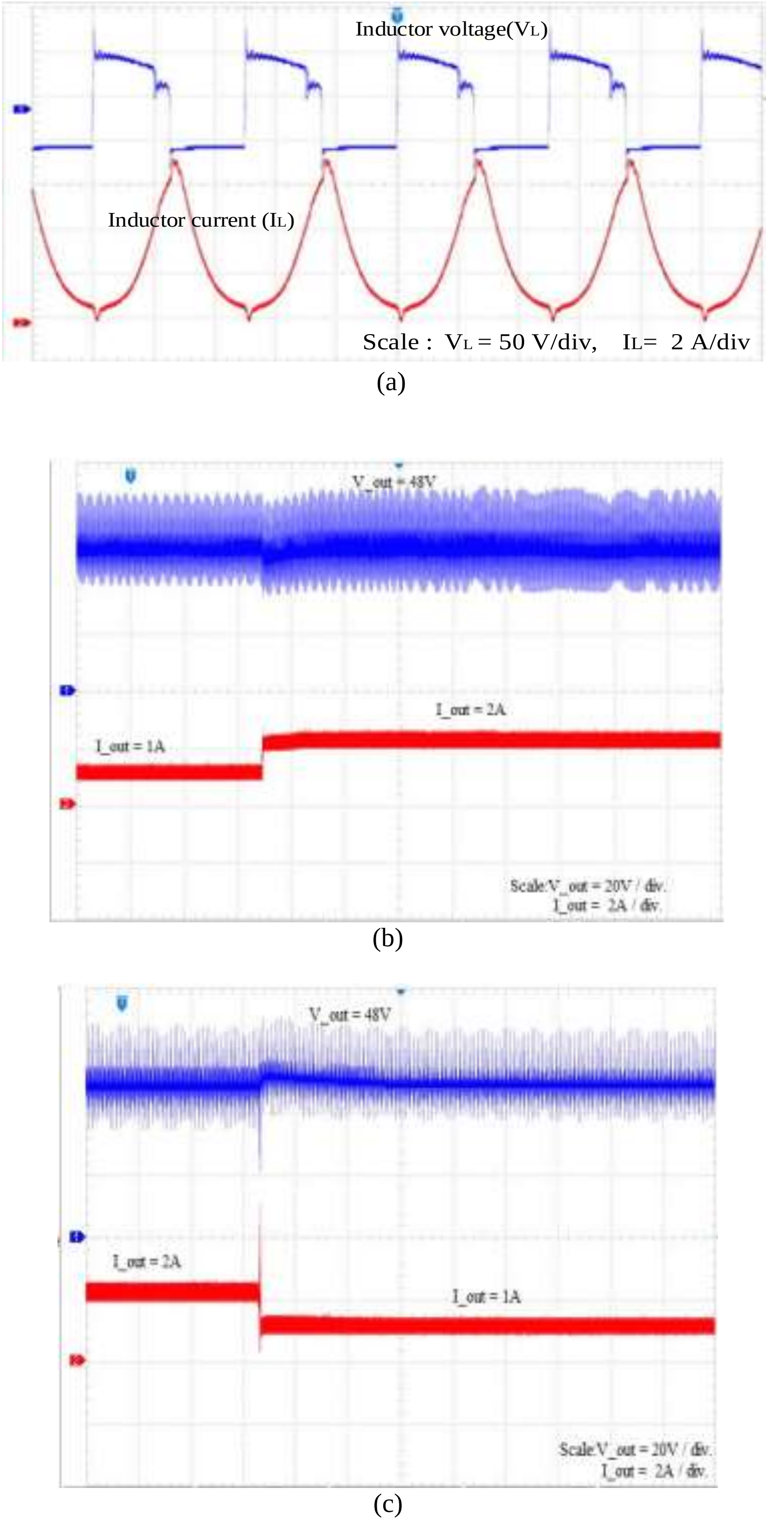


Figure 8. Experimental wave forms MDIDC converter under buck-boost operation (a) Inductor voltage and current wave form (b) Output voltage response due to sudden load current increment (c) Output voltage response due to sudden load current decrement

Finally the comparison MDIDC with other multi input DC-DC converters has been carried out based on several parameters like number of power switches, diodes, storage elements efficiency and voltage stress and are illustrated in Table 4.

Table 4. Comparison of the MDIDC with other multi input DC-DC converters

Topology proposed	Number of switches (Including diodes)	Inductor (L)	Capacitor (C)	Voltage stress (V)	Operating modes	Efficiency (%)
Converter in [4]	2N	N	1	V_o	BD, B	80-90
Converter in [7]	N+4	1	1	V_N	BD, b,b-B,B	82-91
Converter in [12]	N+1	1	1	V_N-V_{N-1}	UD, b-B	82-93
Proposed converter	N+4	1	1	V_N	BD, b,b-B,B	84-93

(Bd: bidirectional, UD: unidirectional, N: Number of input sources, b: buck mode, b-B: buck-boost mode, B: boost mode)

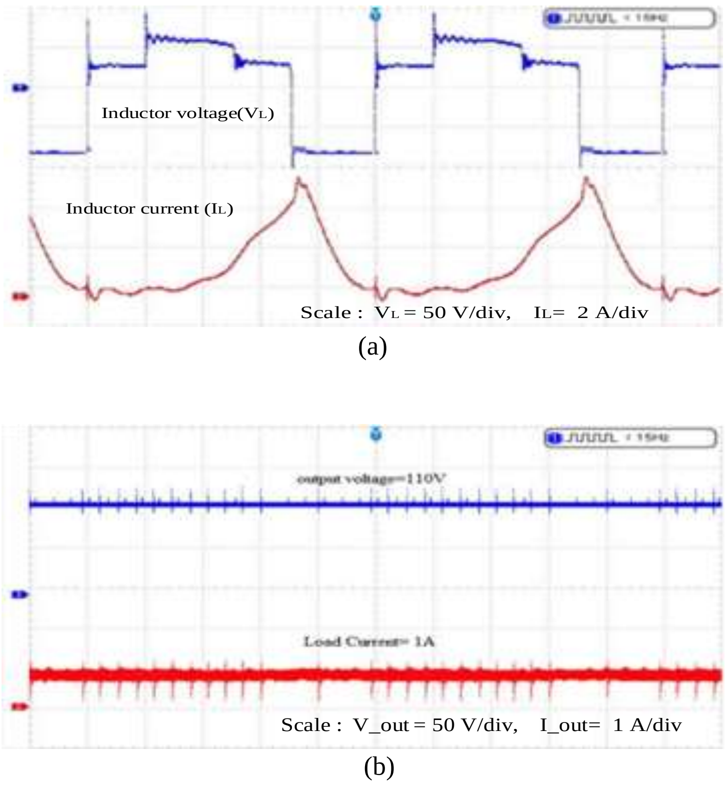


Figure 9. Experimental wave forms MDIDC converter under boost operation (a) Inductor voltage and current wave form (b) Output voltage and current waveform

5. CONCLUSION

A modified dual input DC-DC converter is proposed in this paper, which is capable of integrating different V-I characteristic sources. The analysis of the proposed converter under buck-boost and boost operation has been conducted in a comprehensive manner. The analysis of the proposed converter in the experimental platform has been conducted in a detailed manner to validate the simulation results. From the experimental and simulation analysis, the dynamic and steady state response of the converter have been found satisfactory. The proposed MDIDC converter is well sufficient for energy diversification from the different V-I characteristic source either individually or simultaneously. The proposed MDIDC converter has close-packed structure and lower part counts, which enhances the overall system efficiency and also boost the relevance of the converter in the applications like distributed generation, hybrid energy integration, electric vehicle, aerospace, etc.

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