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# Control strategy for modified CI-based Bi-directional Γ-Z source DC-DC converter for buck-boost operation

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**ABSTRACT**

This paper introduces a novel Bi-directional coupled-inductor (CI) based Γ-Z source converter for step up-step down DC application. It is a modified version of CI based Γ-Z high gain converter. The converter originates under the family of impedance networks with two winding coupled inductor. The said converter when operated with low duty ratio makes converter to achieve high gain compared to conventional DC-DC converters. As the society is in trend with electric vehicles (EV's) are recommending operating the converters in Bi-directional mode to have continuous power flow when those are operated with green technologies. So, the same converter is initially operated and verified as buck and boost converter in open loop mode. Nearly 38 and 4 voltage-gain in boost and buck mode was observed when realized in MATLAB environment for the designed inductor and capacitor values with 49% and 1% duty cycle respectively under open-loop configuration. In the succeeding a PID controller based closed loop control strategy has implemented for the same converter. Gain sensitivity of the converter had been verified in MATLAB Simulink environment. Results obtained from simulation and mathematical found satisfactory in open and closed loop.



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## 1. INTRODUCTION

In recent years, sustainable energy resources became essential for the near future to power grid. Energy storage technologies flourishing for reliable and continuous power to ensure un-interrupted power. Non-conventional electrical energy generation was introduced [1] to store energy when there is surplus power. Renewable energy, like solar, wind, tidal, and geothermal, can be generated in globally or locally. Energy storage technologies were initiated to back up the energy in other forms like chemical, mechanical, thermal, and electrochemical discussed in [2], [3]. Integration related issues such as stability, efficiency, reliability and climatic conditions which are unavoidable with renewables, when they are proposed for energy storage are addressed in [4].

Energy storage systems are the censoriously focused on the electric grids and automotive applications especially EV's. The form of input that needed to store energy in an energy storage device such as capacitor or battery is DC, many a times it is a conversion form of AC when storage system is power with conventional generation. But when charged with renewable energy sources DC-DC converters will be used with regulated power in buck/boost mode of operating proposed in [5], [6].

In the last two decades a rapid work progress was observed in grid interfaced DC-DC converter topologies. Impedance network is one such DC-DC converter popular because of loss less elements and high voltage gain. They are categorized based on combination of passive elements, such as Inductor, capacitor, and coupled inductor, used. Isolated and non-isolated are the two possible converter technologies categorized under this. Numerous impedance converter topologies were discussed for high voltage gain applications in [7]–[15].

A key observation made from the literature survey is that the voltage gain is high of a coupled inductor-based impedance networks with low duty ratio. This feature offered to these converter topologies because of their magnetizing currents and mutual inductance. A gamma (Γ)-Z source network has a better voltage gain compared to all coupled inductor (CI) based DC-DC converter. It has an additional advantage like with less winding turns between the range of 1<w<2 offers high voltage gain operating with an inverter is discussed in [16]–[22]. Owing to this advantage chosen CI-based Γ-Z source DC-DC converter for buck-boost operation in grid connected energy storage system, EV charging applications and pulsed power technology [23]–[27]. The mentioned (CI-based Γ-Z source DC-DC converter) by its nature will work as a high gain DC-DC converter under open circuit (OC) condition proposed in [23], but not focused on buck operation and more over the gain is load sensitive.

In this paper an attempt has been made to alter the converter topology by introducing one more controlled switch in the network to get buck operation. In addition, a closed loop control strategy is explored and implemented with the proposed Bi-directional Γ-Z DC-DC converter to avoid gain load sensitive. The gamma Z source converter is analyzed, designed, and implemented as Bi-directional converter as per the block diagram as per Figure 1.

Section wise is coverage as follows, in section 2 discussed the circuit operation of proposed CI-based Bi-directional DC-DC buck-boost converter. Section 3 covers the design and gain sensitivity of proposed converter. Closed loop control strategy for the demonstrated converter has represented in section 4. Conclusions were discussed in section 5.

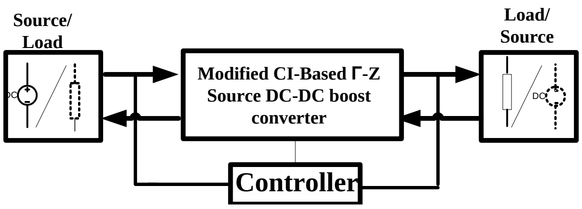


Figure 1. Block diagram of proposed modified CI-based Bi-directional DC-DC buck-boost converter

## 2. PROPOSED CI-BASED BI-DIRECTIONAL DC-DC BUCK-BOOST CONVERTER

The unique structure retrieved from the category of CI-based impedance networks for its less leakage inductance and better co-efficient of coupling. The converter shown in Figure 2, is the modified version of above said converter family. It has one extra switch in the converter to make the proposed converter Bi-directional. The proposed Bi-directional converter gains made insensitive to load and source variation for buck and boost modes of operations.

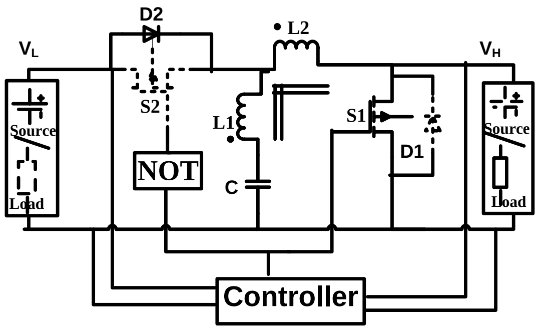


Figure 2. Circuit diagram of proposed CI-based Bi-directional DC-DC buck-boost converter

The proposed converter consists coupled inductor with two windings (L1 & L2), capacitor (C), MOSFET devices (S1 & S2), diodes (D1 & D2). Low voltage ($V_L$), and high voltage ($V_H$) are the bus voltages at input and at output ports converter shown in Figure 2. The converter is operated as boost converter when Switch (S1) and Diode (D2) will be in active state and other devices like S2 and D1 will be in non-active state and vice-versa for buck conversion as shown in Figures 3 and 4 respectively.

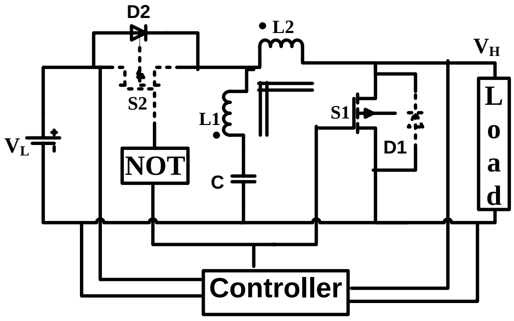


Figure 3. Conductions states of S1, D1, S2, and D2 in boost mode of circuit shown in Figure 2

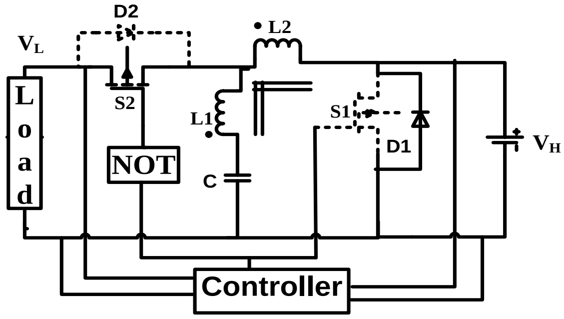


Figure 4. Conductions states of S1, D1, S2, and D2 in boost mode of circuit shown in Figure 2

### 2.1. Boost mode of operation

The equivalent circuit for this mode of operation is shown in Figure 3. Devices with dotted lines shown in Figure 3, has not been considered for analysis, because of non-active states. The mathematical analysis of the converter shown in Figure 3. In boost mode depends on conduction states of S1 and D2. Switch (S1) is ON for a period of D (duty ratio), the diode (D1) is reversed biased because the potential is high at coupled inductor compared to VL then the circuit is shown in Figure 5(a).

By applying KVL in loop in which S1 is present,

$$V_C + V_{L2} - V_{L1} = 0 \tag{1}$$

where VL1, VL2 are the voltage across coupled inductor of L1 and L2. The turns ratio (W) relationship between the coupled inductor is

$$\frac{V_{L1}}{V_{L2}} = W \tag{2}$$

By simplification,

$$V_{L2} = \frac{V_C}{(W-1)} \tag{3}$$

when the switch (S1) is in OFF for a period of (1-D), then the diode (D1) gets forward biased as per the circuit shown in Figure 5(b). By KVL in the circuit,

$$V_{dc} - V_{L2} - V_C = 0 \tag{4}$$

By utilization of (3) in (4),

$$V_{dc} = V_C\left[\frac{1}{W-1} + 1\right] \tag{5}$$

By the concept of averaging technique for the periods of D and (1-D) then,

$$(V_{dc} - V_C)(1 - D) = \frac{V_C}{(W-1)}D \tag{6}$$

By reduction of (6),

$$V_C = \frac{V_{dc}(1-D)}{1-\left(1+\frac{1}{(W-1)}\right)D} \tag{7}$$

It is clear from (7) that, the output voltage is determined the switching action of S1. From the (7), it is observed that the output voltage of the converter will be determined when the switch (S1) is in OFF state. Therefore,

$$\left(1+\frac{1}{(W-1)}\right)=G. \quad (8)$$

The gain is related with windings turns ratio of coupled inductors shown in (8), the boundary limits of turn's ratio is in between 1 to 2 (1<W>2). The relation between output voltage with gain, duty cycle and input voltage are shown in (9).

$$Vo=\frac{V_{dc}}{1-GD} \quad (9)$$


Figure 5. Switching states of S1 and D2 in (a) S1-ON and D2-OFF and (b) S1-OFF and D2-ON

### 2.2. Buck mode of operation

The equivalent circuit for this mode of operation is shown in Figure 4. Under this mode of operation switch (S2) will be in ON state, then the source is supplied to the load as per the circuit diagram Figure 6(a).

$$V_{dc}=V_{L1}+V_{C1}=V_{L2}+V_o \quad (10)$$

Under this mode, the switch (S2) is in OFF state the source disconnects from the source. So, the demand of the load will be taken care by coupled inductor and capacitance as per the circuit in Figure 6(b).


Figure 6. Switching state of S2 of (a) ON state of S2 and (b) OFF state of S2

In this mode, depending upon the charging capacity of inductor and capacitor, either inductor or capacitor will lead the load. So, sometimes capacitor will lead the coupled inductor and load or sometimes coupled inductor will lead the capacitor and load. By the charging and discharging of inductor and capacitor meets the demand of the load. So, the equivalent energy produced by coupled inductor and capacitor resultant to zero.

$$V_o=0 \quad (11)$$

By Implementing the averaging technique for both the modes of operation,

$$V_o=(V_{dc}-V_{L2})D \quad (12)$$

The relation between output voltage with gain, duty cycle and input voltage in buck mode is given by (12).

## 3. RESULTS AND DISCUSSION

### 3.1. Design features

The energy stored in the coupled inductor matters the reduction of output voltage. The output voltage of the converter is less compared to source voltage. With the same specifications the converter is operated as buck converter. To observe the maximum buck of the converter then the duty ratio is applied with 1% under open loop configuration. The simulated results of input and output voltage waveforms are presented in Figure 7.
Converter input voltage (Vdc)=15 volts,
Coupled inductor one of coil Inductance (L1)=2.98e-4 Henry,
Coupled inductor second of coil Inductance (L2)=6e-4 Henry,
Coefficient of coupling(K)= 0.99,
Mutual Inductance (Lm)=4.2e-4 Henry,
Converter capacitor(C1)=470e-6 Farads,
Filter capacitance(C2)=470e-6 Farads,
Load Resistance (RL)=200 Ohm,
Turns ratio between the coils (W)=1.43,
Switching frequency(fs)=10 kHz,
With the above said specifications, the converter is simulated in the MATLAB Simulink environment.

### 3.2. Gain sensitivity

To observe the effect of load on the gain of the proposed Bi-directional DC-DC buck-boost converter simulated for various test conditions. In the initial stage the converter is analyzed in open loop mode with a fixed input voltage (15 V) and 20% duty ratio. Results of the proposed Bi-directional DC-DC buck-boost converter replicates the same and are consolidated and presented in Table 1. In addition, the proposed converter is also get effected with turn-on times of the switching devices. So, the proposed converter further simulated with different duty ratios. Table 2 gives full picture of output voltage variation with variation in the duty cycle for fixed input voltage (15 V) and fixed load resistor (200 Ω).

The proposed converter is simulated for different load conditions starting from 100-1000 Ω for buck-boost operation under open loop condition. Further it is simulated with duty ratio variation between 5-49% with fixed source voltage and resistance. It is observed that the output is boosted up to 38 times of input in boosting mode. In this case the average output is nearly 574 V for 15 V input, the same can be found in Figure 7. Further the proposed converter is simulated with the given specifications with 200 Ω load. In buck mode of operation with 200Ω load resistor the proposed converter gives nearly 40 gains. It means the output is 0.375 V for the same 15 V input voltage, the same is presented in Figure 8.

Table 1. Load voltage @20% duty ratio for various loading conditions

| S.No | Load Resistance (RL) in Ω | Boost mode Output voltage (Vo) in V | Buck mode Output voltage (Vo)volts |
|---|---|---|---|
| 1 | 100 | 74.91 | 6.10 |
| 2 | 200 | 102.1 | 8.54 |
| 3 | 300 | 122.6 | 9.85 |
| 4 | 400 | 140.4 | 10.67 |
| 5 | 500 | 155.7 | 11.22 |
| 6 | 600 | 169.8 | 11.63 |
| 7 | 700 | 181.6 | 11.94 |
| 8 | 800 | 193 | 12.18 |
| 9 | 900 | 204.7 | 12.38 |
| 10 | 1000 | 215 | 12.54 |

Table 2. Load voltage@ fixed load resistance 200Ω for different duty ratios

| S.No | Duty ratio (D') in % | Boost mode Output voltage (Vo) in V | Buck mode Output voltage (Vo)volts |
|---|---|---|---|
| 1 | 5 | 29.67 | 1.3 |
| 2 | 10 | 51.96 | 3.92 |
| 3 | 15 | 76.18 | 6.52 |
| 4 | 20 | 102.1 | 8.54 |
| 5 | 25 | 130.1 | 9.97 |
| 6 | 30 | 160 | 11.00 |
| 7 | 35 | 191.5 | 11.71 |
| 8 | 40 | 224.3 | 12.21 |
| 9 | 45 | 256.5 | 12.6 |
| 10 | 49 | 573.3 | 12.88 |

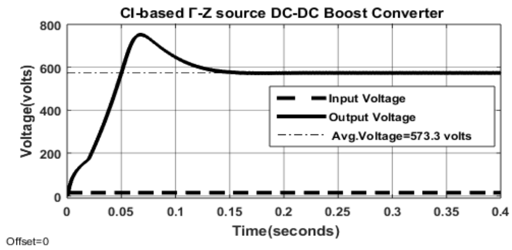


Figure 7. Input and output voltages of proposed converter in boosting mode

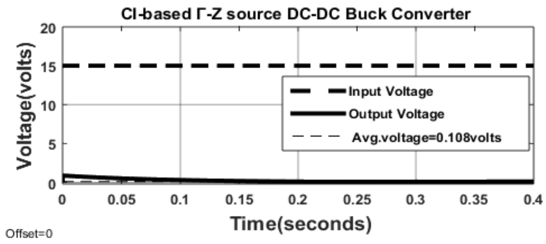


Figure 8. Input and output voltages of proposed converter in buck mode

## 4. RESULTS AND DISCUSSION ON CLOSED LOOP CONTROL STRATEGY FOR THE PROPOSED BUCK-BOOST CONVERTER

To have a load regulation closed loop control strategy is more preferred way to achieve. The load sensitivity problem can be effectively overcome with the help of PI/PID controllers in DC-DC converters. The design specifications of controller are shown in Table 3.

Table 3. Controller constants tuned for load regulation

| S.No. | Proposed Buck-Boost converter operating modes | Proportional (P) | Integral (I) |
|---|---|---|---|
| 1 | Boost mode | 1 | 2 |
| 2 | Buck mode | 2 | 10 |

### 4.1. Boost and buck mode of operation

With the help of closed loop control strategy nearly 700 V in boost mode and 10 V in buck mode respectively was observed for different loading condition starting from 100-1000 Ω are summarized in Table 4 and different input voltages are applied from 5-50 V are summarized in Table 5. Consolidated results for different loading conditions and different input variations are analyzed to verify gain sensitivity of proposed converter in boost operating mode waveforms and buck operating mode are shown in Figures 9 and 10. The output voltage and input voltage waveforms of boost operating mode are shown in Figure 9. Figures 9(a) and 9(b) shows the input and output voltage waveforms @200 Ω and 700 Ω for Vdc @15 V. Similarly Figures 9(c) and 9(d) shows the input and output voltage waveforms @200 Ω and 700 Ω for Vdc @12 V.

Table 4. Gain sensitivity in boost and buck mode using PI controller for different loads

| S.No. | Load resistance ($R_L$)ohms | Boost mode Output voltage (Vo)volts | Buck mode Output voltage (Vo)volts |
|---|---|---|---|
| 1 | 100 | 699.5 | 9.99 |
| 2 | 200 | 699.5 | 9.993 |
| 3 | 300 | 699.6 | 9.993 |
| 4 | 400 | 699.4 | 9.994 |
| 5 | 500 | 699.8 | 9.998 |
| 6 | 600 | 699.8 | 9.999 |
| 7 | 700 | 699.9 | 9.999 |
| 8 | 800 | 699.9 | 9.999 |
| 9 | 900 | 699.9 | 9.999 |
| 10 | 1000 | 699.9 | 9.999 |

Table 5. Gain sensitivity in boost and buck mode using PI controller for different input voltages

| S. No. | Input voltage (Vi)volts | Boost mode Output voltage (Vo)volts | Buck mode Output voltage (Vo)volts |
|---|---|---|---|
| 1 | 5 | 699 | 9.99 |
| 2 | 10 | 699.1 | 9.992 |
| 3 | 15 | 699.4 | 9.991 |
| 4 | 20 | 699.4 | 9.992 |
| 5 | 25 | 699.5 | 9.995 |
| 6 | 30 | 699.6 | 9.995 |
| 7 | 35 | 699.6 | 9.998 |
| 8 | 40 | 699.8 | 9.998 |
| 9 | 45 | 699.9 | 9.998 |
| 10 | 50 | 699.9 | 9.999 |

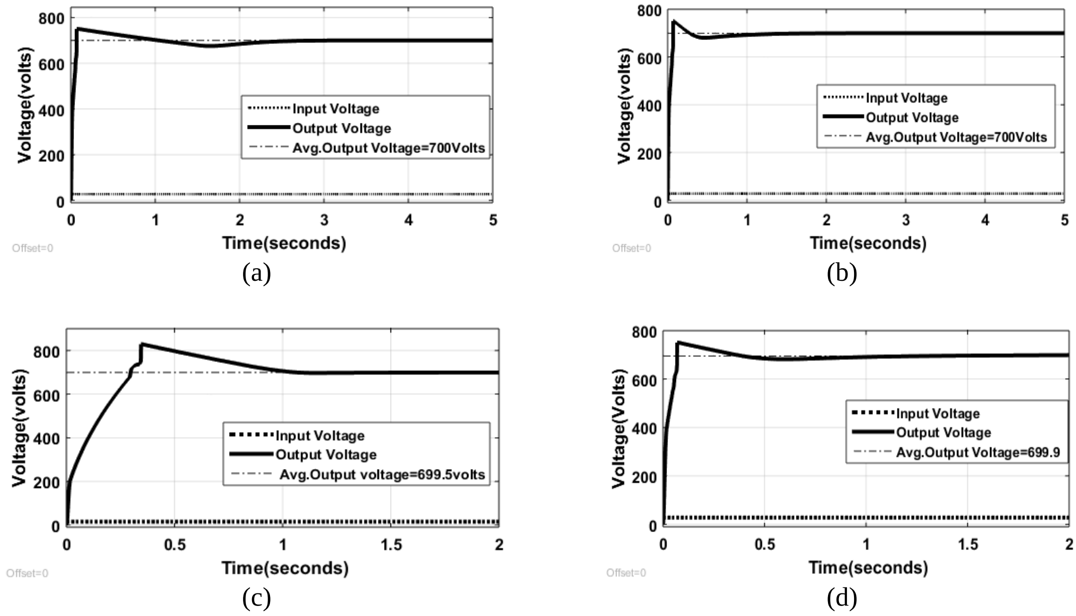


Figure 9. Output voltage (vs) input voltage graphs to verify gain sensitivity of proposed converter in boost operating mode, (a) for Vdc @15 V & $R_L$ @200 Ω, (b) for Vdc @15 V & $R_L$ @700 Ω, (c) for Vdc @12 V & $R_L$ @200 Ω, and (d) for Vdc @12 V & $R_L$ @700 Ω

The output voltage and input voltage waveforms of buck operating mode is shown in Figure 10. Figures 10(a) and 10(b) shows the input and output voltage waveforms @200 Ω and 700 Ω for Vdc @15 V. Similarly Figure 10(c) shows the input and output voltage waveforms @ 200 Ω for Vdc @12 V and Figure 10(d) shows @700 Ω for Vdc @20 V.

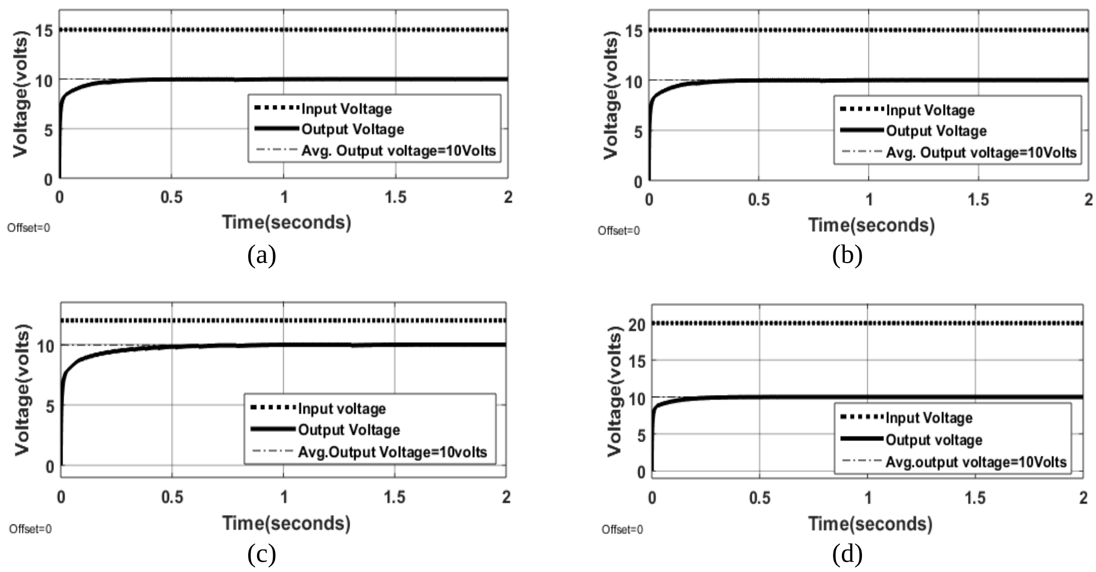


Figure 10. Output voltage (vs) input voltage graphs to verify gain sensitivity of proposed converter in buck operating mode, (a) for Vdc @15 V & $R_L$ @200 Ω, (b) for Vdc @15 V & $R_L$ @700 Ω, (c) for Vdc @12 V & $R_L$ @200 Ω, and (d) for Vdc @20 V & $R_L$ @700 Ω

## 5. CONCLUSION

A novel Bi-Directional DC-DC converter is proposed in this paper for buck-boost operation. It is a modified version of CI-based Γ-Z source DC-DC boost converter. Buck mode is added to the boost mode on adding a Bi-directional controlled switch. The proposed converter realized both in open loop and closed loop mode. Mathematical analysis has been carried out to design the values of energy storage elements inductors and capacitors of proposed converter. Gain sensitivity has been discussed in the open loop configuration and suggested a control strategy using PI controller for two modes of operations. Nearly 40 gain was observed in both buck and boost modes of operation of proposed converter. Verified all the results obtained from MATLAB simulation with that of mathematical results and are in close agreement with each other. This study helps the design engineers to explore this converter for buck-boost applications in EV charging and renewable source integration with grid with low stress on switch.

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