Performance Validation of Quadratic Bi-Directional Buck-Boost Converter

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Abstract. A new Quadratic Bi-Directional Buck-Boost Converter(QBC) is simulated and its performance is validated in this paper. The aim of this paper is to provide a new configuration of a non-isolated Buck-Boost converter with an additional inductor and capacitor and switches. Broad span of the output voltage is one of the advantages i.e., an ultra-high step-up or step-down voltage conversion ratio can be achieved using four power switches in two parallel legs. The proposed topology of QBC includes continuous low ripple input current and positive output voltage. The continuity of the input current makes this type of converters more convenient for renewable energy sources like Solar PV and also decreases the current stress on the load terminal capacitor. Simulations have been carried out in continuous current mode (CCM). Eventually, the implementation of the proposed converter topology is validated based on the simulation outcomes from MATLAB Simulink model.

Keywords: Quadratic, Topology, Solar PV, Buck-Boost, Bi-directional Converter.

1 Introduction

In recent years, the electric power demand has been highly increased and to address the solution, the usage of renewable energy sources like solar and wind as distributed generation has been highly increased and hence, the requirement of power electronic converters has also been increased. Power electronic devices and circuits especially DC-DC converters have numerous usages in utilizing the power that are generated from the renewable energy sources. Generally, a Buck-Boost Converter is an important component in many power electronic applications. Main lack in renewable energy sources is that their output voltage is very low and unstable. Therefore, the output cannot be directly linked to the load. In spite of good efficiency, the conventional Buck-Boost Converters couldn't make a broad span of load terminal voltage. Further, to have a high voltage gain, the duty cycle of the converter must be chosen close to one. Such an extreme duty cycle not only increases the voltage but also the current stresses on the power switches and diodes which in-turn reduces the efficiency of converter. In order to overcome the above mentioned shortages, the Quadratic Bi-Directional Buck-Boost Converter topology has been introduced which provides a wide range of output voltage, continuity in input and output currents which decreases the load capacitor stress due to the output current. Comparing with the conventional topology, the voltage gain ratio of the introduced converter is a quadratic form of the conventional controller[1]. The Buck-Boost

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topology has been utilized as the power interface between the storage system and the DC link in most of the EVs and HEVs, since, the topology protects the storage device whenever the short circuit fault occurs. The dual carrier modulation scheme for the switching of the semiconductor devices decreases their switching losses compared to conventional switching modulation schemes[2]. Since the nature of renewable energy sources is intermittent, there is a need to have a stable voltage at the DC bus. Conventionally, batteries are used but the continuous charging and discharging nature of the batteries reduces their lifetime of operation of batteries. Hence, the super capacitors would be the best alternative to stabilize the DC power grid[3]. The active snubber components used in the soft-switching cell consists of a switch, inductor, and a two-winding transformer along with a magnetizing current reset circuit to reduce the reverse recovery losses and made the Buck-Boost converter to have a controlled turn-off capability[4]. The problem associated with the wind turbine power generation is getting a maximum power at the output side and maintaining a constant DC link voltage against the fluctuating wind. The work described the uses battery as storage device with a bi-directional buck-boost converter used to regulate the charging and discharging cycle. Modified P&O algorithm provides the switching of quadratic buck-boost converter for obtaining the maximum output power with an efficiency of 98.16% [5]. Most of the distributed generation systems require power electronic converters between the DC buses and electrochemical storage systems like batteries and supercapacitors need Bi-Directional DC-DC converters for charging and discharging of the DC power. To maintain a high voltage gain ratio, a non-isolated bi-directional buck-boost converter with quadratic characteristics have been used with a simplified control circuit which results in longer lifetime of the storage devices[6]. Ultra-capacitors are mainly used in renewable power generations to improve the reliability and efficiency. Regulated DC bus voltage is obtained by integration of current control and linear quadratic regulator control methods and to ensure smooth transition from buck to boost and boost to buck modes operation[7]. From the literature search, whenever very high or low voltage conversion is required, the proposed Quadratic Bi-Directional Buck-Boost Converter is useful.This paper introduces an improved DC-DC converter topology with continuous low ripple input current and positive output voltage. The proposed converter is evaluated based onthe simulation outcomes from MATLAB Simulinkmodel.

2. Configurations

Fig. 1 shows a well-known Non-Inverting Bi-Directional Buck-Boost Converter. It consists of two half bridges and four switches. This type of basic converter configuration doesn’t involve the additional coil and the additional capacitor at the mid-point which makes the operation simpler with less no. of components.

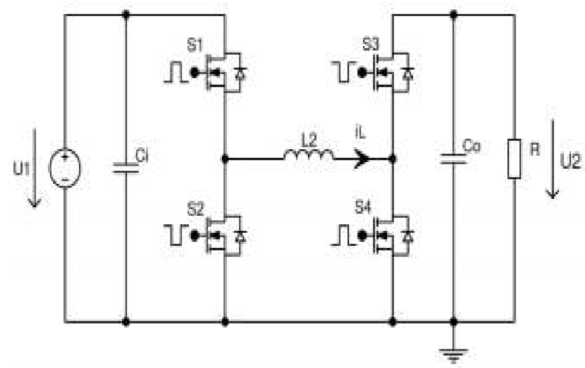

Fig. 1 Type I Configuration

The other type of configuration as shown in Fig. 2, has two Buck-Boost Converters combined together by a bulk capacitor C_1 at the mid-point. It has half-bridge drivers connected to point A and the rate of voltage transformation is same as the proposed converter configuration for the simulation.

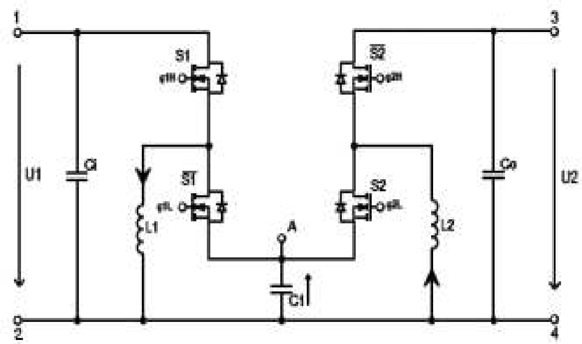

Fig. 2 Type II Configuration

3. Circuit topology

The Fig. 3 shows the circuit topology of the Quadratic Bi-Directional Buck-Boost DC-DC Converter which can step-up or step-down the output level compared to the input depending on the switching operation of the switches connected in the parallel legs. Such switching operation of the switches are controlled by the duty cycle which in-turn controls the voltage level of the DC output at the load side[4].

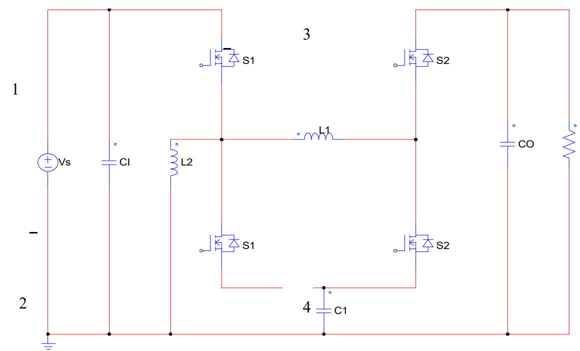

Fig. 3 Circuit Topology

4. Circuit Description

The Quadratic Bi-directional Buck-Boost Converter topology shown in Fig. 3 requires an additional inductor and an additional capacitor at the mid-point than compared to a conventional non-inverting bi-directional Buck-Boost converter to obtain quadratic conversion rate. In this converter topology consists of input voltage V_{in} and a outpus voltage $V_{o.}$ It also consists of four bi-directional current switches (MOSFETs) S1, $\bar{S}1$, S2, and $\bar{S}2$in series forming two half-bridges, two inductors L1 and L2, and a capacitor C1 that are necessary for the energy conversion. The voltage stress across the switches is very much low compared to the voltage stress across the switches in other Buck-Boost converter topologies which lead to the selection of power MOSFET with lower drain-source ON resistance ($R_{DS(ON))}$. Hence, the converter has enough high efficiency operation.The voltages across the connectors 1-2 and 3-4 are buffered by C_i and C_o to get the real voltage sources.

5. Working

There are two operating modes in Quadratic Bi-Directional Buck-Boost DC-DC Converter depending on the switching sequence of the MOSFETs connected in two parallel legs. During each mode of operation, two MOSFETs will be in ON-state and the other two MOSFETs will be in OFF-state.

Based on these modes, the gating pulses for the respective switches are given to the gate terminals of the MOSFETs to turn the switches ON. The converter is always in the continuous mode operation, since during both the modes either of the switches in parallel legs are turned ON.

A. Mode1:

As shown in Fig. 4, during mode 1, the MOSFET switches S1 and S2 are turned ON and the switches $\bar{S}1$ and $\bar{S}2$ are turned OFF and remains in the same state upto the calculated duty cycle that depends on the available input voltage and required output voltage. During this period, the inductor L1 and L2 charges and the capacitor at the mid-point C1 also charges during the same period. Even the load is disconnected from the supply, it is continuously feed by the output capacitor Co. That means the capacitor Co discharges and provides the discharged current to the load.

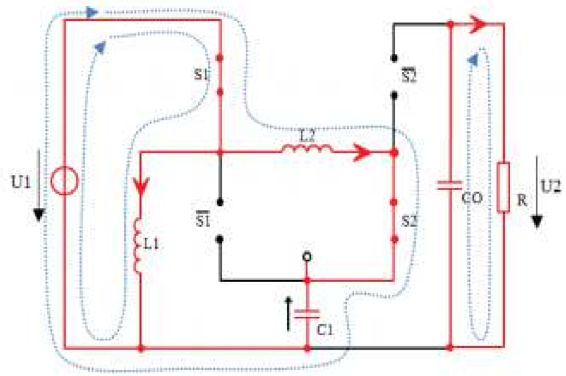

Fig. 4 Working Mode 1

B. Mode2:

As shown in Fig. 5, during mode 2 the MOSFET switches S1 and S2 are turned OFF and the switches $\overline{S}1$ and $\overline{S}2$ are turned ON and remains in the same state upto the total switching time. Even during this mode, the load is disconnected from the supply. But the inductor L1 and L2 discharges and the capacitor at the mid-point C1 also discharges and provides the load current to the load and at the same period, the output capacitor Co charges.

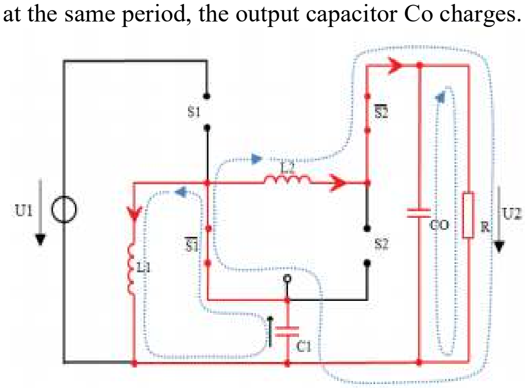

Fig. 5 Working Mode 2

6. Design Calculations

The Table. 1 shows the calculated values of the respective parameters considering the input and output voltage levels. The formula for each and every parameter differs from a conventional Buck-Boost converter, since the inclusion of L and C at the mid-point of the quadratic type of Buck-Boost converter.

Table 1. Designed Values

Parameter	**Formula**	**Designed Value**
Input Voltage	V_{in}	72 V
Output Voltage	$Vo = V_{in} * \frac{D^2}{(1-D)^2}$	160 V
Output Current	Io	6.4 A
Load Resistance	Ro	25 Ω
Duty Cycle	$D = \frac{\sqrt{V_o}}{\sqrt{V_{in}} + \sqrt{V_o}}$	0.6
Switching Frequency	fs	50 kHz
Inductor	$L_1 = \frac{V_{in} * D}{\Delta I_{L1} * f}$	0.308 mH
Inductor	$L_2 = \frac{(V_{in} + V_{C1}) * D}{\Delta I_{L2} * f}$	0.385 mH
Capacitor	$C_1 = \frac{I_{L2} * D}{\Delta V_{C1} * f}$	35.5 µF
Capacitor	$C_O = \frac{I_R * D}{f * \Delta V_{C0}}$	9.6 µF

7. Simulink Model

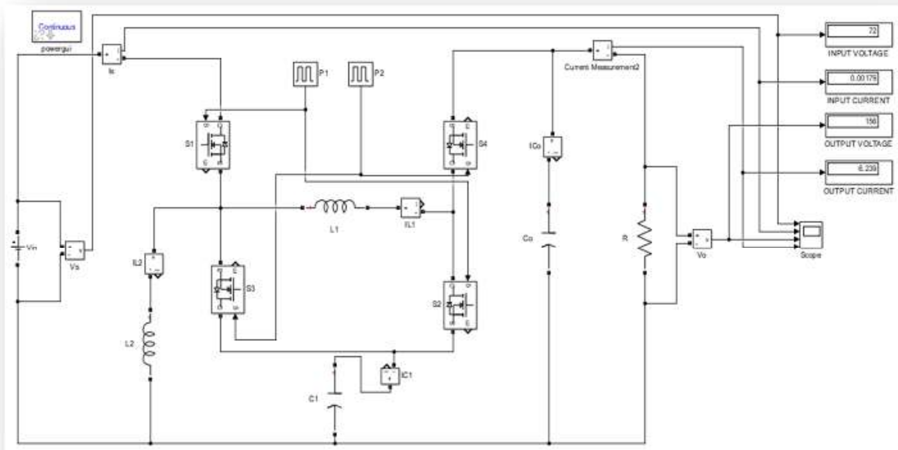

Fig. 6 Simulink Model

The simulink model of the proposed Quadratic Bi-Directional Buck-Boost converter is shown in Fog. 6.. The components have been placed and wired as per the circuit topology in the MATLAB Simulink Model and the passive elements like L and C has been set with their calculated values.

8. Simulation Results

This section discusses the results obtained upon running the Simulink model of the implemented Quadratic Bi-Directional Buck-Boost converter. The corresponding current and voltage waveforms of the input, output, inductors and capacitors are shown in Fig.7 to Fig.12.

A. Input Voltage:

The waveform shown in Fig. 7 represents the DC input voltage supplied to the converter which is about 72 V as per the design requirement.

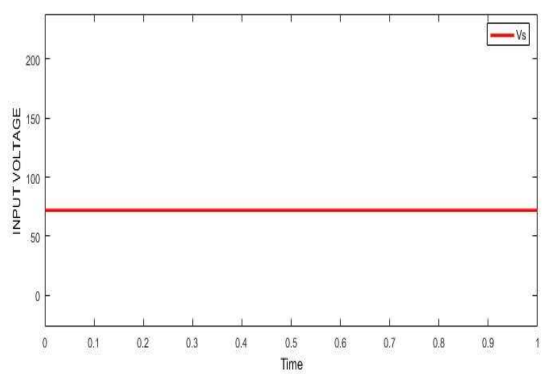

Fig. 7 Input Voltage to the Converter

B. Output Voltage:

The waveform shown in Fig. 8 represents the DC output voltage at the load side which is about 160 V as per the designed specifications. The input 72 V is stepped up to 160 V as per the switching operations and the duty cycle calculated and provided across the load.

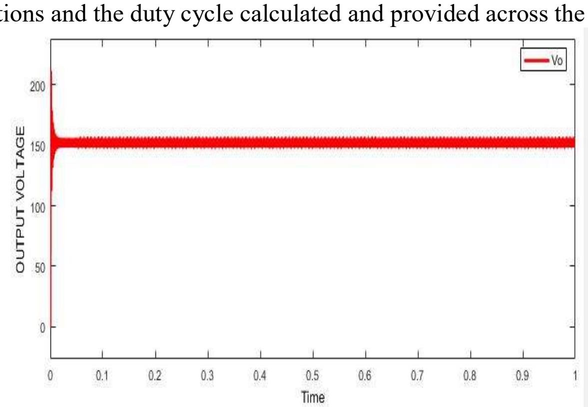

Fig. 8 Output Voltage from the Converter

C. Output Current:

The waveform shown in Fig. 9 represents the output current of 6.4 A flowing through the load at the load side. The load chosen is a resistive load of 25 Ω depending on which the load current flows through the resistive load.

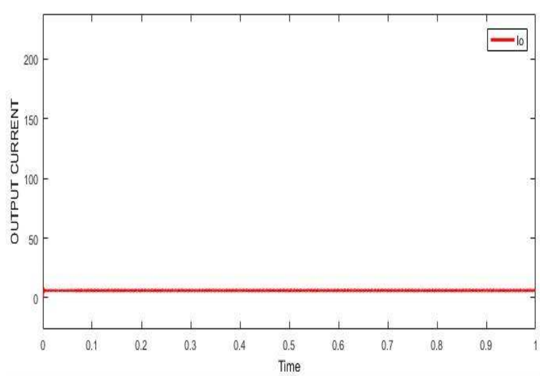

Fig. 9 Output Current from the Converter

D. Inductor Currents (I_{L1} And I_{L2}):

The two waveforms shown in Fig. 10(a) and Fig. 10(b) represents the currents flowing through the inductors I_{L1} and I_{L2} respectively. It is seen that the inductors charges during the mode 1 operation and discharges during mode 2 operation of the switches. Since the duty cycle of the proposed converter is designed as 60 %, the inductors charges for 60% of the total switching time and during the remaining 40% of the total time, it gets discharged.

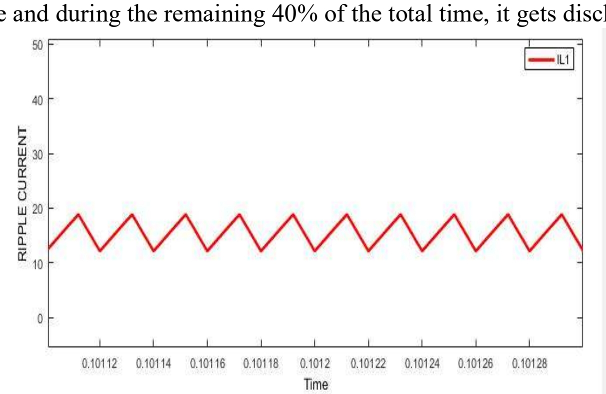

Fig. 10(a) Current through the Inductor L_1

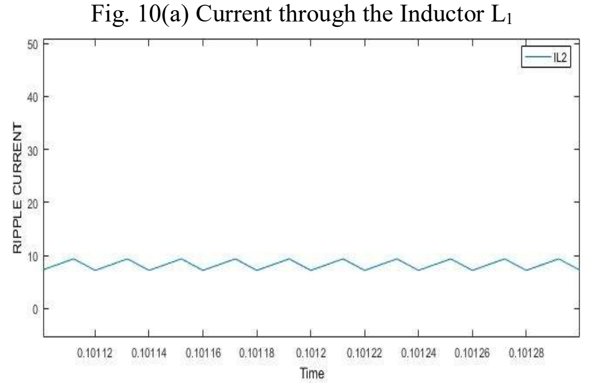

Fig. 10(b) Current through the Inductor L_2

E. Capacitor Current (Ico):

The below waveform shown in Fig. 11 represents the current through the output capacitor Co which supplies the load current during mode 1 operation since, during this mode the load R is disconnected from the DC source. Hence, the output capacitor Co discharges during mode 1 operation i.e., 60% of the total time and supplies the load current to R and charges during mode 2 operation that is, remaining 40% of the total time respectively.

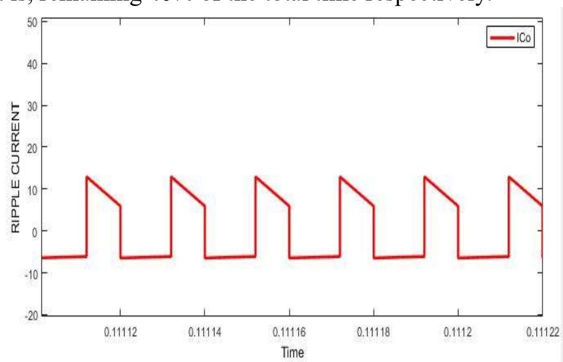

Fig. 11 Current flowing through the Capacitor C_o

F. Capacitor Current (Ic1):

The waveform shown in Fig. 12 represents the current through the mid-point capacitor I_{c1}. The mid-point capacitor C_1 charges during mode 2 operation and discharges during mode 1 operation.

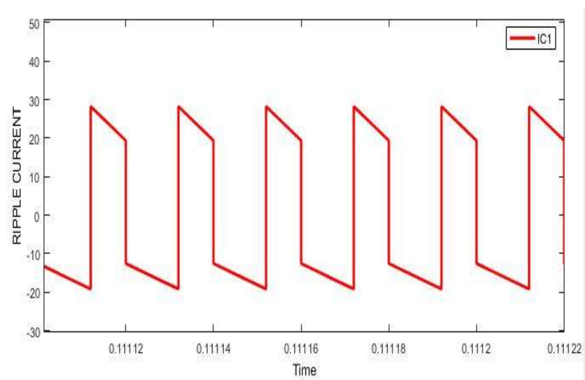

Fig. 12 Current flowing through the Capacitor C_1

9. Conclusion

In this paper, a Quadratic Bi-Directional Buck-Boost DC-DC converter with continuity in input current and output current has been implemented in the SIMULINK model and its performance is validated from the results obtained upon the simulation. Continuousinput current makes this type of converters more suitable for renewable energy sources and they can be used as a link between low voltage power generating sources and the load. The benefit of this type of circuit topology is that it gives a smooth output voltage compared with conventional Buck-Boost converters. The converter also has the capability of providing power demanded by load R even in the absence of one or two sources when they are used in renewable energy applications. Simulation results illustrated the proposed converter has the capability of operating as Buck Converter and as Boost Converter which are used in applications that need a broad span of voltage gain ratio.

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