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Design and Analysis of Quadratic Boost Converter with Inductor-Capacitor-Diode Voltage Multiplier Circuit

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ABSTRACT

In the current study, design and analysis of quadratic boost dc-dc converter with a voltage multiplier are presented. An additional inductor-capacitor-diode circuit is implemented as a voltage multiplier in the designed converter. In comparison with conventional boost converter, the designed quadratic boost converter based on additional multiplier circuit provides high gain voltage conversion with high efficiency. These properties make the designed converter practicable for sustainable energy implementations. The proposed converter is used to obtain higher output voltages employing equal input voltages in comparison with traditional boost converter, two-level cascade boost converter and traditional quadratic boost dc-dc converter. In the current study, operational principles of quadratic boost dc-dc converter with voltage multiplier circuit are clarified in detail. The relationship between input voltage and output voltage is formulized analytically and mathematical analysis of quadratic boost converter with voltage multiplier circuit is comprehensively given for smooth dc-dc converter operation. Subsequently, a controller scheme based on proportional-integral (PI) is presented for quadratic boost converter integrated with multiplier circuit. In the performance results, the operational waveforms of the designed converter are performed by using Simulink simulation program. Voltage gain analysis of designed converter versus conventional boost converters is compared to show the voltage conversion rates for different duty cycle values. In the designed converter, the input voltage is selected as a 24 V dc voltage source. At load side, the resistive load in the rating of 80 Ω consumes 720 W active power. In addition, input/output voltages, power waveforms and current waveforms are introduced.

1. INTRODUCTION

Applications in areas such as electric vehicles, grid integration of renewable energy systems, transmission, and portable electronic devices have increased the need of dc-dc power converters with high voltage gain power supplies in recent years [1]. Also, applications in photovoltaic systems, wind turbines, fuel cell stacks, lightning, switched-mode power supplies, robotics, televisions, personal computers, transportation, battery charger topologies can be given as examples of devices using high conversion dc-dc converters [2, 3]. High efficiency, high gain, and low cost dc-dc step-up converters are power circuits that increase the voltage to a higher value make them significant for optimum operation and design of electronic devices [4, 5]. The conventional boost converters increase the dc voltages at limited conversion rates. For this, advanced high-boost dc-dc converters are implemented to obtain better voltage conversion gain capability in several applications.

Various dc-dc boost converter structures with isolated and non-isolated are used to obtain higher voltage gain than conventional boost converters [6, 7] for different implementations, including renewable energy. Figure 1 shows several application areas of high-gain dc-dc converters. As shown in the figure, these converters can be used for photovoltaic, fuel cell applications, grid integration, electric vehicle interface, and residential usage [8, 9]. Some isolated topologies are bridge [10], flyback [11], and forward [12] dc-dc converters. But, in these topologies, using a step-up transformer induces higher volume and losses together with a high cost. Instead of isolated topologies, the most common boost topologies are interleaved [13], cascaded [14], and quadratic [15] dc-dc converters. In interleaved topology, the voltage gain is constant like a conventional boost converter. This converter is preferred to reduce the current ripples. The cascade converter, the combination of two or more boost converters, is the simple method to obtain a higher voltage conversion rate than the conventional boost power circuits

[16]. However, this converter causes high switching losses and supplementary elements. Quadratic converters use a single switch to obtain better voltage conversion in comparison with interleaved and cascaded boost converters [17, 18].
In the current study, a quadratic boost dc-dc power conversion circuit with an additional inductor- capacitor-diode voltage multiplier circuit is presented. Its performance is compared to conventional boost, cascade boost (two-level) and conventional quadratic converters. The quadratic boost power circuit based on voltage multiplier circuit is a single switching element-based power electronic converter like conventional boost and quadratic topologies. The presented topology consists of a transistor, three inductors, four capacitors, and four diodes. It aims to obtain higher output voltage values than the conventional boost, cascade boost, and conventional quadratic converter with the same switching ratio.

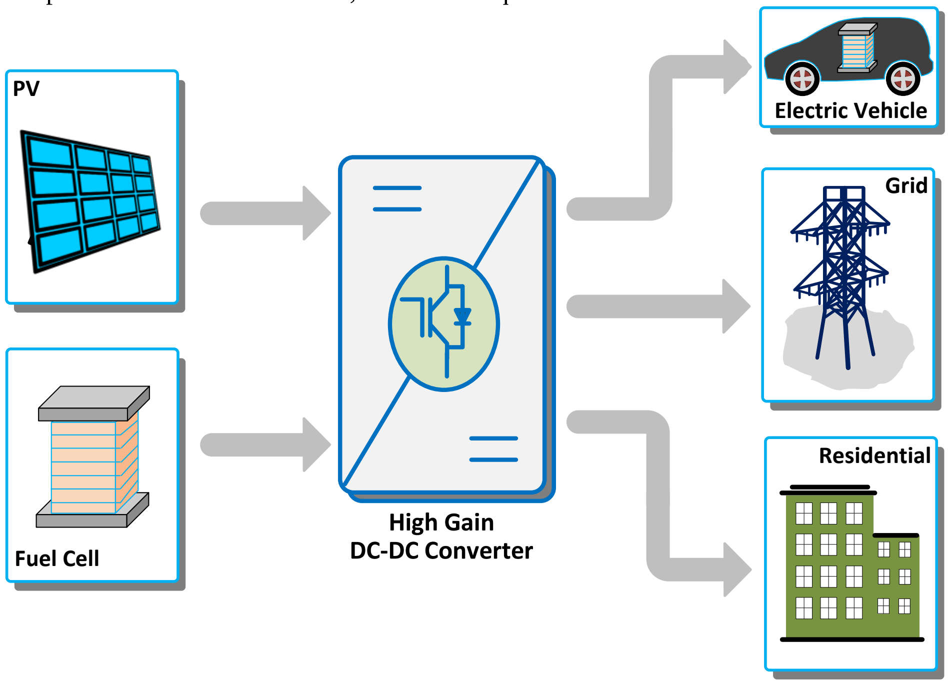

Figure 1. A typical scheme of high gain dc-dc converters for various applications

The rest of the current study is organized as follows: operating principles and analytical behavior of the quadratic boost power circuit with voltage multiplier circuit is given in Section II. The control scheme of the designed converter is given in Section III. The performance evaluation of the presented dc-dc converter topology is introduced in Section IV. And finally, the conclusions are summarized in Section V.

2. QUADRATIC BOOST CONVERTER INTEGRATED WITH VOLTAGE MULTIPLIER

A dc-dc converter is a power electronic circuit that step-up a dc voltage from a level to a different level [19]. In the current study, a quadratic boost power circuit is integrated with a voltage multiplier circuit. The scheme of a quadratic boost converter with a voltage multiplier circuit is presented in Figure 2. It is used to increase the output voltage, and to diminish voltage stress on transistor and diodes. As shown in the electrical scheme, it consists of 3 inductive elements, 4 capacitive elements, 4 diodes and 1 transistor [20]. It is demonstrated that V_{in} symbolizes input voltage while output voltage is defined as V_o.
In the analysis of quadratic boost converter with additional multiplier circuit, all the components are assumed as ideal. We presume that the power circuit works in continuous conduction mode. Furthermore, the values of capacitance voltages and inductance currents are supposed as fixed with minimal ripple [20]. As presented in Figure 3, the designed quadratic boost converter with an additional voltage multiplier circuit has two switching states. Figure 4 shows the quadratic boost converter's electrical waveforms with additional voltage multiplier circuit.

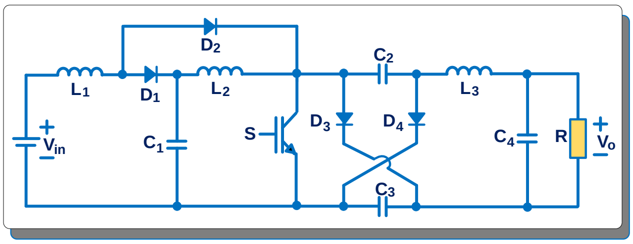

Figure 2. Quadratic boost converter connected with an additional inductive-capacitive-diode multiplier circuit

State 1: In the first state, the switching element is ‘closed’, and its state is defined as ON state. The inductors (L1, L2 and L3) store the energy through the input voltage source. All diodes are open, and this state is defined as a reversing state. C1 capacitor supplies its stored energy to inductor L2. The capacitors, C2 and C3, discharge in this state, and their energy are stored in output inductance (L3). As a result, all inductors’ currents increase linearly in the switching ON state [21]. As shown in the waveforms (given in Figure 4), the inductor currents are linearly reduced between t=0 and t=T.

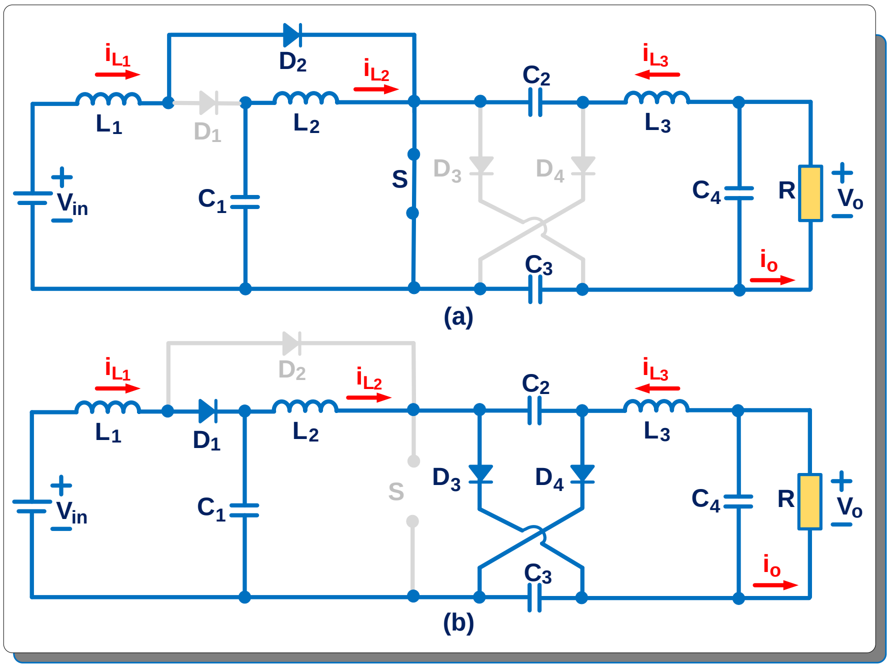

Figure 3. The states of converter (a) switch is ON, (b) switch is OFF

In state 1, the changes in inductors are defined as follows:

$$\begin{cases} \dfrac{di_{L1}}{dt} = \dfrac{V_{in}}{L_1} \\ \dfrac{di_{L2}}{dt} = \dfrac{V_{C1}}{L_2} \\ \dfrac{di_{L3}}{dt} = \dfrac{2V_{C2} - V_o}{L_2} \end{cases} \tag{1}$$

State 2: In the second state, the switching element is ‘open’, and it is said as OFF state. When the switching is in OFF state, the inductor L1 supplied its stored energy to capacitance C1, and the inductor L2 supplies its energy to capacitances C2, C3, and load resistance R. The inductor L3 delivers its stored energy into the load resistance. Thus, all inductors’ currents decrease linearly in the switching OFF state [21]. As shown in the waveforms (given in Figure 4), the inductor currents are linearly reduced between t=DT and t=T.
In state 2, the changes in inductors are expressed as follows:

$$\begin{cases} \dfrac{di_{L1}}{dt} = \dfrac{V_{in} - V_{C1}}{L_1} \\ \dfrac{di_{L2}}{dt} = \dfrac{V_{C1} - V_{C2}}{L_2} \\ \dfrac{di_{L3}}{dt} = \dfrac{V_{C2} - V_o}{L_2} \end{cases} \tag{2}$$

In Eqs. (1-2), $\frac{di_{L1}}{dt}, \frac{di_{L2}}{dt}, \frac{di_{L3}}{dt}$ indicate the changes in inductor current versus time. V_{in} and V_o express input voltage and output voltage in dc-dc converter, respectively. V_{c1} and V_{c2} are capacitance voltages in the converter.

Solving V_o, the net change in inductor currents must be zero for a periodic operation. Using Eqs. (1)-(2), we can arrange the equations to obtain the output voltage [21].

$$L_1 \rightarrow V_{in} DT_s + (V_{in} - V_{C1})(1-D)T_s = 0 \tag{3}$$

$$L_2 \rightarrow V_{C1} DT_s + (V_{C1} - V_{C2})(1-D)T_s = 0 \tag{4}$$

$$L_3 \rightarrow (2V_{C2} - V_o) DT_s + (V_{C2} - V_o)(1-D)T_s = 0 \tag{5}$$

Solving the Eqs. (3-5), the output voltage is obtained as:

$$V_o = V_{in} \frac{1+D}{(1-D)^2} \tag{6}$$

By using Eq. (3-5), the voltage stresses of capacitive elements are computed as:

$$V_{C1} = \frac{V_{in}}{(1-D)} \tag{7}$$

$$V_{C2} = V_{C1}(1-D) = \frac{V_o}{1+D} \tag{8}$$

The voltage stress of the switching element is given as below:

$$V_{S-stress} = V_{C2} \tag{9}$$

The voltage stresses of the diodes (D1, D2 and D3) are defined as follows:

$$V_{D1-stress} = \frac{(1-D)V_o}{1+D} \tag{10}$$

$$V_{D2-stress} = \frac{DV_o}{1+D} \quad (11)$$

$$V_{D3-stress} = V_{C2} \quad (12)$$

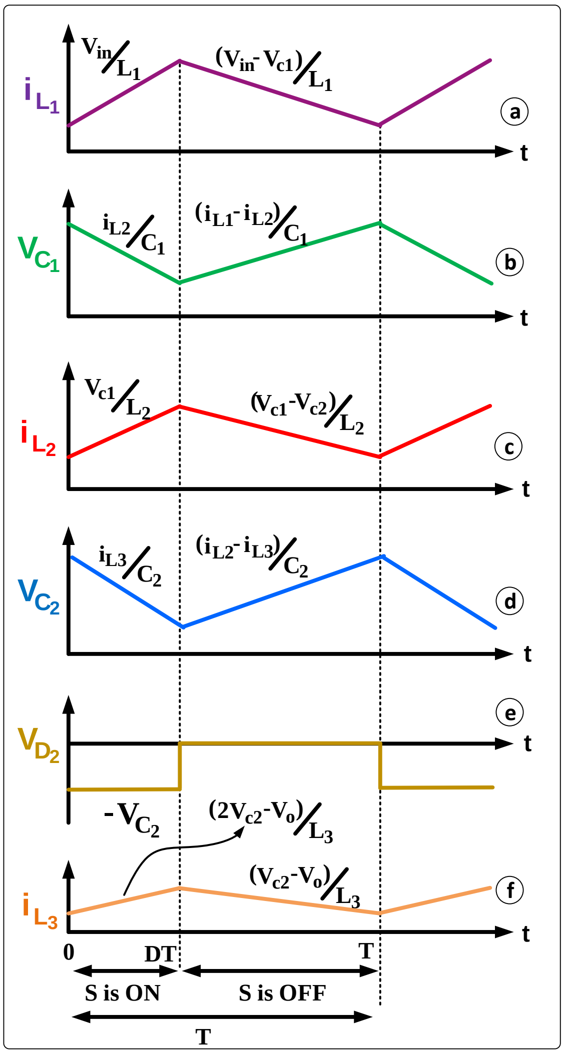

Figure 4. The significant waveforms (a) inductor current iL1, (b) capacitor voltage Vc1, (c) inductor current iL2, (d) capacitor voltage Vc2, (e) diode voltage VD2, and (f) inductor current iL3

3. CONTROL

In order to supervise the output voltage of quadratic boost converter connected with an extra voltage multiplier circuit, a PI controller is used. In PI control method, both proportional and integral gains are used together [22], as shown in Figure 5.

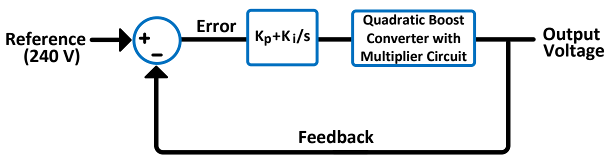

Figure 5. PI controller for quadratic boost converter integrated with additional multiplier circuit

In the controller, an error signal is produced with dc-link voltage at the output. The obtained voltage is measured and compared to the reference voltage value [23]. In the designed system, the reference voltage value is selected as 240 V.

4. RESULTS

The quadratic boost power circuit integrated with an additional voltage multiplier circuit is tested with an input voltage of 24 V (dc) for a 720 W resistive load. The proposed converter has been built and analyzed through Simulink software. The parameter values of the designed power circuit are also given in Table 1. The component values are selected according to the design criteria in Ref. [20].

TABLE 1
PARAMETERS OF THE DESIGNED CONVERTER

Parameters		Value	Unit
Input Voltage	Vin	24	[V]
Inductances	L1	0.1	[mH]
	L2	1	[mH]
	L3	1	[mH]
Capacitances	C1	100	[uF]
	C2	47	[uF]
	C3	47	[uF]
	C4	100	[uF]
Resistance	R	80	[Ω]
Switching	f	5000	[Hz]
Duty cycle	D	0.6	[-]

Figure 6 exhibits the voltage gain waveforms of the converters tested in the simulation program. When the results are examined, it is seen that the voltage conversion gain of the quadratic boost converter connected with voltage multiplier circuit is higher than other topologies. At D=0.6, the voltage gain of the quadratic boost converter with the voltage multiplier circuit is 10. The gain values of quadratic boost, cascade boost, and conventional boost are 6.25, 6.25, and 2.5, respectively.

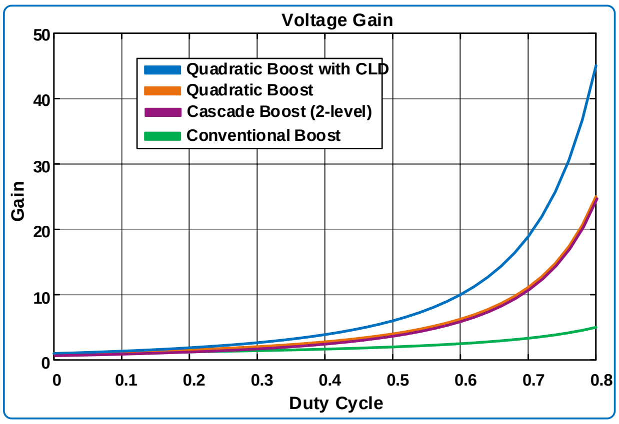

Figure 6. Voltage gain analysis of the converters tested in the simulation environment

The input/output voltages and switching signals are presented in Figure 7. The dc-dc converter is performed at 5000 Hz and 250 W load rating. As shown in waveforms, the magnitude of the input voltage is 24 V. The switching process is achieved with 0.6 duty cycle and 5 kHz. The

quadratic boost power circuit's output voltage with inductive-capacitive-diode structure is measured as 240 V, which is appropriate with the theoretical analysis.
Figure 8 introduces inductor currents IL1, IL2, and IL3, and output current Io, respectively. As shown in the results, the net change in the inductor current is zero. Also, the value of the output load current is fixed, and it equals to 3 A.

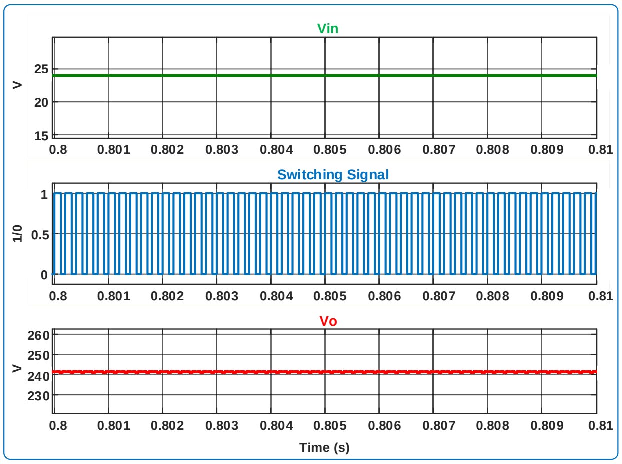

Figure 7. The input voltage, switching, and output voltage

The power waveform at the output load is presented in Figure 9. At the steady-state situation, the stepped-up voltage of the converter is equal to 240 V. In this way, a current in the rating of 3 A flows through the resistive load (80 Ω). For this, the consumed power by the resistive load is calculated as 720 W. As shown in the waveform, the output power value is equal to 720 W for steady-state situation.

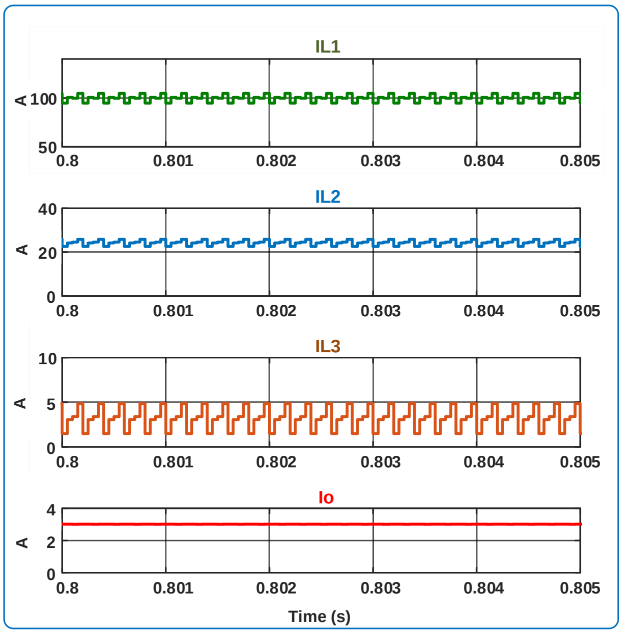

Figure 8. Inductor currents and output current

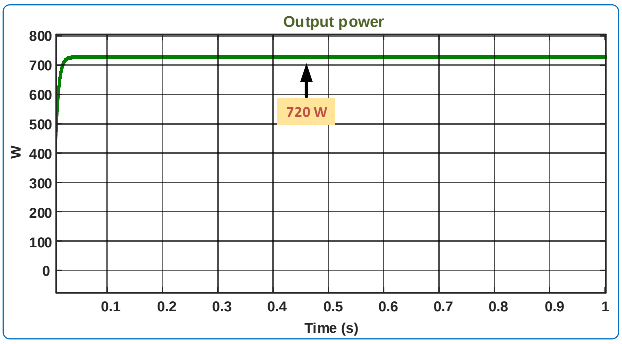

Figure 9. Output power waveform

5. CONCLUSION

In this study, the performance evaluations of the quadratic boost converter integrated with inductive-capacitive-diode structure are presented. This converter is a single switch-based dc-dc converter similar to conventional boost, cascade boost, and quadratic topologies. It consists of a transistor, three inductors, four capacitors, and four diodes to convert low voltage into higher voltages. In the current study, it is also mentioned that this converter, which has high gain and high efficiency, is important in energy applications. Using this converter aims to obtain higher output voltage values compared to conventional boost, cascade boost, and conventional quadratic converter with the same switching and input voltage ratings. The quadratic boost power circuit with voltage multiplier structure is performed for low voltage low power in the performance results. Also, the voltage conversion superiority of the converter is supported through voltage gain analysis compared to the aforementioned dc-dc converters. Besides, the input/output waveforms are given to verify the operation of quadratic boost converter with inductive-capacitive-diode circuit.

DECLARATION

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The abstract of this study was presented at International Conference on Engineering Technologies (ICENTE'20).

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BIOGRAPHY

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