A Quadratic Switched-Capacitor Boost Converter

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Abstract. With the development of renewable energy, the demand for related power equipment is growing. This study addresses the issues of high voltage and current stresses on switching devices in conventional quadratic Boost converters under high-voltage-gain applications, and proposes a novel quadratic switched-capacitor Boost converter topology. The proposed topology incorporates a series charge–discharge switched-capacitor structure and optimizes the energy storage stage. By analyzing the converter's operating principles during the switch-on and switch-off states, the mechanism for voltage gain enhancement is elucidated. Under a typical operating condition with a 45% duty cycle, simulation results verify that when the input voltage is 20 V, the output voltage reaches 117.2 V, yielding a gain of 5.85, while maintaining low average inductor currents, with 1.57 A for L_1 and 1.79 A for L_2. Moreover, the voltage stress on switch S_1 is reduced to 0.25 u_0. This topology offers a high-efficiency, low-stress DC–DC conversion solution for renewable energy applications such as photovoltaic generation and fuel cell systems.

Keywords: Quadratic Boost Converter, High-Voltage-Gain, Switched-Capacitor, Mechanism for Voltage Gain.

1 Introduction

With the continuous advancement of society, the challenges of the energy crisis and environmental degradation have become increasingly severe. The progressive depletion of fossil energy has prompted nations to actively seek green development pathways, making the development and utilization of clean energy or the improvement of resource-use efficiency an urgent priority [1–5]. Against this backdrop, step-up DC–DC converters play an important role in applications such as photovoltaic power generation and fossil fuel combustion. However, conventional quadratic converters, while achieving high voltage gain, suffer from excessive voltage and current stresses, which have become a major bottleneck restricting their widespread application.

In recent years, conventional Boost converters have been able to achieve relatively high voltage gains to some extent. However, to obtain a high gain, the converter must operate with a duty cycle D close to unity, which significantly increases voltage stress and the conduction losses of the switching devices. Quadratic Boost converters, developed through optimization of conventional topologies, have inspired various improved

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designs as research has progressed. Rezaie et al. proposed a novel quadratic converter composed of a quadratic step-up stage and a multiplier cell, but the voltage stresses on the switch and output diode were not significantly reduced when achieving higher gain [6]. Sudarsan Reddy et al. further introduced a single additional switch, enabling higher gain at reduced duty cycles [7]. Zeng et al. incorporated a switched-capacitor cell to enhance the boosting capability, expand the input voltage range, reduce conduction losses, and significantly lower the voltage stresses on both the switch and the output diode [8]. Jin introduced a dual-main-switch soft-switching scheme, which reduced the average current and, by employing a high-frequency isolation transformer, achieved simultaneous turn-off of the switches and implemented closed-loop control of the converter [9]. Jiang proposed two topological structures that enhance the output gain while also reducing switching stress and improving conversion efficiency [10].

In this work, a novel topology is proposed based on the conventional quadratic Boost converter. By introducing a capacitor energy-reuse mechanism and a series charge–discharge switched-capacitor network, overall performance optimization is achieved. First, the structural improvement effectively shortens the magnetic energy storage period during the switch-on state, thereby achieving higher voltage gain. Second, during the switch-off state, multiple inductors are engaged in a cooperative charging path, which effectively reduces inductor current peaks and lowers device stress. Finally, by reducing the average inductor current and enhancing circuit stability, the proposed topology attains a theoretical voltage gain higher than that of conventional designs, demonstrating clear advantages in efficiency and steady-state performance.

2 Principle Analysis of the Quadratic Switched-Capacitor Boost Converter

2.1 Topology of the Boost Converter

The topology of the quadratic switched-capacitor Boost converter is shown in Fig. 1. The converter consists of two switches S_1 and S_2, three inductors L_1, L_2, L_3, four capacitors C_1, C_2, C_3, C_4, three power diodes D_1, D_2, D_3, and a load resistor R. The two switches are driven simultaneously by a PWM signal with period T and duty cycle D.

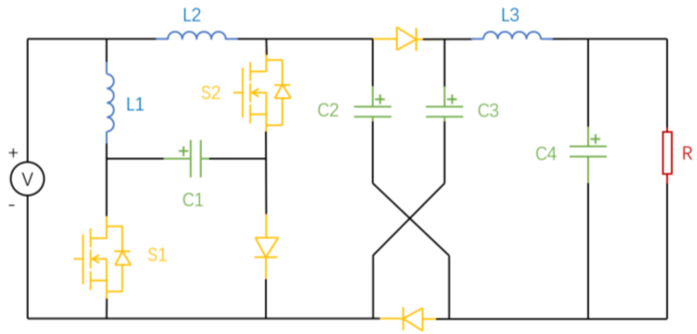

Fig. 1. Topology of the quadratic switched-capacitor Boost converter.

According to the on/off states of S_1 and S_2, the quadratic switched-capacitor Boost converter operates in two basic modes: the conduction (ON) mode and the turn-off (OFF) mode. The conduction mode is illustrated in Fig. 2.

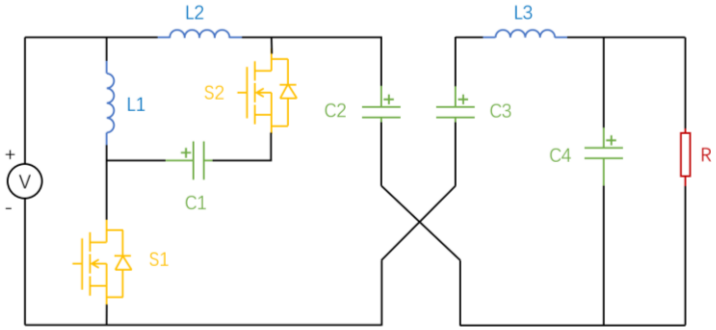

Fig. 2. Equivalent circuit in the conduction state

In the conduction mode, both switches S_1 and S_2 are turned on, while diodes D_1, D_2, D_3 are reverse-biased and therefore remain off. At this time, the input source u_{in} charges inductor L_1, causing the inductor current I_{L1} to gradually increase. Meanwhile, u_{in} together with capacitor C_1 provides a charging path for inductor L_2, resulting in an increase in I_{L2}. In addition, capacitors C_2 and C_3 charge inductor L_3 while simultaneously supplying energy to the load. Based on the energy transfer paths and circuit characteristics in this mode, the following voltage relationship can be established, as given in Equation (1):

$$\begin{cases} L_1 \dfrac{dI_{l1}}{dt} = u_{in} \\ L_2 \dfrac{dI_{l2}}{dt} = u_{in} + u_{c1} \\ L_3 \dfrac{dI_{l3}}{dt} = u_{c2} + u_{c3} - u_0 \\ C_1 \dfrac{du_{c1}}{dt} = -I_{l2} \\ C_2 \dfrac{du_{c2}}{dt} = C_3 \dfrac{du_{c3}}{dt} = -I_{l3} \\ C_4 \dfrac{du_{c4}}{dt} = I_{l3} - \dfrac{u_0}{R} \end{cases} \tag{1}$$

Where L_i denotes the inductance of the *i-th* inductor, u_{Ci} the voltage across the *i-th* capacitor, I_{Li} the current through the *i-th* inductor, and C_i the *i-th* capacitor.

The turn-off mode of the quadratic switched-capacitor Boost converter is shown in Fig. 3. In this mode, both switches S_1 and S_2 are turned off, while diodes D_1, D_2, and D_3 conduct in the forward direction. At this time, the input source u_{in} simultaneously charges two branches: one branch charges inductor L_1 and capacitor C_1, causing the inductor current I_{L1} and the capacitor voltage u_{C1} to increase; the other branch charges inductor L_2 and capacitor C_2, resulting in an increase in I_{L2} and u_{C2}. In addition, capacitors C_2 and C_3 are connected in parallel to jointly charge inductor L_3 while continuing to supply energy to the load. Based on the operating principles of the turn-off mode, the following equation can be established, as shown in Equation (2):

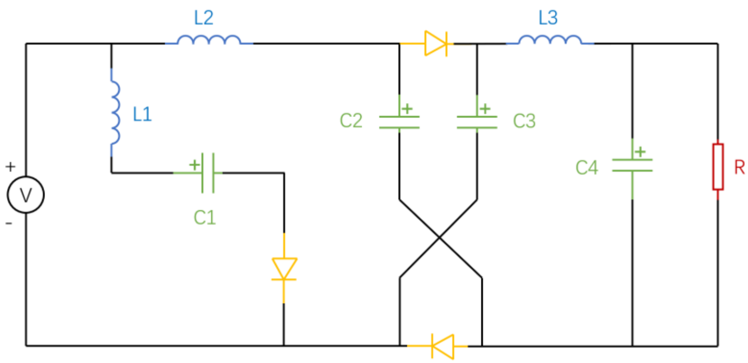

Fig. 3. Equivalent circuit in the turn-off state.

$$\begin{cases} L_1 \dfrac{dI_{l1}}{dt} = u_{in} - u_{c1} \\ L_2 \dfrac{dI_{l2}}{dt} = u_{in} - u_{c2} \\ L_3 \dfrac{dI_{l3}}{dt} = u_{c2} + u_{c3} - u_0 \\ C_1 \dfrac{du_{c1}}{dt} = I_{l1} \\ C_2 \dfrac{du_{c2}}{dt} = C_3 \dfrac{du_{c3}}{dt} = -I_{l3} \\ C_4 \dfrac{du_{c4}}{dt} = I_{l3} - \dfrac{u_0}{R} \end{cases} \tag{2}$$

According to the inductor volt–second balance principle, and noting that $u_{C2} = u_{C3}$ in the circuit, Equations (1) and (2) yield:

$$u_0 = \frac{2}{(1-D)^2} u_{in} \tag{3}$$

Where D is the duty cycle of switches S_1 and S_2, u_0 is the output voltage, and u_{in} is the input voltage. From Equation (3), the voltage gain of the proposed quadratic Boost converter can be derived as given in Equation (4):

$$M = \frac{u_0}{u_{in}} = \frac{2}{(1-D)^2} \tag{4}$$

2.2 Switch Voltage Stress Analysis

The voltage stress of a switch refers to the voltage it must withstand during the OFF state. As shown in Fig. 3, in the OFF mode of the quadratic Boost converter, S_1 withstands the voltage across capacitor C_1, denoted u_{C1}. From the volt–second balance of inductor L_1, we have:

$$u_{C_1} = \frac{D}{1-D} u_{in} \tag{5}$$

Substituting the voltage gain Equation (3) into the above expression yields:

$$u_{S_1} = u_{C_1} = \frac{D(1-D)}{2} u_0 \tag{6}$$

At the typical duty cycle $D = 45\%$, $u_{S1} = 0.12375\ u_0$, which is significantly lower than that of a conventional quadratic Boost converter.

During the OFF state, S_2 withstands the series voltage of capacitors C_2 and C_3. Owing to circuit symmetry and the capacitor voltage relationship $u_{C2} = u_{C3}$, we have:

$$u_{S_2} = 2u_{C_2} = u_0 \tag{7}$$

2.3 Inductor Current Stress Analysis

When the quadratic switched-capacitor Boost converter operates in steady state, applying the ampere–second balance principle to the capacitors yields:

$$I_{L_2} = \frac{1-D}{D} I_{L_1} \tag{8}$$

From the principle of power conservation, we have:

$$u_{in}(I_{L_1} + I_{L_2}) = u_0 I_0 \tag{9}$$

From Equations (8) and (9), the average currents of inductors L_1, L_2, and L_3 can be expressed as:

$$\begin{cases} I_{L_1} = \dfrac{1}{1-D} I_0 \\ I_{L_2} = \dfrac{1}{(1-D)^2} I_0 \\ I_{L_3} = I_0 \end{cases} \tag{10}$$

where $I_0 = \frac{u_0}{R}$, denotes the output current.

3 Simulation Results and Analysis

In the simulation study, the case of $L_1 = L_2$ was adopted, and the specific parameters are given in Table 1. As shown in Table 1, when the duty cycle is 45%, the average currents of inductors L_1, L_2, and L_3 after processing by the quadratic Boost converter are 1.57 A, 1.79 A, and 0.58 A, respectively, which are in close agreement with the theoretical results for voltage gain and inductor currents presented earlier.

Table 1. Simulation components and parameters.

Parameter	Value
Input voltage / V	20
Output voltage / V	117.2
Switching frequency / kHz	5
Duty cycle / %	45
Capacitor C_1 / μF	10
Capacitor C_2 / μF	10
Capacitor C_3 / μF	10
Capacitor C_4 / μF	100
Inductor L_1 / mH	3
Inductor L_2 / mH	3
Inductor L_3 / mH	3
Load resistance R / Ω	200

Fig. 4 and Fig. 5 show the simulated output voltage and output current waveforms, respectively. As can be seen, both waveforms exhibit triangular ripple, which can be attributed to the low-pass filter formed by inductor L_3 and capacitor C_4, ensuring a continuous output voltage u_0. In Fig. 4, the output voltage fluctuates between 117.06 V and 116.99 V, and in Fig. 5, the output current varies between 0.5852 A and 0.58496 A. Thus, both voltage ripple and current ripple meet the design requirements. PLECS simulation results yield an average output current of 0.58 A and an average voltage of 117.0 V, corresponding to a voltage gain of 5.85. Compared with other Boost converter topologies, the proposed quadratic switched-capacitor Boost converter achieves a higher voltage gain under the same duty cycle, meeting the needs of applications requiring higher step-up ratios.

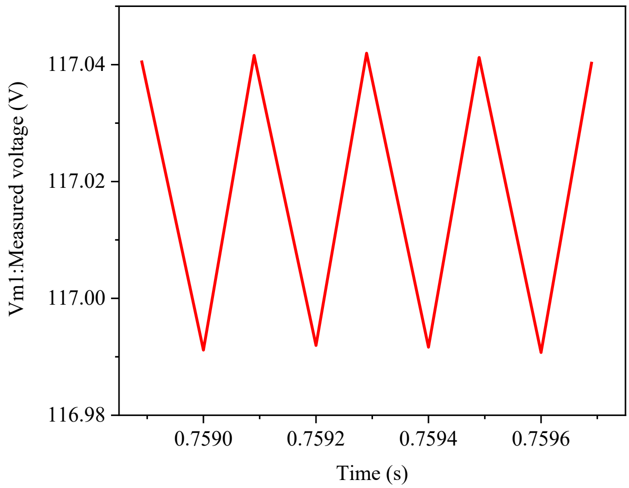

Fig. 4. Output voltage waveform.

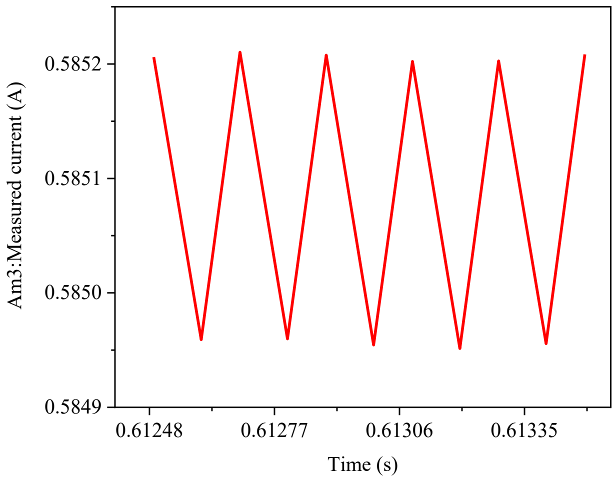

Fig. 5. Output current waveform

Fig. 6 and Fig. 7 present the simulated current waveforms of inductors L_1 and L_2, respectively. According to PLECS simulation, their average currents are 1.57 A and 1.79 A. The waveforms indicate that, while achieving a higher voltage gain, the average currents of all inductors remain at relatively low levels. Compared with a conventional quadratic Boost converter, the proposed topology effectively reduces the average current flowing through the inductors, thereby lowering the electrical and thermal stresses on these components, improving system stability, and promoting reliable long-term operation.

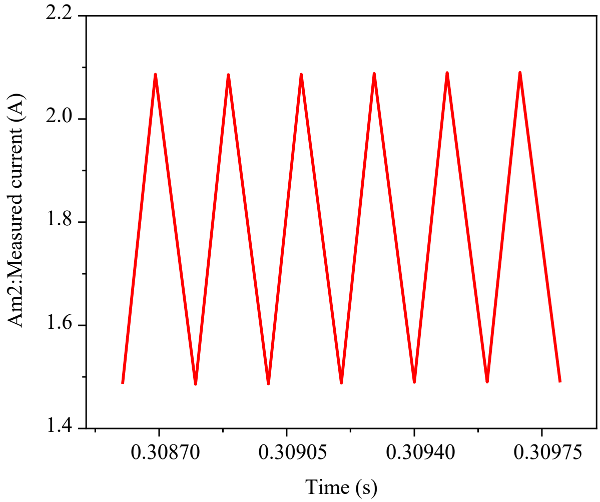

Fig. 6. Current waveform through inductor L_1.

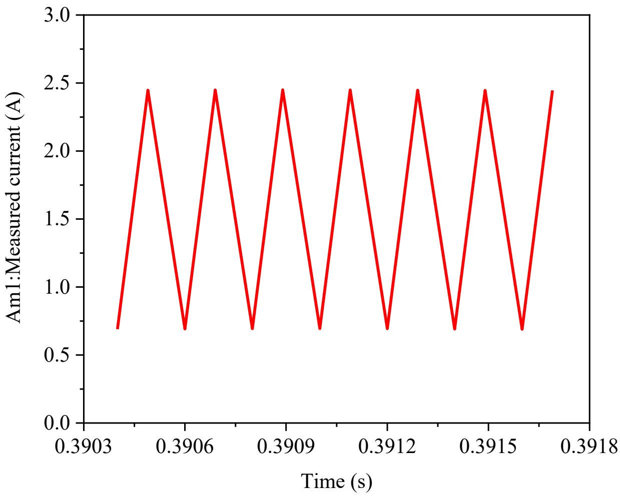

Fig. 7. Current waveform through inductor L_2.

From Fig. 6 and Fig. 7, it can be observed that the current through inductor L_1 fluctuates between 0.7 A and 2.4 A, while the current through inductor L_2 varies between 1.5 A and 2.1 A. The ripple in both cases is less than 20%, meeting the design requirements. These simulation results validate the theoretical calculations of average inductor current and voltage gain.

4 Conclusion

This study proposes a novel quadratic switched-capacitor Boost converter that addresses the issues of excessive voltage and current stresses in electronic devices under high-voltage-gain requirements through topology optimization. The following conclusions are drawn:

1. By replacing the conventional diode network with a series switched-capacitor structure and reconfiguring the energy transfer path at the energy storage stage, the proposed topology reduces both voltage and current stresses on the switches and inductors.

2. Under the same duty cycle, compared with the conventional quadratic Boost converter, the proposed topology achieves higher voltage gain while reducing switch voltage stress and average inductor currents.

3. This topology offers a high-efficiency, low-stress power conversion solution for high-gain scenarios such as photovoltaic generation and fuel cell systems, and it has broad application prospects.

In summary, the proposed topology effectively overcomes the performance bottlenecks of conventional high-gain converters. Its high efficiency and low-stress characteristics are expected to promote the development of photovoltaic, fuel cell, and other clean energy systems toward higher power density and longer service life.

Authors Contribution. All the authors contributed equally and their names were listed in alphabetical order.

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