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A Review of Non-isolated High Step-up DC-DC Converter Structures and Simulation Analysis of a High Gain Quadratic Converter

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Abstract: In this paper, certain non-isolated high step-up DC-DC converter topologies operating in continuous conduction mode (CCM) are reviewed. The review is presented based on the voltage gain, voltage–current stress of the power switches and diodes, the number of passive components, the efficiency, and the types of configurations. The DC-DC converter topologies considered for review are compared in terms of voltage gain pertaining to CCM for duty ratio k = 0.6. The simulation results and discussion are explored for a diode rectifier-fed high gain quadratic DC-DC converter configuration.

Keywords: CCM, DC-DC converter, Duty ratio, Quadratic converter, Voltage-current stress, Voltage gain.

I. INTRODUCTION

Recently, the research is focused towards improvement of the voltage gain of DC-DC converters suitable for renewable energy applications. The topology of a DC-DC converter comprises of power MOSFETs/IGBTs, diodes, and passive components. The DC-DC converters are classified into two categories: non-isolated and isolated topologies [1]-[6]. Both categories have their own merits and demerits. The drawbacks of isolated converter configuration include complicated structure, complex control strategy, core saturation, and high voltage spikes across the power switches [7]-[9]. Certain applications require the non-isolated DC-DC converters with high voltage conversion ratio and power density [10]-[11]. The traditional DC-DC boost converter can have high voltage gain at high duty ratio [12]-[13]. The high duty ratio causes the switching and conduction losses to increase thereby reducing the efficiency of the conversion scheme. However, a required number of boost converters can be connected in series to achieve high voltage gain. But, the cost of conversion increases. The single ended primary inductor converter (SEPIC) providing non-inverting output and the CUK converter providing inverting output have low complexity, cost effective and easy to control. However, the SEPIC topology has poor voltage gain and the duty cycle control is difficult for multi-input and multi-output configurations. It is required to have complex compensation circuitry for proper operation of the CUK converter. The Z-source converter and Zeta converter have the same features as that of SEPIC topology but with medium complexity. Both converters have unidirectional power flow. Also, the Z-source converter has large recovery issue and discontinuous input current. The Zeta converter often requires compensation circuitry [4].

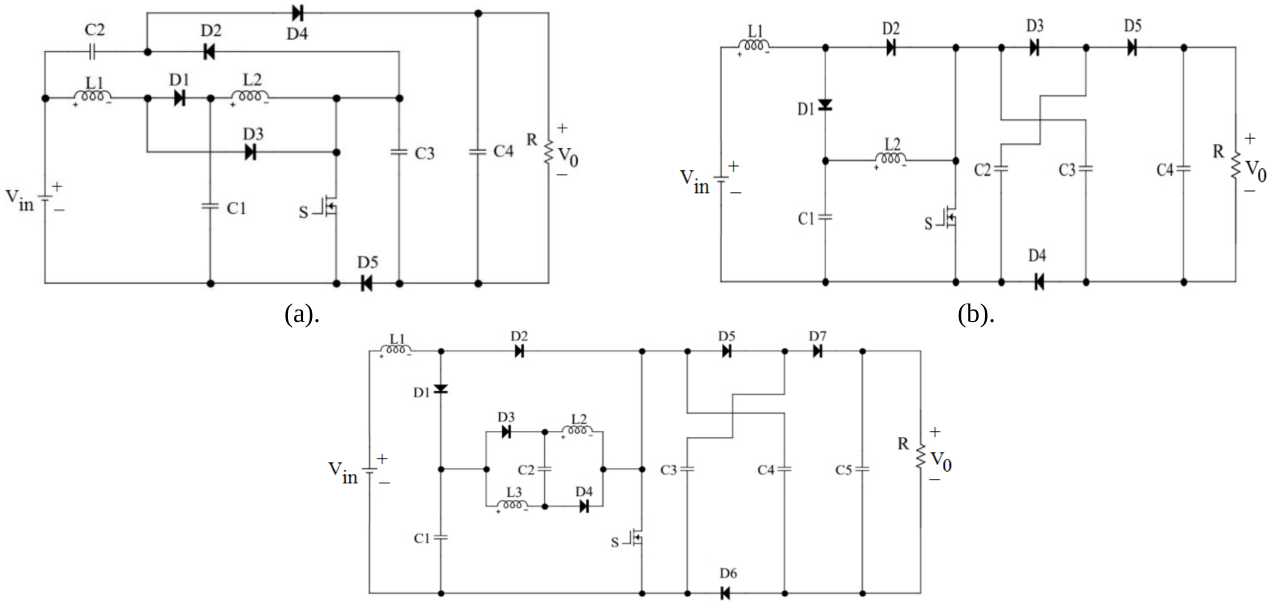
Recently, there are certain topologies developed for non-isolated high gain DC-DC converters with high voltage gain, high efficiency, and reduced switch voltage stress to meet the demands of modern applications [14]. A review of certain recently developed non-isolated high voltage gain DC-DC converter structures is presented in this paper.

This article is structured as follows: Section 2 explores the literature review of certain non-isolated high gain DC-DC converter topologies. The simulation results and discussion for a quadratic boost DC-DC converter with high voltage gain are presented in section 3. Section 4 concludes the proposed research work.

II. RECENTLY DEVELOPED NON-ISOLATED DC-DC CONVERTER TOPOLOGIES

(i). Quadratic boost DC-DC converter [15]:

The three topologies of non-isolated quadratic single switch DC-DC boost converters as shown in Fig.1 are explored in [15]. The designed converters are suitable for DC microgrid and solar PV (photovoltaic) applications. These converters include voltage multiplier cell (VMC) consisting of switched inductors and switched capacitors for achieving high voltage gain. The voltage gain equations for the three topologies with duty ratio ‘k’ for the switch ‘S’ are given by Equations (1) and (2). For duty ratio k = 0.6, the converter-I and converter-II have ideal voltage gain of 12.5 and converter III has ideal voltage gain of 25. The converter II has high efficiency than other two converters. The advantages of these single switch topologies are high voltage gain, and the voltage stress across the power switch and the diodes are reduced.



(a). (b).

(c).

Fig. 1. (a). Quadratic converter topology-I, (b). Quadratic converter topology-II, (c). Quadratic converter topology-III

$$G_{CCM-I} = G_{CCM-II} = \frac{V_0}{V_{in}} = \frac{2}{(1-k)^2} \qquad (1)$$

$$G_{CCM-III} = \frac{V_0}{V_{in}} = \frac{4}{(1-k)^2} \qquad (2)$$

(ii). High step-up DC-DC converter based on the Voltage Lift technique [16]:

A high gain non-isolated single switch quadratic boost converter as shown in Fig.2 is proposed in [16]. The converter proposed in [16] is suitable for renewable energy applications, DC microgrids and electric vehicles. The dual voltage lift technique has been used in [16] to obtain high voltage gain. The features of the converter include high voltage gain than the conventional quadratic boost converter, low switch voltage stress, common ground connection, a smaller number of components than that of topology-II shown in Fig.1(b), and high efficiency. The voltage gain equation for the converter proposed in [16] is given by Equation (3). For duty ratio k = 0.6, the converter proposed in [16] has ideal voltage gain of 12.25.

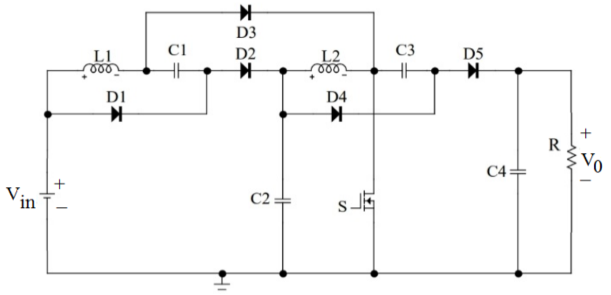


Fig. 2. High step-up DC-DC converter

$$G_{CCM} = \frac{V_0}{V_{in}} = \left(\frac{2-k}{1-k}\right)^2 \qquad (3)$$

(iii). High gain modified quadratic boost DC-DC converter [17]:

A single switch modified quadratic DC-DC boost converter with high gain as shown in Fig.3 is proposed in [17] for renewable energy applications. The dual voltage boost cell comprising of two capacitors in series with two inductors is used to improve the voltage conversion ratio of the converter. The advantages of this proposed converter include high voltage gain than that of topology-II (Fig.1(b)), common ground connection, high efficiency, and low switch voltage stress. The voltage gain equation for the converter proposed in [17] is given by Equation (4). For duty ratio k = 0.6, the converter proposed in [17] has ideal voltage gain of 17.5.

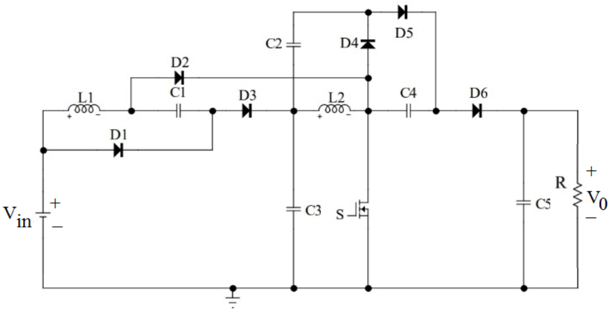


Fig. 3. High gain modified quadratic boost converter

$$G_{CCM} = \frac{V_0}{V_{in}} = \left(\frac{2-k}{1-k}\right)^2 \tag{4}$$

(iv). Modified SEPIC DC-DC converter with coupled inductor [18]:

A highly efficient non-isolated modified single switch SEPIC topology consisting of coupled inductor as shown in Fig.4 is proposed in [18]. The proposed converter is constructed by integrating a voltage multiplier module with conventional SEPIC. The converter has high voltage gain of 14.5 for duty ratio k = 0.6 and turns ratio T = 3 compared to that of topology-II (Fig.1(b)). The use of coupled inductor leads to high switch voltage stress. Hence, resistor-capacitor-diode clamp circuit is used to reduce the voltage stress across the switch [18]. The voltage gain equation for the converter proposed in [18] is given by Equation (5).

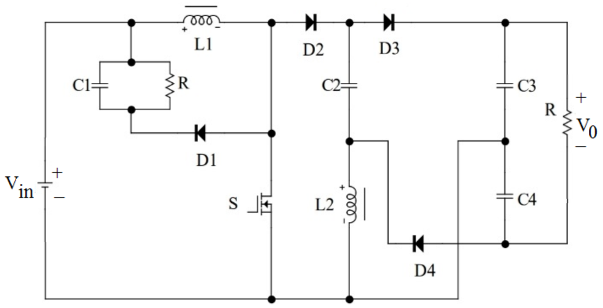


Fig. 4. Modified SEPIC DC-DC converter with coupled inductor

$$G_{CCM} = \frac{V_0}{V_{in}} = \frac{1+T+kT}{1-k} \tag{5}$$

(v). High step-up single switch quadratic modified SEPIC converter with voltage boosting module [19]:

A non-isolated single switch quadratic modified SEPIC topology as shown in Fig.5 is proposed in [19]. The proposed converter is suitable for DC microgrid and renewable energy applications. A diode-capacitor based voltage boosting module is used to improve the output voltage level. The merits of the converter include low switch voltage stress and reduced number of passive components. The voltage gain equation for the converter proposed in [19] is given by Equation (6).

$$G_{CCM} = \frac{V_0}{V_{in}} = \frac{(1+k)}{(1-k)^2} \qquad (6)$$

The comparison of the converter topologies mentioned in [15], [16], [17], [18], & [19] is shown in Table I.

TABLE I: COMPARISON OF CONVERTER TOPOLOGIES

Converter topology	Number of Components				Switch voltage stress	Voltage gain (G_{CCM})
	Inductors (L)	Capacitors (C)	Switch (S)	Diodes (D)		
]15] – I & II	2	4	1	5	Low	$\frac{2}{(1-k)^2}$
[15] – III	3	5	1	7	Low	$\frac{4}{(1-k)^2}$
[16]	2	3	1	5	Low	$\left(\frac{2-k}{1-k}\right)^2$
[17]	2	5	1	6	Low	$\frac{2(2-k)}{(1-k)^2}$
[18]	1	4	1	4	Low	$\frac{1+T+kT}{(1-k)}$
[19]	3	4	1	4	Low	$\frac{1+k}{(1-k)^2}$

III. SIMULATION RESULTS AND DISCUSSION

One ([15]-III) of the converter topologies shown in Table I is taken for simulation. The converter topology ([15]-III) is fed by a diode rectifier bridge energized by a sinusoidal voltage source. The corresponding MATLAB/SIMULINK model is developed with the help of Simscape Electrical toolbox and 'ode 45' solver as shown in Fig.5, and is simulated at switching frequency of 50 kHz. The simulation results are viewed using Multi-plot and Scope. The circuit components for the simulation are selected based on the design considerations and are listed in Table II shown below. The specifications of the selected topology are given in Table III. The graphical user interface (GUI) is used for solving process simulations. Discrete state variable model of sampling time $T_s = 5$ μsec. is used for simulation. The switching pulse to the MOSFET switch 'S' is shown in Fig.6. The various waveforms for the selected converter configuration are shown in Fig.7, Fig.8, Fig.9, and Fig.10 respectively. The simulation results demonstrate that the selected topology shows improved voltage gain compared to that of other configurations shown in Table I.

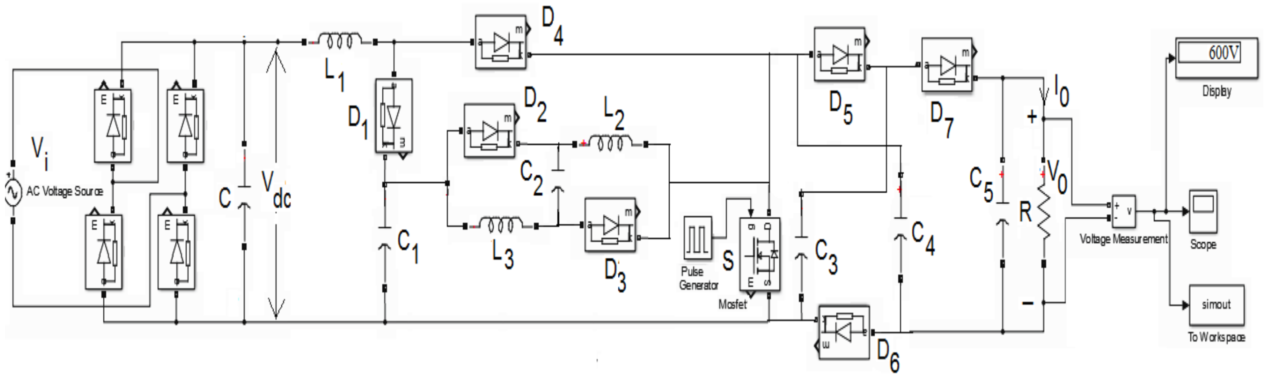


Fig. 5. Simulation model of the selected DC-DC converter structure

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TABLE III: SIMULATION PARAMETERS FOR THE CONVERTER TOPOLOGY [15-III]

Circuit components	Values
Inductors (L_1, L_2, L_3)	330 µH
Filter Capacitor (C)	100 µF
Capacitors (C_1, C_2, C_3, C_4)	47 µF each
Capacitor (C_5)	68 µF
Load Resistance (R)	450 Ω
Duty ratio (k) of the Switch ‘S’	0.6

TABLE IIIII: SPECIFICATIONS OF THE CONVERTER TOPOLOGY [15-III]

Specifications	Values
Input AC voltage (V_i)	$(40 / \sqrt{2})$ V (rms)
Output voltage (V_0)	600 V (DC)
Switching frequency (f_s)	50 kHz
Maximum output power (P_0)	800 W
Average output current (I_0)	1.3 A

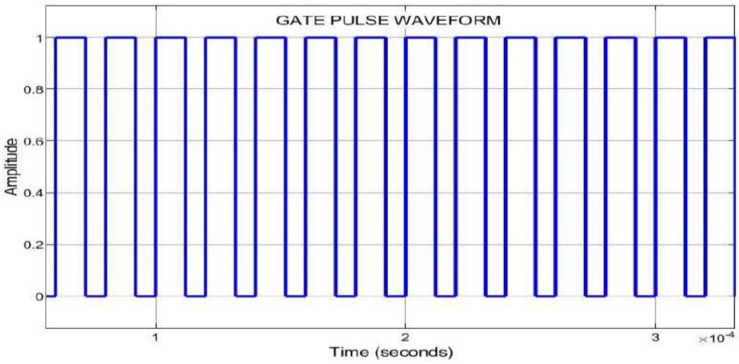

Fig.6 Switching pulse waveform for the switch ‘S’

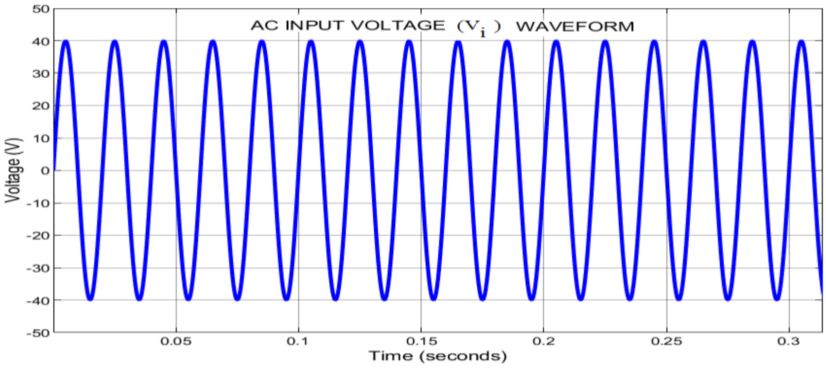

Fig.7 AC input voltage waveform

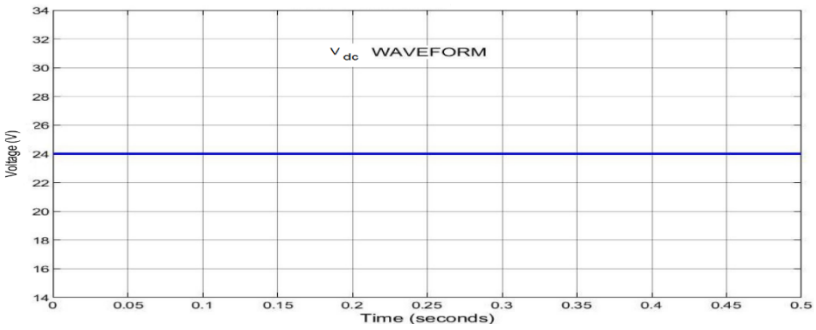

Fig.8 DC input voltage (V_{dc})

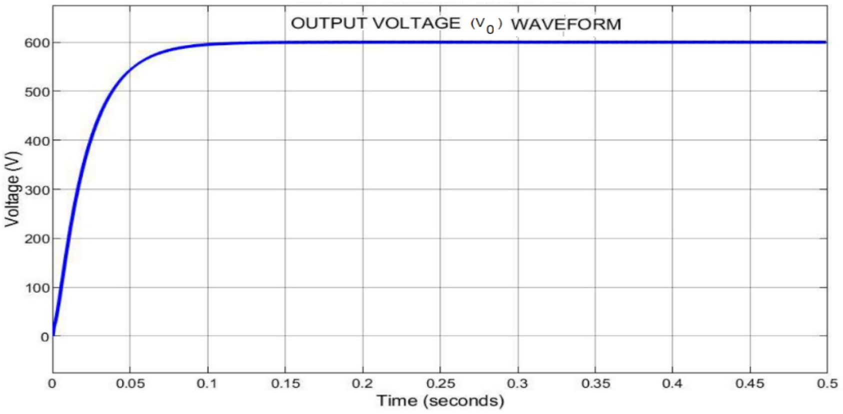

Fig.9 Output DC voltage (V_0)

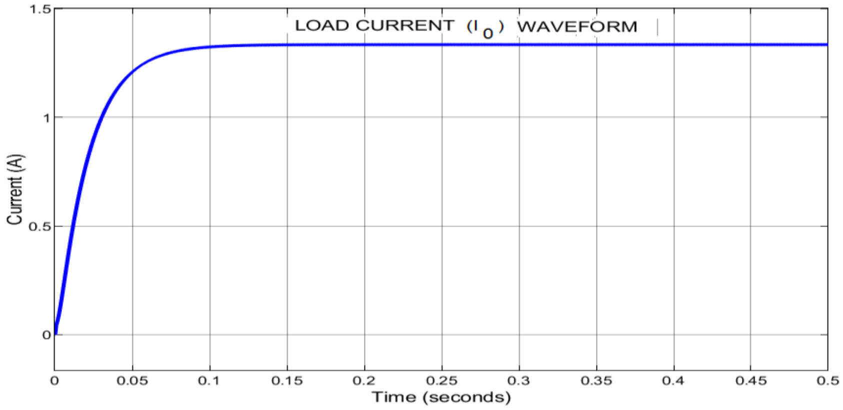

Fig.10 Load current (I_0)

IV. CONCLUSION

This paper presents the comparative review of certain recently developed non-isolated single switch high gain DC-DC boost converters based on voltage gain, number of active and passive components, and voltage stress. The time-domain simulation of the DC-DC converter topology that has highest voltage gain among the converters taken for review has been carried out in MATLAB/SIMULINK platform to validate the effectiveness of the topology. The selected converter is fed by a diode bridge rectifier whose input source is AC voltage of 50 Hz frequency.

The results demonstrate that the selected converter topology has the capability to produce an output voltage $V_0 = 600V$ which is almost 25 times the DC input voltage $V_{dc} = 24V$ for duty ratio $k = 0.6$. Hence, the selected converter topology shows the improved voltage gain than that of other configurations.

The conventional (PWM) Pulse Width Modulation technique is used to turn on and turn off the MOSFET switch ‘S’. Further, the switching losses and the switch voltage-current stress found to be low for the simulated converter. The reviewed converters in this paper are suitable for renewable energy and electric vehicle applications.

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