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Review of DC-DC boost converter derived topologies for renewable energy applications

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ABSTRACT

This paper deals with three different power converter topologies for boosting the available dc input voltage. The converters considered for the study are conventional DC-DC boost converter, quasi switched boost DC-DC converter (qSBC) and quasi Z source converter (qZSC). The converters are designed for an input voltage of 24 V to deliver a power of 200 W to a resistive load. The steady-state analysis of all three topologies is discussed to determine the key characteristics of the proposed topologies. All the converters are simulated in MATLAB/Simulink environment and the outcomes are explained in detail. The performance comparison of the converters such as switch stress, diode stress and boost factor versus duty ratio are presented. Thus, this comparison helps to choose a suitable boost converter topology for a specific application.

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1. INTRODUCTION

As the conventional energy sources are facing the issues like depletion of fossil fuels and the increase in pollution, the need for the clean and green energy using renewable energy sources such as photovoltaic, wind, wave, tide, geo-thermal, is of great importance. As most of the renewable outlets, such as photovoltaic (PV) systems and wind energy systems, produces a low output voltage which is not sufficient to meet the specific requirements. Hence DC/DC converters are very essential units that are used in renewable power conversion systems as electronic operating systems for power applications. They demand booster circuits to provide sufficient voltage at the output side [1]–[3]. The efficacy of DC/DC conversion is progressive in the electrical industry. The DC/DC converters used in the electrical industry are simulated to cater to the certain advanced applications [4]–[6]. In addition, fuel cell based distributed power system generates voltage less than the requirements.

Additional boosting circuit is expected to boost the available DC voltage [7]–[11]. The innovative designing of DC/DC converters accounts for an enormous proportion of entire conversion equipment turnover. These DC converters are classified after their function namely buck converter, boost converter, buck-boost converter, zero current switching (ZCS) and zero voltage switching (ZVS) converters. Now-a-days in most of the applications, bidirectional DC-DC converters with negligible ripple content is the desired feature. Compared to the conventional DC-DC converters, the derived DC-DC converters have lower conduction losses [12]. The high gain is achievable in quasi networks rather than conventional boost converter. As the demand is more and more for the renewable energy-based hybrid energy systems, multi-input converter (MIC) has got a newer perspective in the converter domain. In the last decade, many topologies have been emerged. Though there are many topological developments, there exist drawbacks when it comes to design complexity and efficiency. The proposed multi-input converter is able to hybridize different sources such as solar PV array and proton-exchange membrane fuel cells (PEMFC) [13]. The voltage output from solar PV systems is of low in nature, which needs to be boosted to a level required with the help of DC-DC converters for grid-connected systems. To solve this, a new high gain and efficient boost converter which is a combination of buffer capacitor, passive clamp recovery circuit to restore leakage energy in coupled inductor is presented [14]. As Cuk converter has the feature of both stepping up and stepping down the input voltage, it can act as an interface in PV systems i.e., in both classical and distributed maximum power point tracking systems. The filtering elements required in case of Cuk converter interfaced circuits are less as the converter itself basically involves two inductors which provide continuous input and output currents [15].

The multi input multilevel output (MIMLO) DC-DC converter is used in renewable energy, such as fuel cells, wind turbines and PV, to get the best output voltages. The MIMLO DC-DC converter powers the load from renewable energy sources through the independence of the availability of other sources. The MIMLO design has certain features such as simplicity in configuration, a smaller number of switches, maximum efficiency, and high conversion ratio. The multilevel output DC-DC converter offers reduction of losses, low stress voltage on switches and diode high voltage transfer [16]. By adopting Z source network and its derived circuits, higher boost voltage is achieved [17], [18]. A double output port DC-DC quasi-impedance source converter is proposed. Each of the converter provides different voltage gain. One of the output port converters is capable of providing bidirectional (four-quadrant) operation by only varying the duty ratio. The second output has the voltage gain of traditional two-switch buck-boost converter [19]. Similar to Z source converter derived topologies, switched boost converters are proposed in the literature to obtain higher boost with lower duty ratio for nano and microgrid applications [20]–[22].

The converter can be designed to provide required voltage at the preferred magnitude. Right design and near-optimal usage of components leads to the development of the different power conversion methods, providing a variety of reliable and efficient energy to power up most of the electrical devices and components. Bi-directional DC-DC converter integrated with battery energy management in hybrid PV and wind-based grid connected system controlled by fuzzy logic controller proposed in [23]. Asymmetric quasi-impedance source buck-boost converter is proposed in [24].

A converter basically uses semiconductor switches and components such as inductors, transformers, and capacitors for intermediate energy storage as well as for filtering purpose. The component selection plays a major role in attaining the optimal size, weight and cost of the converter. A converter is an electrical circuit that converts electrical energy from one form to a desired form which can perform one or more functions and give an output different from that of the input, suitable for a particular load.

This article mainly discusses about various converter topologies for boosting the available source voltage to the required level for meeting the load demand. The article is organized as follows: i) Section 2 deals with DC-DC Conversion technology; ii) Section 3 presents the configuration of basic boost converter circuit and its operating modes; iii) Section 4 and 5 discusses the working modes of the quasi Z source converter (qZSC) and quasi switched boost converter (qSBC) respectively; and iv) The performance comparison, results and discussions are presented in section 6. The conclusion of the article is presented at the end of the article and it shows the research directions.

2. DC/DC CONVERSION TECHNOLOGY

The DC/DC convertors established initially are designed with the help of potential divider circuits resulting in reduced voltage at the output. Figure 1 elucidates the development of DC/DC converters branching into first to sixth generation with upgraded techniques. The generation-wise upgraded converters presented in Figure 1 (see Appendix) [3] edify a few limitations which may have to be addressed as the need of the time. Some of the limitations of these converters are of low voltage gain, high source current ripples, voltage stress across the devices are high, voltage rating of the output capacitor needed is high and there is no common ground between input and output terminals. These limitations kindled the devising of DC/DC converters of this study as an enhanced strategy to overcome the restrictions.

3. CONVENTIONAL BOOST CONVERTER CIRCUIT

A typical DC-DC boost converter circuit used for boosting the voltage is depicted in Figure 2(a). Figures 2(b) and 2(c) depict the mode I and Mode II operation of DC/DC boost converter. The available DC source is connected to an inductor. A MOSFET switch is connected across the voltage source. A diode is connected to a capacitor and the load is connected in parallel to the capacitor. The constant input current is caused by the inductor linked to the input source; hence the boost converter is referred to as a constant current input source. The load can also be thought of as a constant voltage source. Pulse width modulation is used to turn on and off the controlled switch. The pulse width modulation (PWM) can be based on time or frequency.

The use of a wide range of frequencies to accomplish the desired control of the switch, which in turn gives the desired output voltage, is a disadvantage of frequency-based variation. DC-DC converters commonly use time-based modulation. It's easy to put together and use. In this sort of PWM modulation, the frequency remains constant. Boost converter operates under two operating modes. When the switch is in closed position, the first mode is activated.

3.1. Mode I: The switch is in closed position and the diode is turned off

As shown in Figure 2(b), the switch is turned on representing a short circuit, preferably with zero resistance to current flow, and hence all the current flows through the switch and returns to the DC input source. Assume the switch is on for time duration of T_{on} and off for time duration of T_{off}. The time period, T= T_{on} + T_{off} and the duty cycle, D = T_{on} / T. Steady-state operation for this mode using Kirchhoff's Voltage Law is given by (1)-(4).

$$V_{in} = V_L \quad (1)$$

$$V_L = L\frac{di_L}{dt} = V_{in} \quad (2)$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_{in}}{L} \quad (3)$$

Because the switch is temporarily closed, we may assert that Δt = DT since T_{on} = DT.

$$\Delta i_{L\,(closed)} = \frac{V_{in}}{L}DT \quad (4)$$

3.2. Mode II: The switch is turned off, but the diode is turned on

In this mode II as shown in Figure 2(c), the inductor's polarity is inverted and the energy held in the inductor is released and eventually dissipated in the load resistance, which helps to keep the current flowing in the same direction through the load. It steps up the output voltage because the inductor is now operating as a source in series with the input source. However, while analyzing the circuit with Kirchoff's Voltage Law (KVL), we stick to the original conventions.

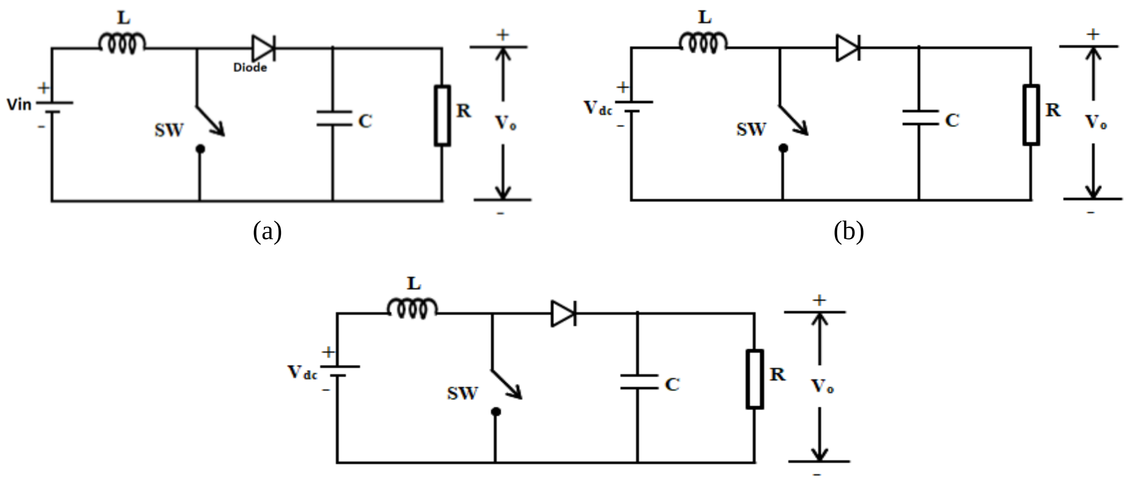

Figure 2. DC/DC boost converter topology under various modes of (a) DC/DC boost converter topology [3], (b) mode-I, and (c) mode-II

Let us now examine the Boost converter in steady-state mode II applying KVL equations from (5)-(11).

$$V_{in} = V_L + V_O \quad (5)$$

$$V_L = L\frac{di_L}{dt} = V_{in} - V_O \quad (6)$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)T} = \frac{V_{in} - V_O}{L} \tag{7}$$

$$\Delta i_{L\,(open)} = \frac{V_{in} - V_O}{L}\,(1-D)T \tag{8}$$

It is previously known that the net change in inductor current during a complete cycle is zero.

$$\Delta i_{L\,(open)} + \Delta i_{L\,(closed)} = 0 \tag{9}$$

$$\frac{V_{in} - V_O}{L}\,(1-D)T + \frac{V_{in}}{L}\,DT = 0 \tag{10}$$

$$\frac{V_o}{V_{in}} = \frac{1}{1-D} \tag{11}$$

Simulations studies of the conventional boost converter were carried out considering the parameters as, R = 288 Ω, L = 500 µH, C = 200 µF, V_{in} = 24 V and T = 20 µs and the results are presented in the section 6 for comparison of performance parameters with other converter circuits.

4. QUASI Z SOURCE CONVERTER (qZSC)

Figure 3(a) shows the topological structure of qZSC topology. The circuit diagram of shoot through mode is shown in Figure 3(b) and non-shoot through mode of operations is depicted in Figure 3(c). The circuit is derived from the basic conventional Z source converter. Here the switch and capacitor stress are less compared to the basic z source converter. The network is placed between source and the switching circuit to increase the DC output voltage of the converter by modifying the shoot through (ST) duty cycle. Only direct current flows through the inductor during normal operation. Inductor current increases and decreases respectively in ST and non-shoot through mode. The source current is found to be continuous in nature.

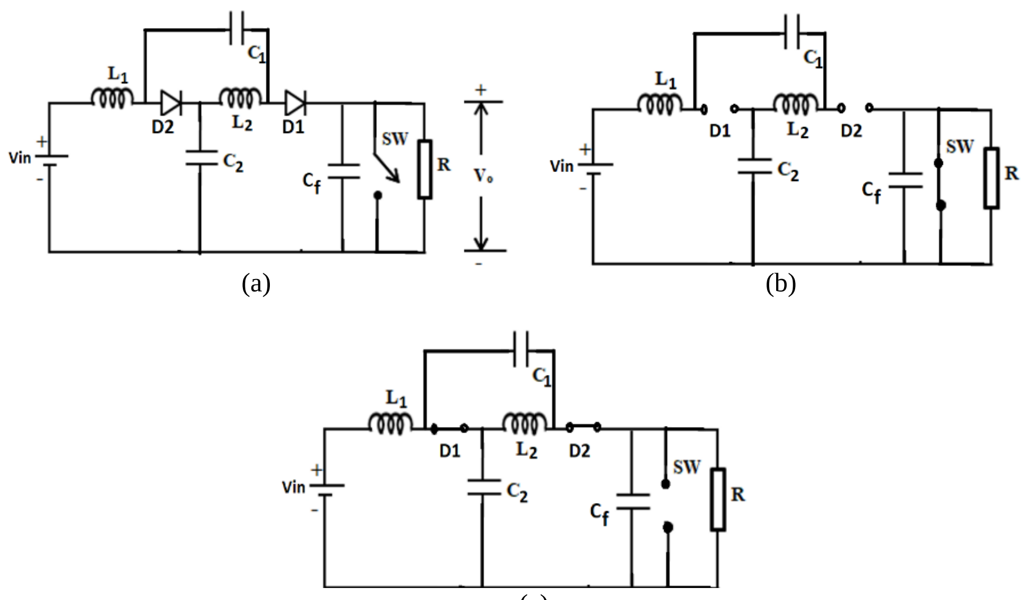

Figure 3. DC/DC qZSC (qZSC) circuit under different modes of (a) DC/DC qZSC topology [17], (b) shoot through mode, and (c) non shoot through mode

According to the symmetry of the Z source network, the bands of inductance L_1 and L_2 are chosen by L; the capacitor banks C_1 and C_2 are chosen using C. Then the values of I_{L1} and I_{L2} are equal to I_L, V_{L1} and V_{L2} are equal to V_L, V_{C1} and V_{C2} are equal to V_C. The state equations for the system are given by (12)-(18),

$$Current\ in\ the\ Inductors:\ I_{L1} = I_{L2} = \frac{(1-D)^2\,V_{in}}{(1-2D)^2\,RL} \tag{12}$$

$$Voltage\ of\ Capacitors:\ V_{C1} = V_{C2} = \frac{(1-D)\,V_{in}}{(1-2D)} \quad (13)$$

$$Inductor\ current:\ I_L = \frac{(1-D)\,V_{in}}{(1-2D)\,RL} = \frac{P}{V_{in}} \quad (14)$$

$$Output\ DC\ Voltage:\ V_0 = \frac{V_{in}}{(1-2D)} \quad (15)$$

$$Current\ Ripple:\ \Delta I_L = 2\,\%\ of\ I_L \quad (16)$$

$$Inductance:\ L = \frac{V_L D T_S}{\Delta I_L} \quad (17)$$

$$Capacitance:\ C = \frac{I_L D T_S}{V_C \delta V\%} \quad (18)$$

In the shoot through operation, the ripple current of the converter decreases because the current through the inductor and the capacitor are equal. The voltage ripple of the converter depends on Vc and δV%, the range of the capacitor is calculated according to the given formula. The qZSC topology is shown in Figure 3. Simulation studies are carried out considering the following parameters: R = 250 Ω, $L_1 = L_2$ = 2.3 mH, $C_1 = C_2$ = 100 µF, C_f = 470 µF, V_{in} = 24 V and T = 20 µs and the results are presented in the section 6.

5. QUASI SWITCHED BOOST CONVERTER (qSBC)

The circuit topology of basic switched boost DC-DC converter and its modes of operations are shown in Figures 4(a), 4(b) and 4(c) respectively. The qSB network consists of one inductor, one capacitor, two diodes and two switches. It has a smaller number of passive elements compared to quasi Z source DC-DC converters.

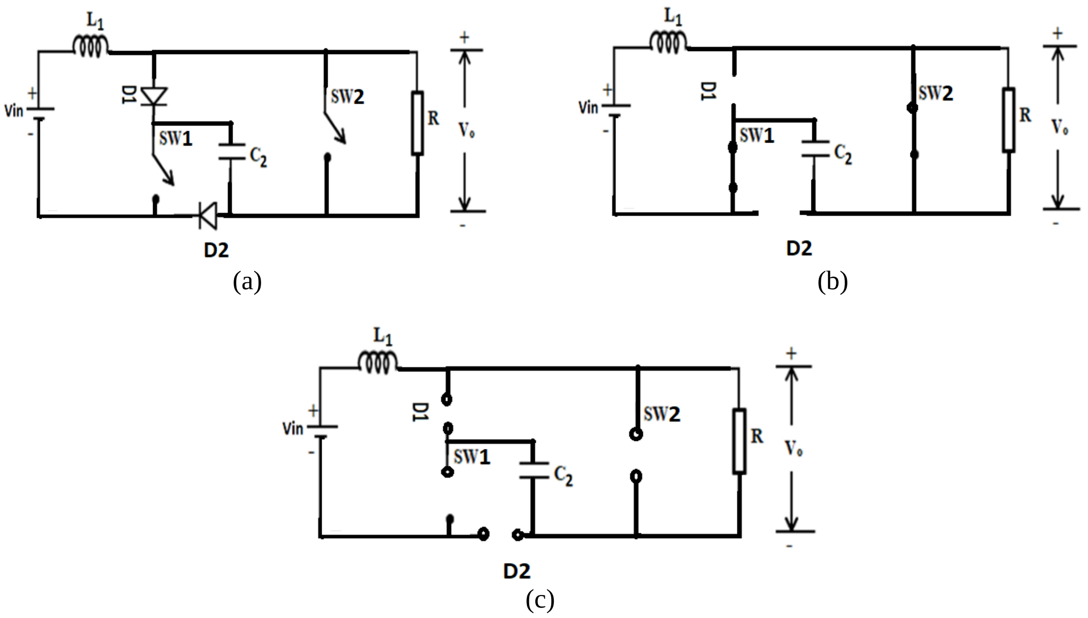

Figure 4. DC/DC quasi switched boost converter (qSBC) topology under various modes of (a) DC/DC qSBC topology [25], [22], (b) shoot through mode, and (c) non shoot through mode

The network components are designed using the following set of (19)-(26).

$$In\ non\ shoot\ through\ mode:\ L\,\Delta i_L = V_{dc} - V_C \quad (19)$$

$$C\,\Delta V_C = I_L - i_{PN} \quad (20)$$

$$In\ shoot\ through\ mode:\ L\,\Delta i_L = V_{dc} + V_C \tag{21}$$

$$C\,\Delta V_C = -I_L \tag{22}$$

$$V_C = \frac{V_{dc}}{(1-2D)} \tag{23}$$

$$I_{PN} = I_L\,\frac{(1-2D)}{(1-D)} \tag{24}$$

$$Peak\ Voltage\ in\ non\ shoot\ through\ mode:\ V_{PN} = V_C = \frac{V_{dc}}{(1-2D)} \tag{25}$$

$$Boost\ Factor:\ B = \frac{V_{PN}}{V_{dc}} = \frac{1}{(1-2D)} \tag{26}$$

The voltage gain of qZS/qSBC is not high if simple boost control technique is adopted. Because the ST duty cycle is constrained to (1-M), where M is the modulation index. Passive elements such as inductors, coupled inductors, switched capacitor cell/switched inductor cell qZS/qSBC to increase the boost factor and improve the voltage gain of qZS/qSBC. In some articles, modified PWM is used to increase the converter boost. Simulation studies are carried out for the following parameters: R = 250 Ω, $L_1 = L_2$ = 1 mH, $C_1 = C_2$ = 100 µF, V_{in} = 24 V and T = 20 µs and the results are presented in the next section.

6. RESULTS AND DISCUSSION

Table 1 summarizes the general operating parameters and their values used for simulation and the results obtained from simulation. Although all three DC-DC converter topologies (boost converter, qZSC and qSBC) may be utilized for voltage step-up, it is appropriate to evaluate their specifications, potentiality and operation. Comparison among the converters have been presented considering the operating scenario to be the same i.e., the source voltage, switching frequency and the power rating to be the same. The Simulink model of conventional boost converter is shown in Figure 5. The output waveforms obtained from simulation using MATLAB/Simulink is represented in Figure 6 for boost converter, Simulink model of qZSC is presented in Figure 7 and the output waveforms are shown in Figure 8. Simulink model of qSBC is shown in Figure 9 and waveforms are shown in Figure 10.

Figure 6 shows the MATLAB Simulink waveforms of DC- DC boost converter. It depicts the source voltage, source current, load voltage and load current waveforms of DC-DC boosted converter. The load current of 0.8 A, is flowing through the resistive load. The voltage across the load is seen as about 240.6 V. Here to attain this load output voltage, the input voltage of 24 V at the duty ratio of 0.9, along with one inductor, one capacitor, a MOSFET and a diode are used. Figure 8 depicts the source current, load current, load voltage and source voltage waveforms of quasi Z source converter. The load current of 1 A, is flowing through the resistive load. The voltage across the load is seen as about 241.1 V at the shoot through duty ratio of 0.4574.

Here to attain this load output voltage, the input voltage of 24 V along with two identical inductors and capacitors are used. Figure 9 shows the simulink model of quasi switched boost inverter. Figure 10 shows the source voltage, source current, load voltage and load current waveforms of quasi switched boost converter. It gives the output voltage of 247.4 at the input of 24 V and the duty ratio of 0.4547. It is around 10 times the source voltage. From Table 1, it is obvious that the power delivered by the boost converter to the load is 201 W. The qZSC delivers the power of 232 W power. Similarly, qSBC delivers the output power of 244.9 W. Among all three topologies, qSBC delivers high output power with reduced value of shoot through duty ratio.

Table 1. MATLAB/Simulink parameters for three topologies of DC/DC converters

Parameters	Boost Converter	qZSC [17]	qSBC [22]	Parameters	Boost Converter	qZSC [17]	qSBC [22]
Input Voltage	24 V	24 V	24 V	Pulse Width	90.4	45.75	45.47
Inductor	500 µH	L_1=L_2=2.3 mH	0.2 µH	Phase Delay	0	0	2.7e-3 and 12.7e-3
Capacitor	200 µF	C_1=C_2=100 µF C_f=470 µF	C_1=100 µF	Output Voltage	240.6 V	241.1 V	247.4 V
Resistor	288 Ω	250 Ω	250 Ω	Input Current	8.72 A	13.88 A	13.37 A
Frequency	50 kHz	50 kHz	50 kHz	Output Current	0.8354 A	0.9643 A	0.9897 A
Time Period	20 µs	20 µs	20 µs				

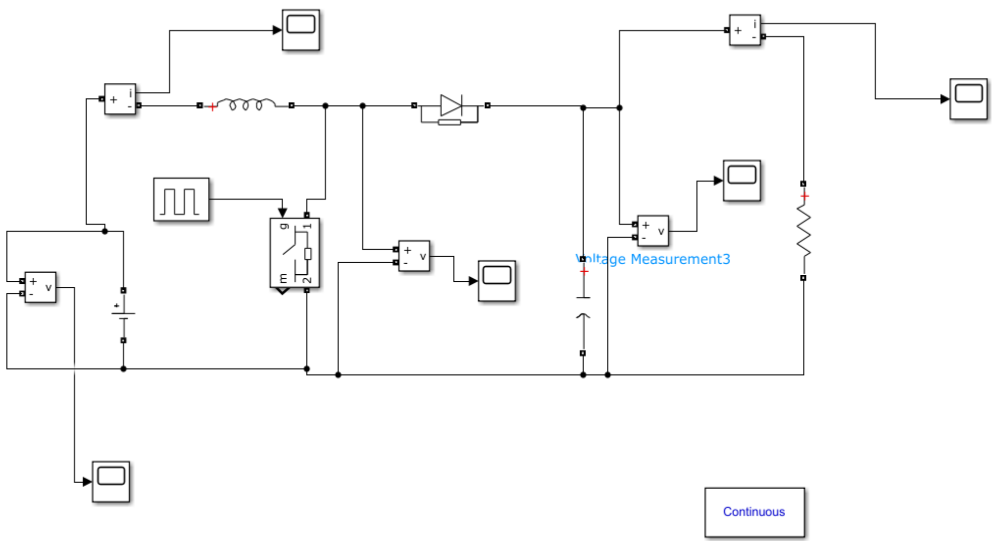

Figure 5. Simulink model of conventional boost converter

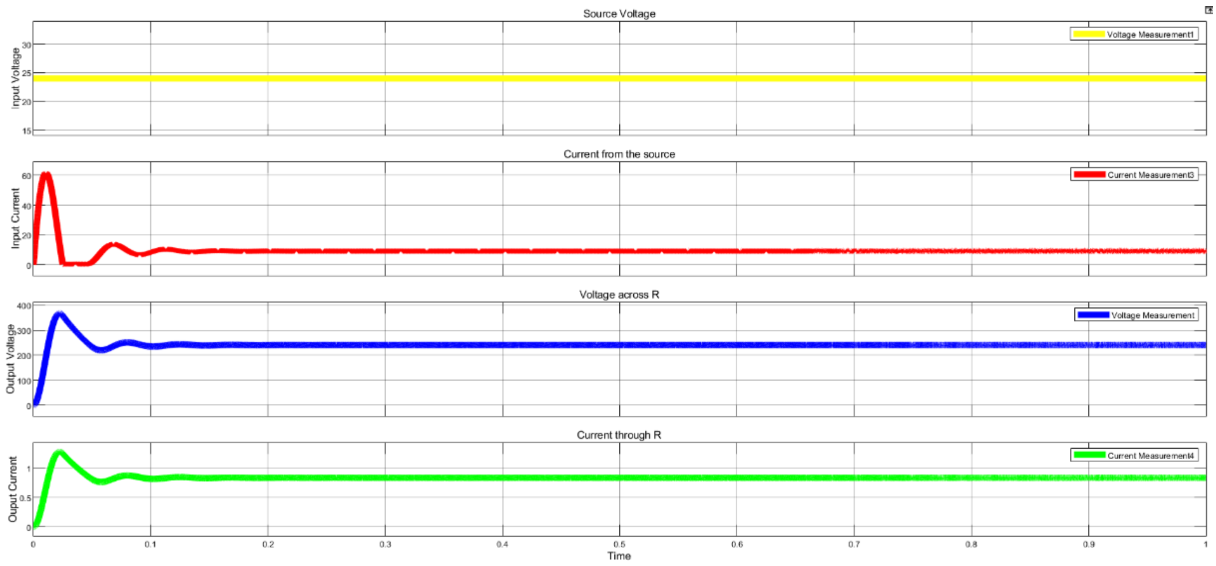

Figure 6. MATLAB Simulink waveforms of boost converter

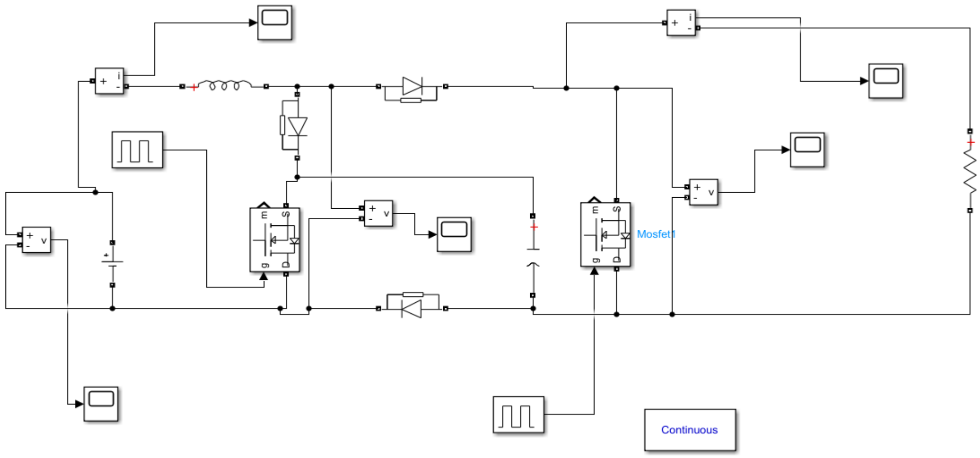

Figure 7 Simulink model of quasi Z source converter

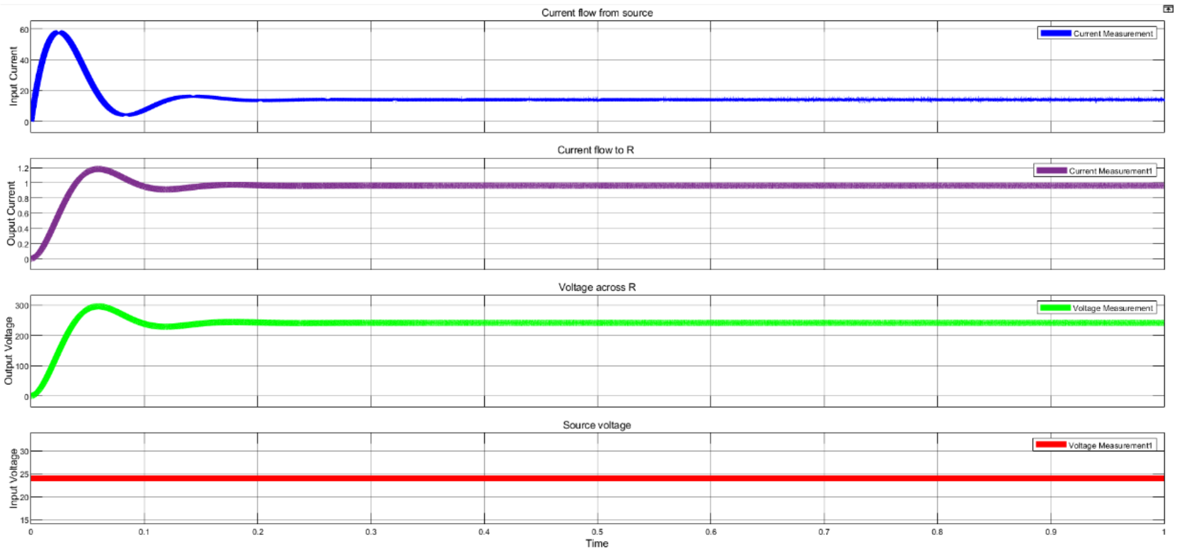

Figure 8. MATLAB Simulink waveforms of quasi Z source converter

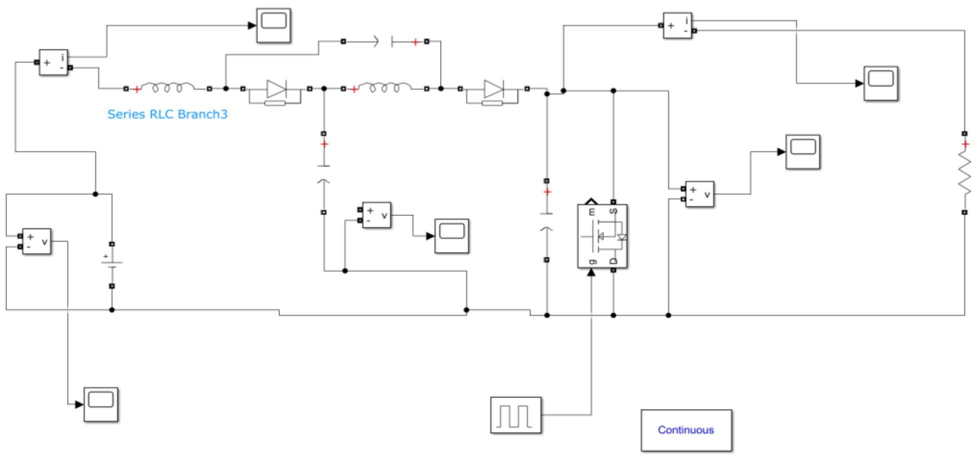

Figure 9. Simulink model of quasi switched boost inverter

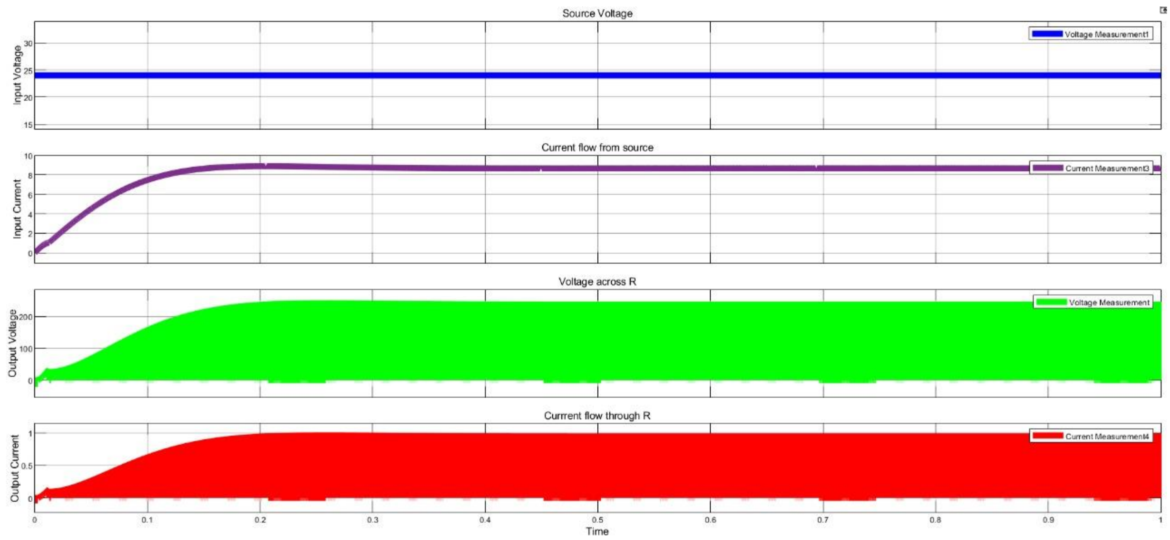

Figure 10. MATLAB Simulink waveforms of quasi switched boost converter

6.1. Device comparison

Table 2 and Figure 11 presents the number of components used in the DC-DC conventional boost converter, quasi Z source converter and quasi switched boost converter. The number of diodes, inductors, capacitors and MOSFET switches are tabulated below. The number of passive elements count is less for DC-DC boosted converter compared to other two topologies. At the same time, the boost factor obtained by the conventional DC-DC boost converter is less compared to other two topologies. The quasi switched boost converter has less number of passive elements, but it has additional diode. On the other hand, quasi Z source converter has more number of passive elements and no additional switches or diodes.

6.2. Boost factor and shoot-through duty ratio

Figure 12 shows the relation between boost factor and shoot through duty ratio. Boost converter provides the boost of 10 times the input voltage at the duty ratio of 0.9. Similarly, quasi-Z source and quasi-switched boost converter provides the same boost at the shoot through duty ratio of 0.45 which almost half the value which is used with DC-DC boost converter.

Table 2. Component comparison of DC-DC boost converter, quasi Z source converter, and quasi switched boost converter

Topology	No. of inductors	No. of capacitors	No. of diodes	No. of MOSFET Switches
DC -DC boost converter	1	1	1	1
Quasi Z source converter [17]	2	2	1	0
Quasi switched boost converter [22]	1	1	2	1

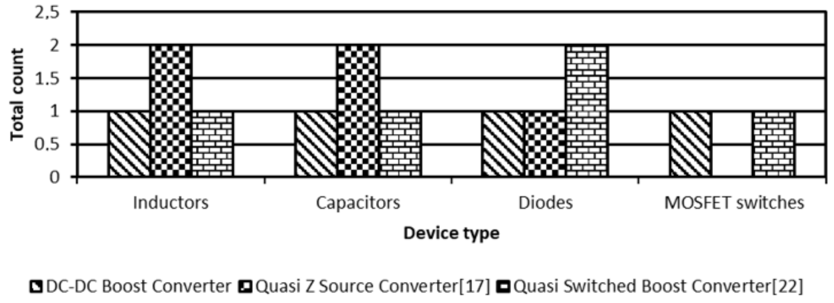

Figure 11. Component comparison of various topologies

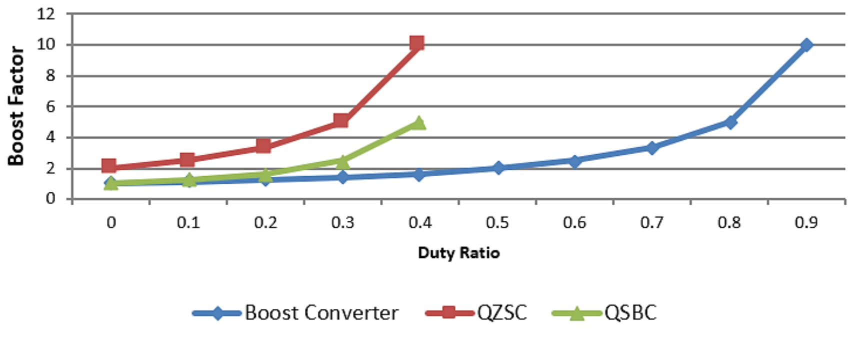

Figure 12. Comparison of boost factor (vs) duty ratio for the three topologies

7. CONCLUSION

This paper discusses the comparative analysis of the classical DC-DC boost converter, qZSC and qSBC topologies. Analytical expressions for the estimation of parameters in different operating modes for the selected converters of the study are detailed. The efficacy of these topologies is validated by steady-state analysis with extensive simulation results. The advantages of the converters addressed in this work are continuous input current, decreased capacitor voltage stress, low voltage stress across the output diode, and power switches. These are cost effective and user-friendly. Possibility of further enhancement of these topologies such as boost converter, quasi Z source converter and quasi switched boost converter are useful in power amplifier applications, photovoltaic applications, hybrid electric vehicles, where low DC input voltage need to be boosted. This article gives the basic idea to the researchers for selecting a suitable DC-DC converter for a specific application.

APPENDIX

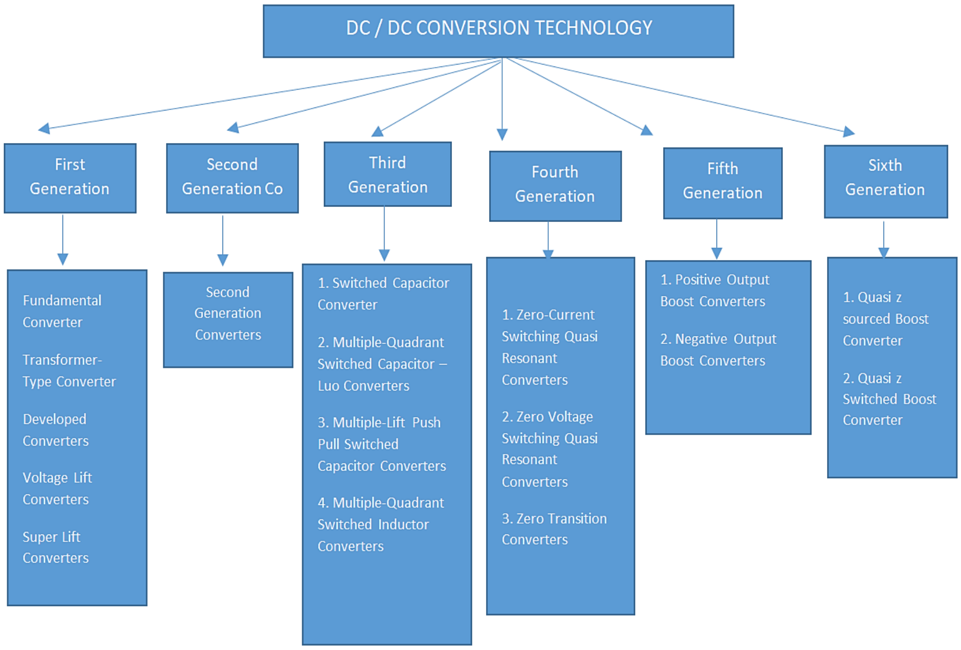

Figure 1. Evolution of DC/DC conversion technology

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