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Switched Inductor Z-source/quasi Z-source Network: State of Art and Challenges

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***Abstract*—In recent years, the impedance source network has been studied by many researchers focusing on high conversion gain power electronics. Several number of topologies have been developed. The combination of the Switched inductor cells and Z-source networks has shown its capability of achieving high voltage gains and good power conversion at low shoot through duty cycle values as compared to traditional Z-source network. This paper contributes as an overview of different Switched inductors cells combined with Z-source or quasi Z-source network. General analytical classification, main charachterestics, and comparison of different topologies and their modifications, are provided in this paper. This study should be of interest for engineers and researchers when selecting their high voltage gain impedance source converter.**

Keywords— Voltage gain, inrush current, continuous current, low shoot-through, boost factor.

I. INTRODUCTION

In recent years, renewable energy sources (RES) capacity has been steadily increasing rapidly. The solar photovoltaic (PV) and wind power share of this installed capacity has increased from around 62.6 GW in 2005 to around 1049.5 GW in 2018 according to IRENA [1].

The main characteristics of RES are the variation of the climate temperature, solar irradiance, wind speed, hydrogen capacity, etc. Accordingly, the generated voltage and power from such RES is fluctuating. These challenges require power electronics interface that assures high quality output power, that can adapt with wide input power and voltage variations, where it complies with the required IEEE standars [2], [3]. The voltage source inverters (VSI) have been extensively used in various power electronics applications, such as motor drives, distributed generation, energy storage systems and uninterruptible power supplies (UPS) [4]. Nevertheless, VSIs feature the following limitation and technical barriers [5]:

- The ac output voltage is always lower than the input one, and for this cause they can be classified as buck converters (step-down). In order to increase the ac output voltage, an extra dc-dc boost converter is required to achieve the sought voltage level at the ac output. This extra stage affects the cost and complexity of the controller, negatively. Furthermore, it lower its efficiency.
- To prevent the shoot through (short circuit) between the upper and lower dc-link terminals, a dead time is introduced between the gating pulses which increases the output current and voltage waveforms distortion.

The impedance source inverter (ISI) was originally invented to cope with the aforementioned limitations of VSIs and current source inverters (CSI). The first ISI topology is Z-source inverter (ZSI) and was designed in 2003, by Prof. Fang Chang Peng.

The Z-source network (ZSN) is composed by two inductors L_1 and L_2, two capacitors C_1, C_2 and one inverse diode D, and are coupled with the inverter dc-link. This converter class can perform all dc-ac, dc-dc, ac-dc, and ac-ac power conversions [6]. This converter can be operated in buck-boost conversion in a single stage converter by exploiting the shoot through state (two switches in one leg fired simultaneously). The ZSI can boost the inverter's dc input voltage to the sought dc-link voltage [7], which is advantageous to reduce the cost and improve the efficiency compared with the extra dc-dc boost circuit based two stage inverter [8], [9]. The ISI have been utilized in different applications, like adjustable speed drives [10], electric vehicles [11], distributed power generation (fuel cell, photovoltaic (PV), wind, etc.) [12], [13], and [14], and energy storage [15], [16]. This paper presents a comprehensive overview of the existing Switched inductor (SL) combined with the Z-source and quasi Z-source network (qZSN) and their associated characteristics. The remaining of this overview paper is consituted as follows. Section II discusses the basic working principle of the ZSI, section III introduces the Switched inductor based impedance source networks, section IV presents a comparison of these topologies, and finally the presented work is concluded in section V.

II. OPERATING PRINCIPLE

An impedance source network can be described as a two ports network with a combination of inductors, capacitors, and semiconductor devices. There are different derivations and modifications of this circuit by adding and combining different elements in the impedance source network [17] .

Fig. 1 depicts the three phase voltage fed ZSI used to explain its operating principle. The conventional three-phase VSI has six active states and two null ones.

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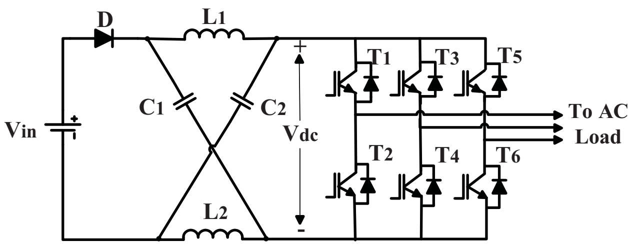

Fig. 1 Schematic of Z-source inverter topology.

The shoot through state is possible by turning on both upper and lower switches of any phase leg (T_1, T_2), any two phase legs (T_1, T_2, T_3, T_4), or all three phase legs $(T_1, T_2, T_3, T_4, T_5, T_6)$ [5], thus shorting the output terminals of the ZSI produces the zero voltage vector across the filter and load. The dc input voltage source and the two inductors feed the load and charge the two capacitors in the active states, which makes the bridge dc- link voltage boosted.

The Z-source inverter along with the shoot through state achieve a unique buck and or boost capability and by regularing the modulation index (M) and shoot through duration.

The capacitor voltage (V_C), the dc-link voltage (V_{dc}), and the ac peak phase output voltage (V_{ac}) of the Z-source inverter, are giving by:

$$V_{C_1} = V_{C_2} = \frac{1-D_{sh}}{1-2D_{sh}} V_{in} \quad (1)$$

$$V_{dc} = B.V_{in} = \frac{V_{in}}{1-2D_{sh}} \quad (2)$$

$$V_{ac} = M.V_{dc} = M.B.\frac{V_{in}}{2} \quad (3)$$

Such as the shoot through duty cycle $D_{sh} = T_{sh}/T_s$, T_{sh} is the shoot through duration per switching period (T_S), and B is the boosting factor. From(3), the phase output voltage peak can be controlled either by adjusting the modulation index or shoot through time, where it can be higher than the dc input one. This is the prominent advantage of the ZSI.

III. Switched inductor-based Impedance source converters

The traditional ZSN has some disadvantages such as, discontinuous conduction mode (DCM) of the input current, high voltage stress in the passive components, and low boost factor [9]. In order to enhance the boost factor of the ZSN/qZSN, many topologies have been studied on the impedance source network. These topologies are subdivided in to two main subgroups .

- Separated inductors: Z-source [5], quasi Z-source [21] Embedded Z-source [22], improved Z-source [23], Switched inductor Z-source [24], and Switched inductor quasi Z-source [25].
- Magnetically coupled inductors and transformer: Trans Z-source [26], Switched coupled inductor quasi Z-source [27], Y-source [28], TZ-source [29], Γ Z-source [30], and LCCT Z-source [31].

Nowadays, to achieve the high boost factor, different combination of topologies were used such a switched inductors (SL), Switched coupled inductors (SCL), etc. Enhancing the ac output voltage, reducing the capacitor voltage stress and suppress the startup inrush current are also other motives [32].

A .Quasi Z-source Network

The qZSN, shown in Fig. 2(a) was introduced an improvement to the traditional the ZSN, which uses two inductors L_1 and L_2, two capacitors C_1 and C_2, and one diode D. All these elements are connected at the input of the inverter. The qZSN inherits all the merits of the ZSN, such as a common ground of the dc input on the dc-link bus and continuous input current. Moreover, the capacitor voltage is minimized resulting in a smaller size of components. The qZSN is very attractive for application in photovoltaic system. In steady state, the two capacitor voltages and peak dc-link voltage are given by [21]:

$$V_{C_1} = \frac{1-D_{sh}}{1-2D_{sh}} V_{in} \quad (4)$$

$$V_{C_2} = \frac{D_{sh}}{1-2D_{sh}} V_{in} \quad (5)$$

$$V_{dc} = V_{C_1} + V_{C_2} = \frac{1}{1-2D_{sh}} V_{in} = B.V \quad (6)$$

As can be noted from (5) and (6), the qZSN has the same boosting factor of the ZSN while the capacitor voltage V_{C_2} is reduced.

B. Switched Inductor Z-source Network

In order to improve the boosting ability of the ZSN, the concept of SL technique is merged in ZSN. The two inductors have been replace by two SL cells. Consequenctly, a higher dc-link voltage can be produced for the main power circuit from a low input dc voltage [24], [33]. Fig. 2(b) presents the Switched inductor Z-source network (SL-ZSN). In the steady state, the average capacitor and dc-link voltages are defined by:

$$V_{C_1} = V_{C_2} = \frac{1-D_{sh}}{1-3D_{sh}} V_{in} \quad (7)$$

$$V_{dc} = \frac{1+D_{sh}}{1-3D_{sh}} V_{in} = B.V_{in} \quad (8)$$

From (7) and (8), it can be noted that the boost factor is highly increased and the capacitors voltage is smaller in compare with the ZSN. This implies, by using a shorter time for the shoot through state, a high voltage gain can be attained. Although, the main disadvantages of this topology are the discontinuous dc input current and inrush current at the startup [34], [35].

C. Switched inductor quasi Z-source Network

The Switched inductor quasi Z-source network (SL-qZSN) is presented in [25], [36]. For the limitation of the boost factor in the qZSN and the discontinuous dc input current of the SL-ZSN, the SL cell is replaced by the output side inductor L_2. This cell consists of two inductors and three diodes, as illustrated in Fig. 2(c). In steady state, the following equations are valid:

$$V_{C_1} = \frac{1-D_{sh}}{1-2D_{sh}+D^2{}_{sh}} V_{in} \quad (9)$$

$$V_{C_2} = \frac{2D_{sh}}{1-2D_{sh}+D^2{}_{sh}} V_{in} \quad (10)$$

$$V_{dc} = V_{C_1} + V_{C_2} = \frac{1+D_{sh}}{1-2D_{sh}+D^2{}_{sh}} V_{in} \quad (11)$$

As can be seen from the (9)-(11), the boost voltage ability of the SL-qZSN is higher than the one of the ZSN and lower than the one of the SL-ZSN. On the other hand, the voltage stress on the capacitors is less. This topology is applicable for fuel cells or renewable sources, where a low input voltage is converted to a significantly high output voltage [37].

D. Voltage lifting switched inductor quasi Z-source Network

For improving the boost ability while keeping all inherit of the SL-qZSN, one of the diodes in SL unit can be replaced by a capacitor, as shown in Fig. 2(d). For the same input and output voltage, voltage lifting switched inductor quasi Z-source (VL-SL-qZSN) can greatly reduce the shoot through duration. This advantage decreases the conduction loss during the shoot through state, and eventually improves the efficiency [38], [39]. In steady state, the average voltages of capacitors and dc-link can be assessed, respectively as:

$$V_{C_1} = V_{VL} = \frac{1-D_{sh}}{1-3D_{sh}} V_{in} \quad (12)$$

$$V_{C_2} = \frac{1-D_{sh}}{1-3D_{sh}} V_{in} \quad (13)$$

$$V_{dc} = \frac{2}{1-3D_{sh}} V_{in} \quad (14)$$

According to (14) and compared to the ZSN [5], and SL-qZSN [25], the VL-SL-qZSN can attain high voltage conversion ratio when the shoot through duty ratio $0 < D_{sh} < 1/3$. Therfore it is suitable for low voltage and low power applications.

E. Switched coupled inductor quasi Z-source Network

To overcome the boost ability limitations of the qZSN, higher voltage stresses in components and low output power quality, recently, the coupled inductors based impedance networks have been set in [20], which offer higher boost factor with a very short shoot through time and reduces the number and the size of passive components. The switched coupled inductor quasi Z-source network (SCL-qZSN) is introduced in [27]. It incorporates a three winding switched coupled inductor (SCL) and Switched capacitor in the classical qZSN. Fig. 2(e) presents the SCL-qZSN, which maintains all of the advantages of qZSN topology such as continuous input current, common ground between the main circuit and dc voltage source, and startup inrush current suppression [40]. In steady state, the following relationships are obtained:

$$V_{C_1} = \frac{1-D_{sh}}{n+2} V_{in} \quad (15)$$

$$V_{C_2} = \frac{n+1+D_{sh}}{n+2} V_{in} \quad (16)$$

$$V_{C_3} = \frac{(n+1)(1-D_{sh})}{n+2} V_{in} \quad (17)$$

$$V_{dc} = \frac{n+1}{(1-(3+n)D_{sh})} V_{in} \quad (18)$$

When the turn n is 1, $V_{dc} = \frac{3}{1-4D_{sh}} V_{in}$ (19)

The SCL consists of three windings $(N_1, N_2 \, and \, N_3)$. Winding N_1 and N_2 have the same turns number$(N_1 = N_2)$ and the turn ratio of windings N_3 of N_1 $(\, or \, N_2)$ is

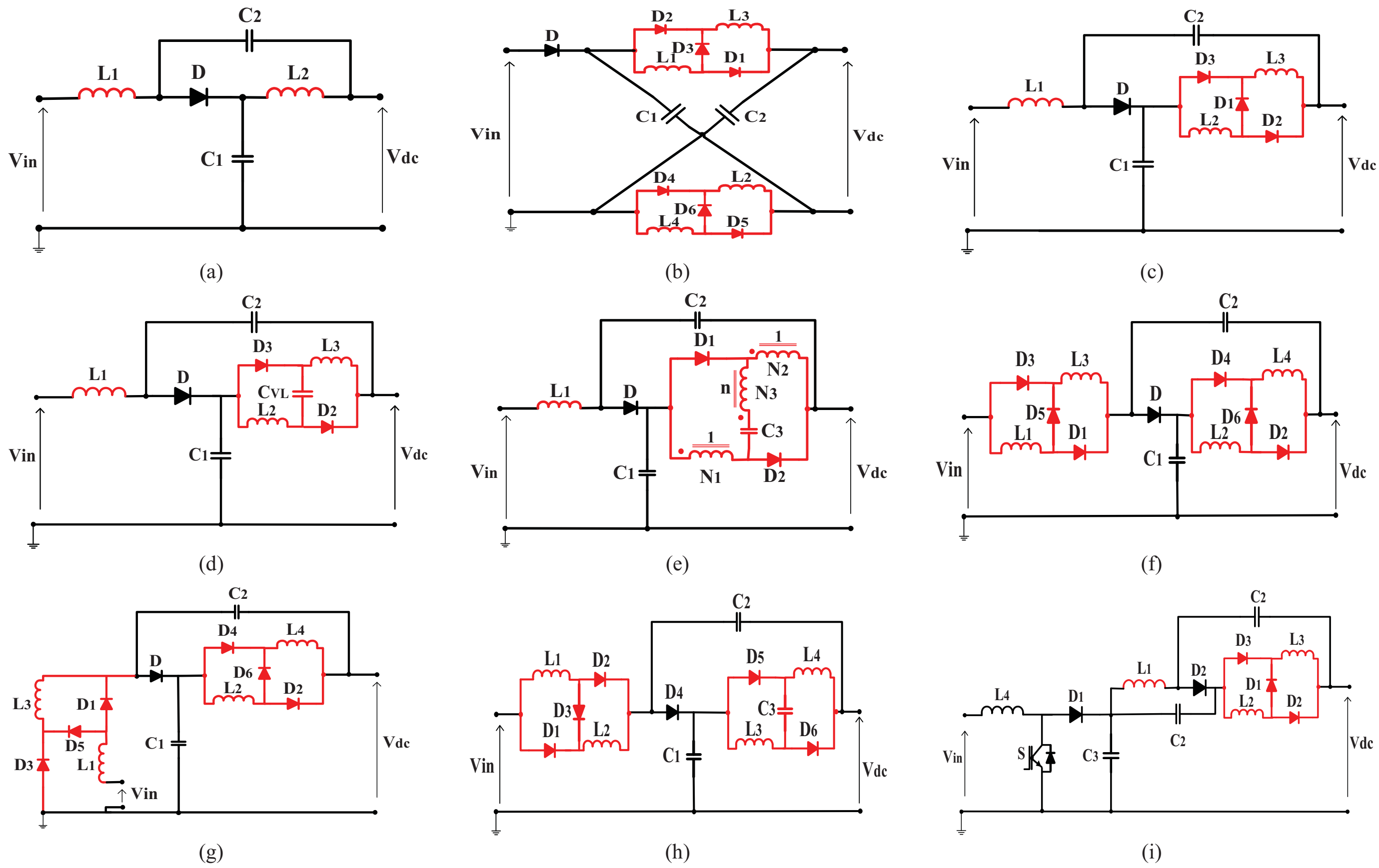

Fig. 2 Switched inductor Z-source Network, (a) quasi Z-source, (b) Switched inductor Z-source, (c) Switched inductor quasi Z-source, (d) Voltage lifting Switched inductor quasi Z-source, (e)Switched coupled inductor quasi Z-source, (f) Ripple Switched inductor quasi Z-source, (g) Switched inductor quasi Z-source with Continuous input current, (h) Switched inductor-improved Switched inductor quasi Z-source, (i) Extended Switched inductor quasi Z-source.

n ($n = N_3/N_1 = N_3/N_2$). This topology offers higher step-up gains with winding turn ratios capability low as unity ($n = 1$). Its voltage boost is, thus, higher that of the existing qZSN.

F. Ripple Switched inductor quasi Z-source Network

Fig.2(f). shows the ripple Switched inductor quasi Z-source network (rSL-qZSN). To overcome the problem of startup inrush current of the SL-qZSN, the two inductors $L_1$and L_2 are replaced by two cells in the conventional qZSN. This topology suffers from reduced voltage stress on the capacitors and improves the system reliability [41].

$$V_{C_1} = \frac{1-D_{sh}}{1-3D_{sh}} V_{in} \quad (20)$$

$$V_{C_2} = \frac{2D_{sh}}{1-3D_{sh}} V_{in} \quad (21)$$

$$V_{dc} = V_{C_1} + V_{C_2} = \frac{1+D_{sh}}{1-3D_{sh}} V_{in} \quad (22)$$

By comparing (22) and (8), the boost factor of the rSL-qZSN is equivalent to that found in the SL-ZSN [24], and suffers from lower voltage stress on the capacitors. This is advantageous for applications of low and medium power photovoltaic or fuel cell energy generation.

G. Switched inductor quasi Z-source Network with Continuous input current

Switched inductor cell is utilized to the conventional qZSN topology as an alternative to the two main inductors for giving a new topology that has been denoted to as continuous input current Switched inductor quasi Z-source cSL-qZSN [41], as show in Fig. 2(g). In steady state, the following relationships are obtained:

$$V_{C_1} = \frac{1-D_{sh}}{(1+D_{sh})(1-3D_{sh})} V_{in} \quad (23)$$

$$V_{C_2} = \frac{2D_{sh}}{(1+D_{sh})(1-3D_{sh})} V_{in} \quad (24)$$

$$V_{dc} = \frac{1}{1-3D_{sh}} V_{in} \quad (25)$$

By comparing (25) to (8), the boost factor of the cSL-qZSN is lower than that given by the SL-ZSN and offers decreased voltage stress on the capacitors, and it became soft starting by limitting the startup inrush current, which improves the lifetime of the devices [42].

H. Switched inductor-improved Switched inductor quasi Z-source Network

The Switched inductor-improved Switched inductor quasi Z-source network (SL-ISL-qZSN) inherits all the advantages of the qZSN such as common ground between the dc input and output, and also enhanced boosting ability and reduced voltage stress of the switches, and for that reason, the reliability and efficiency of the SL-ISL-qZSN can be enhanced [43]. Fig.2(h) presents the configuration of the SL-ISL-qZSN, which can be achieved through replacing the main inductors of the qZSN with SL cell and ISL cell respectively The voltages across the capacitors and dc link voltage can be finally derived as follows.

$$V_{C_1} = V_{C_3} = \frac{1-D_{sh}^2}{1-4D_{sh}-D_{sh}^2} V_{in} \quad (26)$$

$$V_{C_2} = \frac{(1+D_{sh})^2}{1-4D_{sh}-D_{sh}^2} V_{in} \quad (27)$$

$$V_{dc} = V_{C_1} + V_{C_2} = \frac{2(1+D_{sh})}{1-4D_{sh}-D_{sh}^2} V_{in} \quad (28)$$

As can be seen from (28) and (25), the SL-ISL-qZSN can achieve the highest boost factor with the same total components count compared to other networks if they are all under the same duty cycle. Therefore, it can be applied in photovoltaic power generation applications and other systems that require high voltage conversion gain.

I. Extended Switched inductor quasi Z-source Network

Fig. 2(i). presents the extended switched inductor quasi Z-source network (ESL-qZSN) with higher boosting voltage, which consolidates the SL-qZSN with classical boost converter [44], as well as enhances the SL cell [38]. The improved SL cell replaces the original output side inductor. Although some components are added, this topology achieves a higher boost capability with an equivalent shoot through duty cycle to the other topologies. For the same input and output voltage, the ESL-qZSN suffers from lower voltage stress on the capacitors, diodes and switches, which affects the network's reliability. The voltages across capacitors and dc-link voltage can be given as:

$$V_{C_1} = \frac{2D_{sh}}{(1-3D_{sh})(1-D_{sh})} V_{in} \quad (29)$$

$$V_{C_2} = \frac{1+D_{sh}}{(1-3D_{sh})(1-D_{sh})} V_{in} \quad (30)$$

$$V_{C_3} = \frac{1}{(1-D_{sh})} V_{in} \quad (31)$$

$$V_{C_4} = \frac{1-D_{sh}}{(1-3D_{sh})(1-D_{sh})} V_{in} \quad (32)$$

$$V_{dc} = \frac{2}{(1-3D_{sh})(1-D_{sh})} V_{in} \quad (33)$$

The ESL-qZSN obtains high voltage gain with continuous input current and lower voltage stress across the capacitor. According to the above, it can be stated that the ESL-qZSN is more suitable for distributed generation with low voltage input sources, such fuel cells and photovoltaic sources.

IV. Comparative Analysis

Table I presents different characteristics of the formerly discussed netwoks, and Fig. 3 exhibits the relation of the boost factor and the shoot through duly cycle for these different topologies. The topologies SL-ZSN, rSL-qZSN, and cSL-qZSN have similar number of components. In addition to that, the SL-ZSN, rSL-qZSN topologies have the same boosting ability and the cSL-qZSN has a little lower boost factor. Nonetheless, the SL-ZSN has discontinuous input current while the rSL-qZSN has a rippled but continuous input current. Therefore, the SL-ISL-qZSN topology can be selected to be the one having the higher boost factor with below $\sqrt{5} - 2$ of the shoot through duty ratio. The ESL-qZSN topology has a higher boost factor with lower shoot through duty cycle $0 < D_{sh} < 1/3$. The SL-qZSN and SCL-qZSN topologies have a lower number of components than the previous topologies. Moreover, the SL-qZSN topology has the lowest boost factor but higher than the classical ZSN topology, while the SCL-qZSN topology has the highest boost factor used magnetically coupled inductor . Therefore, the SL-ISL-qZSN topology may be the best choice, especially if a high boost factor, small shoot through duty cycle, lower component count, continuous input current, common earthing, and higher efficiency, are demanded.

V. CONCLUSION

Existing Switched inductor combined with Z-source and quasi Z-source network were analyzed in this paper. Moreover, the analysis highlighted the advantages and disadvantages of these topologies. It has been shown that SL-ISL-qZSN, SCL-qZSN and ESL-qZSN reach the highest boost factor while the ZSN and qZSN attain the lowest. All networks are the most suitable for single stage high voltage step-up conversion of low dc voltage sources such as photovoltaic and fuel cells generation systems.

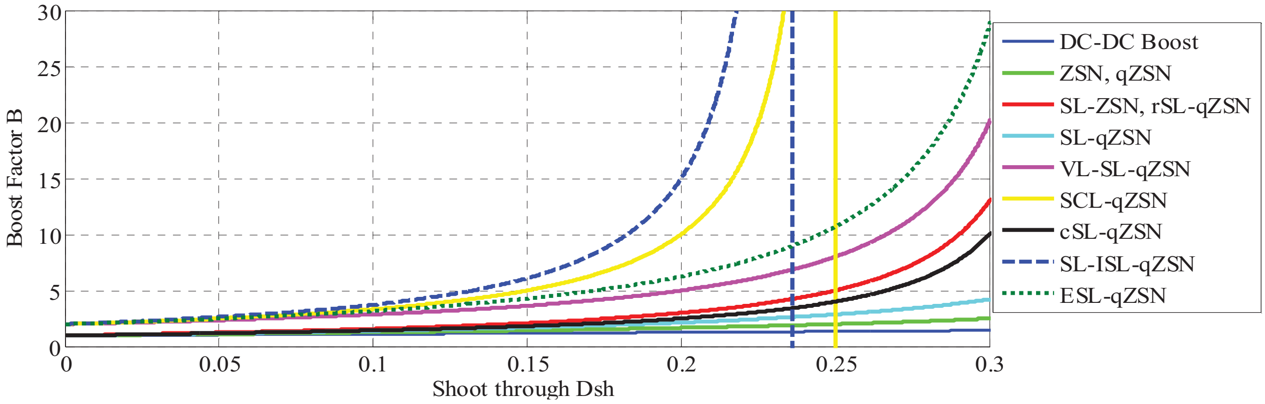

Fig.3 The boost factor B as a function of the Shoot Through duty cycle D_{sh} for different networks.

TABLE I. CHARACTERISTICS OF DIFFERENT SWITCHED INDUCTOR Z-SOURCE/QUASI Z-SOURCE COMBINATIONS

Converter	**No. of elements**	**Boost Factor**	**Continuous input Current**	**Startup inrush Current**	**Common Earth**
DC-DC Boost [45]	1Capacitor 1 Inductor 1 Diode 1 Switch	$\frac{1}{1-D}$ Where $0 < D < 1$	Yes	No	Yes
ZSN [5]	2 Capacitors 2 Inductors 1 Diode	$\frac{1}{1-2D_{sh}}$ Where $0 < D_{sh} < 1/2$	No	Yes	No
qZSN [21]	2 Capacitors 2 Inductors 1 Diode	$\frac{1}{1-2D_{sh}}$ Where $0 < D_{sh} < 1/2$	Yes	No	Yes
SL-ZSN [24]	2 Capacitors 4 Inductors 7 Diode	$\frac{1+D_{sh}}{1-3D_{sh}}$ Where $0 < D_{sh} < 1/3$	No	Yes	No
SL-qZSN [25]	2 Capacitors 3 Inductors 4 Diode	$\frac{1+D_{sh}}{1-2D_{sh}-D^2{}_{sh}}$ Where $0 < D_{sh} < 1/2$	Yes	No	Yes
VL-SL-qZSN [38]	3 Capacitors 3 Inductors 3 Diode	$\frac{2}{1-3D_{sh}}$ Where $0 < D_{sh} < 1/3$	Yes	No	Yes
SCL-qZSN [27]	1 Coupled inductor 3 Capacitors 1 Inductors 3 Diode	$\frac{2}{1-4D_{sh}}$ For $n = 1$, Where $0 < D_{sh} < 1/4$	Yes	No	Yes
rSL-qZSN [41]	2 Capacitors 4 Inductors 7 Diode	$\frac{1+D_{sh}}{1-3D_{sh}}$ Where $0 < D_{sh} < 1/3$	Yes, rippled	No	Yes
cSL-qZSN [41]	2 Capacitors 4 Inductors 7 Diode	$\frac{1}{1-3D_{sh}}$ Where $0 < D_{sh} < 1/3$	Yes	No	Yes
SL-ISL-qZSN [43]	3 Capacitors 4 Inductors 5 Diode	$\frac{2(1+D_{sh})}{1-4D_{sh}-D_{sh}^2}$ Where $0 < D_{sh} < \sqrt{5}-2$	Yes	No	Yes
ESL-qZSN [44]	4 Capacitors 4 Inductors 1 Switch 5 Diode	$\frac{2}{(1-3D_{sh})(1-D_{sh})}$ Where $0 < D_{sh} < 1/3$	Yes	No	Yes

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