Journal of International Conference on Electrical Machines and Systems, Vol.1, No.1, pp.67~76, 2012

Switched Inductor Z-Source AC-DC Converter

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Abstract–Due to the increasing amount of applications of power electronic ac–dc converters, it is necessary to design a single-stage converter that can reliably perform both buck and boost operations. Traditionally, this can be achieved by double-stage conversion (ac/dc-dc/dc) which ultimately leads to less efficiency and a more complex control system. This paper discusses two types of modern ac-dc converters. First, the novel impedance-source ac-dc converter, abbreviated as custom Z-source rectifier, is analyzed; and then, switched inductor (SL) Z-source ac-dc converter is proposed. This paper describes the Z-source rectifiers' operating principles, the concepts behind them, and their superiorities. Analysis and simulation results show that the proposed custom Z-source rectifier can step up and step down voltage; and the main advantage of the SL Z-source ac-dc converter is its high step-up capability. Low ripple of the output dc voltage is the other advantage of the proposed converters. Finally, the SL Z-source ac-dc converter is compared with the custom Z-source ac-dc converter.

Keywords: Z-source converter, Switched-inductor converter, AC-DC converter.

1. Introduction

Nowadays, power rectifiers are being used increasingly in energy conversion systems, including uninterruptible power supplies and motor drives. Traditionally, ac–dc power conversion has been dominated by diode or phase-controlled rectifiers, which act as nonlinear loads in power systems and draw input currents which are rich in harmonics and have a poor supply power factor. Therefore, power quality problems are created in the power distribution network and other electrical systems in the vicinity of the rectifier. Ordinarily, ac to dc conversion is carried out by using a switched-mode voltage source rectifier (VSR) topology as shown in Fig. 1. In some applications, current source rectifier (CSR) topology is also used (Fig. 2) [1]. The main problems associated with these converters include [2]:

1) Voltage drop at the buses.
2) Large reactive power drawn by the rectifiers from the power system, which requires that distribution equipment handle large amounts of power. Thus, their volt-ampere ratings increase.
3) Higher harmonics of input current that result in a distorted line current, which tends to distort the line voltage waveform. This often causes problems in the reliable operation of sensitive equipment operating on the same bus.
4) Increase in losses in the equipment (due to harmonics) such as transformers and motors connected to the utility.
5) Electromagnetic interference with the nearby communication circuits.
6) blown-fuses on power factor correction capacitors due to high voltages and currents from resonance with line impedance and capacitor bank failures;

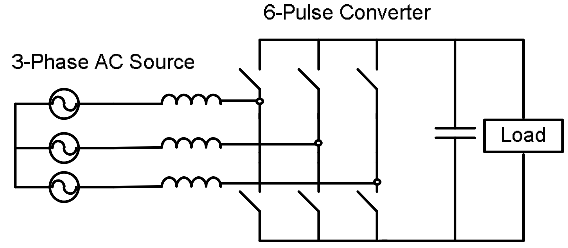

Fig. 1. Voltage source rectifier

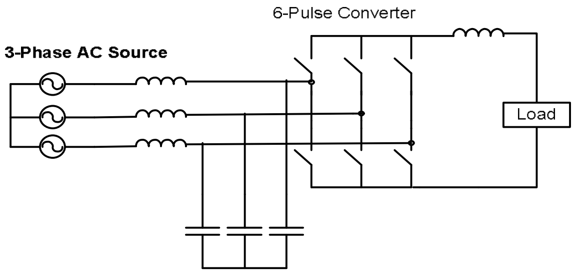

Fig. 2. Current source rectifier

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Received 03 July 2011 ; Accepted 08 November 2011

7) Nuisance tripping of the protective devices, including false tripping of relays.

8) Damaging dielectric heating in cables.

9) They are boost or buck rectifiers. So, their obtainable output dc voltage is only greater or smaller than the input ac voltage.

10) In view of reliability, any short circuit of a switch in any phase leg of a VSR could damage the rectifier, and the same is true for a CSR in the case of an open circuit in any leg.

Most of these applications would require rectifiers to have both buck and boost capabilities, in order to increase load current or regulate input voltage variations. In general, this may be achieved by two-stage power conversion with the connection of an additional dc-dc converter to the traditional ac-dc converter, as shown in Fig. 3. Also, for high power applications, some schemes have been proposed, such as the 12-pulse rectifier shown in Fig. 4. However, this scheme leads to an inefficient system due to an increase in switching losses. Also, system complexity increases with a two-stage converter. Therefore, alternative single-stage buck-boost rectifier topologies are desired [3].

To overcome these drawbacks, improved-power-quality ac-dc converters are proposed as an inherent part of an ac–dc conversion system produces high efficiency and well regulated output dc voltage.

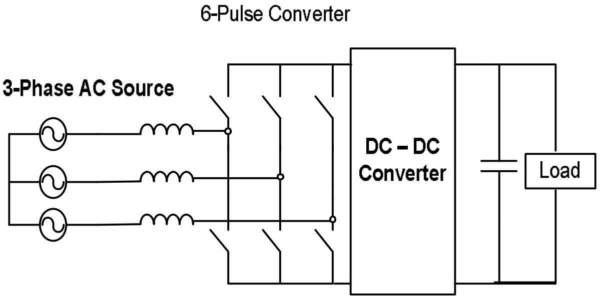

Fig. 3. Two stage buck-boost rectifier

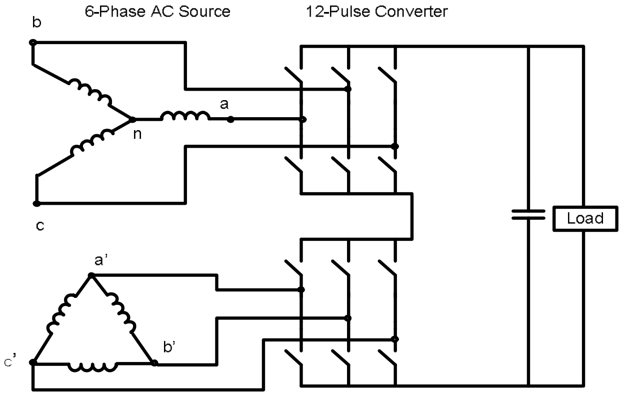

Fig. 4. 12 pulse ac-dc converter

The output voltage in these converters is regulated even under fluctuations of the input ac voltage and changes in the load.

Since the converter output voltage remains constant, even under supply-voltage fluctuations, the power-quality-improvement converters can solve the supply-brownout problem. This new breed of rectifiers has been made possible mainly because of the use of modern solid-state self-commutating power semi-conducting devices such as power MOSFETs, IGBTs, GTOs, etc., and are specifically known as switched-mode rectifiers (SMRs). Three-phase ac–dc converters have been developed to a matured level with improved power quality in terms of power-factor correction, reduced total harmonic distortion at the input ac mains, and regulated output dc voltage in buck, boost, buck–boost, multilevel, and multi-pulse modes with unidirectional and bidirectional power flow [4].

This paper discusses two types of new improved-power-quality three-phase rectifiers, denoted as Z-source rectifiers. First, a Z-source ac-dc converter with a custom impedance network (Z-network) is discussed and then, a Z-source ac-dc converter with a switched-inductor impedance network (SL Z-network) is discussed. These converters differ from conventional converters, like VSR and CSR, due to the presence of a unique X-shaped impedance network on the dc side, which serves as an interface between the H-bridge and the load. These rectifiers overcome the limitations of conventional rectifiers. The proposed converters produce output dc voltages that are greater than or smaller than the input ac voltages. In Section 2, a general review—of improved-power-quality converters is performed. In Section 3, the custom Z-source ac-dc converter's principle of operation in steady state is analyzed. Then, in Section 4, a new family of Z-source converter with switched-inductor impedance network is analyzed in steady state. Also in Section 4, SL Z-source ac-dc converter equivalent circuits, and the converters' operation principles, are presented. Finally, in Section 5, both custom and switched-inductor Z-source rectifiers are simulated, and then they are compared with each other.

2. Improved-Power-Quality Converters

2.1 State of the Art

Nowadays, we are interested in improved-power-quality converter (IPQC) technology, which is booming in response to the requirements of high power quality for sensitive loads, power loss reduction, and so on [3]. IPQCs may be considered to be a good alternative for power quality improvement because of reduced size of the overall converter, higher efficiency, lower cost, and enhanced reliability as compared to other means of power quality improvement. These converters provide improved power quality, not only at the input ac mains but also at the dc output, for a better overall design of the equipment. Moreover, the use of these IPQCs results in the equipment behaving as a linear resistive load to the ac mains. New developments in device technology, processors, magnetic devices and control algorithms will result in a real boost to the popularity of these converters in the near future.

IPQCs are classified on the basis of converter circuit topologies, such as buck, boost, buck–boost, multilevel and multi-pulse modes with unidirectional and bidirectional dc output voltage, current and power flow [2]-[4].

2.2 Selection of IPQCs for a Specific Application

The selection of IPQCs for a specific application is an important decision. The following are some of the factors that need to be considered in order to select the proper converter for a specific application [3]:

1) Required level of power quality in the converter input (permitted power factor, total harmonic distortion, etc.)
2) Type of output dc voltage (constant, variable, etc.)
3) Power flow (unidirectional or bidirectional)
4) Number of quadrants (one, two or four)
5) Nature of the dc output (isolated or non-isolated)
6) Requirement of the dc output (buck, boost or buck–boost)
7) Required level of power quality in the output (voltage ripple, sag and swell)
8) Type of dc load (linear, nonlinear, etc.)
9) Cost, size, and weight
10) Efficiency
11) Noise level (Electromagnetic Interference, etc.)
12) Rating (kilowatt, megawatt, etc.)
13) Reliability
14) Environment (ambient temperature, altitude, pollution level, humidity, and types of cooling)

3. Proposed Z-Source AC-DC Converter with Custom Z-Network

The proposed ac-dc converter in this paper differs from conventional ac-dc converters in structure and operation due to the presence of a unique X-shaped impedance network on the dc side, which serves as an interface between a diode bridge and the load, as shown in Fig. 5. Because of this impedance network, this converter is named, “Z-source ac-dc converter”.

In order to overcome conceptual and theoretical barriers and limitations, the proposed Z-source rectifier structure can do the following:

1) Produce any desired output dc voltage that is greater or smaller than the input ac voltage.
2) Reduce inrush and harmonic current and achieve unity power factor without the need of any extra circuits.
3) Reduce the sizes of both the dc-link inductor and capacitor, as compared to traditional two-stage buck-boost rectifiers.
4) Increase the reliability of the circuit due to the addition of the unique Z-network.
5) Control the output dc voltage by using only one active switch (S_1).
6) Be controlled easily in order to obtain the desired output voltage.

Three-phase Z-source rectifiers use an impedance network (Z-network) to replace the traditional dc link. Rectifier circuits can be either of the voltage-source type or of the current-source type. The proposed converter operates with pulse-width modulation (PWM) duty-ratio control, in exactly the same way that the conventional converters operate. The impedance network is implemented using a split inductor (L_1 and L_2) and capacitors (C_1 and C_2) connected in an X shape, as shown in Fig. 6. This unique impedance network allows the Z-source rectifier to step up and step down the output voltage [5]. The Z-network has some particular features that are discussed in detail in [6]. The Z-network is the main core of the various Z-source converters, such as the Z-source ac–ac converter discussed in [7] and [8], the Z-source inverter discussed in [9], the Z-source dc-dc converter discussed in [10] and [11], and the Z-source rectifier discussed in [1]. In this paper, this impedance network is named the “custom Z-network”. So, the converters with custom Z-networks are called “custom Z-source converters”.

3.1 Z-Source AC-DC Converter Steady-State Analysis

If we assume V_{dc} to be the uncontrolled three-phase full-bridge diode rectifier output dc voltage, then V_{dc} is the Z-network input dc voltage. From this point, we are faced with the dc-dc converter that is described in [10], [11]. Fig. 7 shows the equivalent circuit.

The custom Z-network of the Z-source ac-dc converter is symmetrical, so that the L_1 and L_2 inductors, as well as the C_1 and C_2 capacitors, have the same inductance and capacitance, respectively. In this condition we have:

$$v_{C1} = v_{C2} = v_C \tag{1}$$

$$v_{L1} = v_{L2} = v_L \tag{2}$$

where v_{C1} and v_{C2} are the voltage across capacitor C_1 and C_2. v_{L1} and v_{L2} are the voltage across inductor L_1 and L_2.

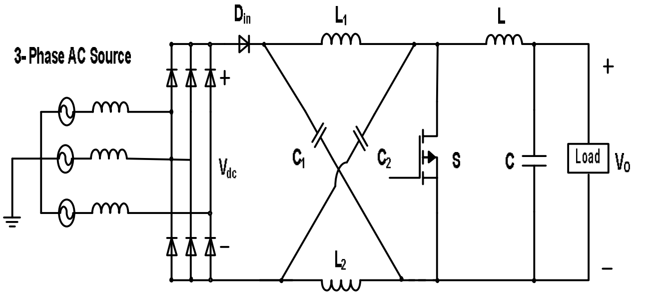

Fig. 5. Z-source ac-dc converter with custom Z-network

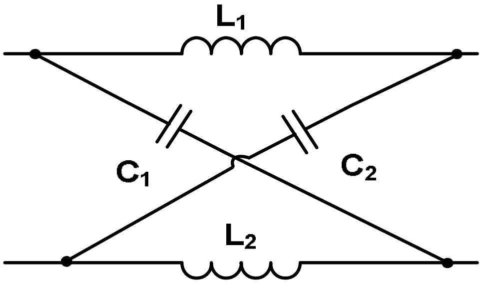

Fig. 6. Custom Z-network

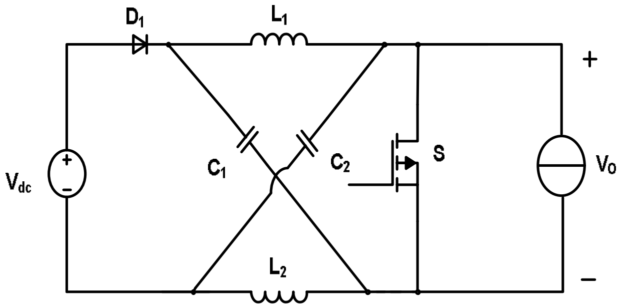

Fig. 7. Equivalent circuit of the proposed custom Z-source ac-dc converter

The proposed custom Z-source ac-dc converter has two operation modes. In mode 1, diode D_1 turns on and switch S is turned off. The DC source charges the Z-network capacitors, while the inductors discharge and transfer energy to the load.

The converter operating interval in this mode is (1-D)·T, where D is the duty cycle of switch S, and T is the switching period. Fig. 8 shows the mode 1 equivalent circuit. In this interval, the following equations are obtained:

$$v_C = V_{dc} - v_L \tag{3}$$

$$v_O = V_{dc} - 2v_L \tag{4}$$

where v_o is the load voltage

In mode 2, switch S is turned on as diode D_1 turns off. The Z-network capacitors discharge, while the inductors charge and store energy to be released and transferred to the load in the next interval. The converter operating interval in this mode is D·T. Fig. 9 shows the mode 2 equivalent circuit. In this interval, the following equations are obtained:

$$v_C = v_L \ , \ v_O = 0 \tag{5}$$

The average voltage of the inductors during one ac line period in steady state should be zero. By ignoring the fundamental voltage drop, and from equations (3) to (5), the following equation is obtained:

$$V_L = \bar{v}_L = \int [V_C.DT + (V_{dc} - V_C).(1-D)T]\ dt \tag{6}$$

This equation results in:

$$\frac{V_C}{V_{dc}} = \frac{1-D}{1-2D} \tag{7}$$

Similarly, the peak output voltage of the converter in a switching cycle can be expressed as follows:

$$\hat{V}_O = 2V_C - V_{dc} = \frac{V_{dc}}{1-2D} \tag{8}$$

The average output voltage of the converter can be expressed as follows:

$$\bar{V}_O = V_C = \frac{1-D}{1-2D} V_{dc} \tag{9}$$

And, in summary:

$$V_O = \frac{1-D}{1-2D} V_{dc} \tag{10}$$

Fig. 10 shows the converter voltage gain versus duty cycle.

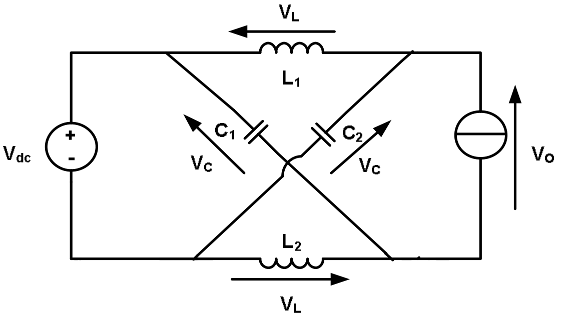

Fig. 8. Custom Z-source ac-dc converter mode 1 equivalent circuit

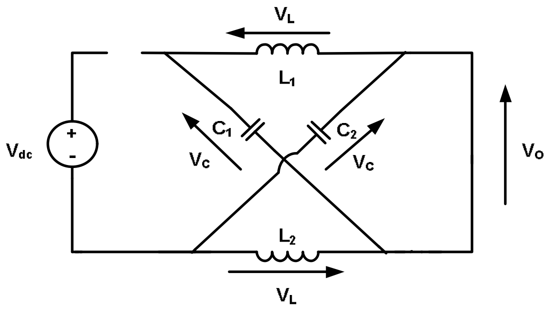

Fig. 9. Custom Z-source ac-dc converter mode 2 equivalent circuit

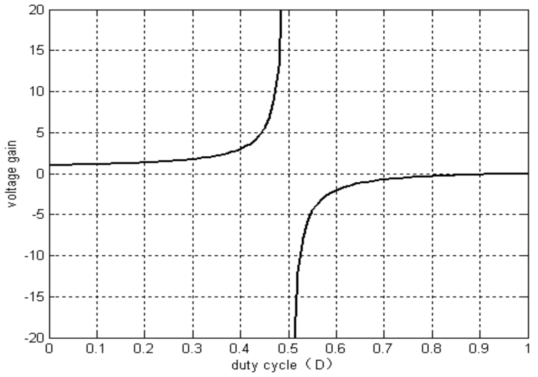

Fig. 10. Custom Z-source ac-dc converter voltage gain versus duty cycle

Obviously, by controlling the switch S duty cycle, the converter output dc voltage can be stepped up and stepped down. Since the switching frequency is very high, the inductance and capacitance of the Z-source network are low. Therefore, the size and weight of all of the system components are also low [10], [11].

4. Proposed Z-Source AC-DC Converter with Switched Inductor Z-Network

In recent years, advanced dc-dc conversion enhancement techniques, such as switched capacitor (SC), switched inductor (SL), hybrid SC/SL, voltage multiplier cells, and voltage lift techniques have been greatly explored [12]–[19]. These techniques are used to achieve high step-up capacity in transformer-less and cascade structures. The main objectives of the use of these techniques are to obtain high efficiency, high power density, and to create simple structures. Therefore, the combination of the Z-source converter with the advanced dc–dc enhancement techniques could be a good solution for improving the performance of impedance-type converters and could promote their further use in industrial applications [20].

One of the novel structures of Z-source converters is the switched inductor Z-source converter. An example of such a converter is the switched inductor Z-source inverter, proposed in [20]. Now, in this section, a novel structure of ac-dc converter is discussed. The proposed ac-dc converter is named “switched inductor Z-source ac-dc converter” or “SL Z-source ac-dc converter”, and its main difference from custom Z-source converters is its impedance network. Fig. 11 shows the proposed structure. As this figure shows, the Z-network of the proposed rectifier consists of four inductors (L_1, L_2, L_3 and L_4), two capacitors (C_1, C_2) and six diodes (D_1, D_2, D_3, D_4, D_5 and D_6). The combination of L_1–L_3–D_1–D_2–D_3 and the combination of L_2–L_4–D_4–D_5–D_6 perform the functions of the top SL cell and the bottom SL cell, respectively. Both of these SL cells are used to store and transfer energy from the capacitors to the dc bus under the switching action of the main circuit [20].

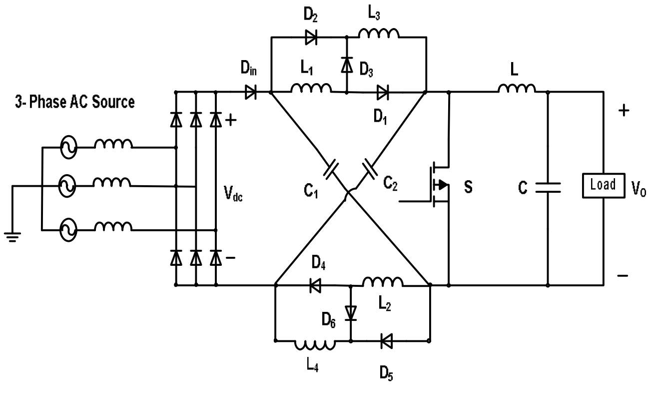

Fig. 11. Topology of the proposed switched inductor Z-source ac-dc converter

4.1 Operation Principle

From the viewpoint of the switching states of the main circuit connected with the SL impedance network, the operation principle of the proposed impedance network is similar to that of the custom Z-source impedance network.

If we assume V_{dc} to be the uncontrolled three-phase full-bridge diode rectifier output dc voltage, then V_{dc} is the SL Z-network input dc voltage. Based on this, Fig. 12 shows the converter equivalent circuit. There are two operation modes for the proposed SL Z-source ac-dc converter:

1) Mode 1: During this mode, switch S is ON, while diode D_{in} is OFF. For the top SL cell, D_1 and D_2 are ON, and D_3 is OFF. L_1 and L_3 are charged by C_1 in parallel. For the bottom SL cell, D_4 and D_5 are ON, and D_6 is OFF. L_2 and L_4 are charged by C_2 in parallel. The equivalent circuit for this mode is shown in Fig. 13. It can be seen that both the top and bottom SL cells perform the same function, that is, to absorb the energy stored in the capacitors. In this mode, the following equations are obtained:

$$v_C = V_{dc} - 2v_L \tag{11}$$

$$v_O = V_{dc} - 4v_L \tag{12}$$

2) Mode 2: The equivalent circuit for this mode is shown in Fig. 14. During this mode, switch S is OFF, while diode D_{in} is ON. For the top SL cell, D_1 and D_2 are OFF, and D_3 is ON. L_1 and L_2 are connected in series, and the stored energy is transferred to the main circuit. For the bottom SL cell, D_4 and D_5 are OFF, and D_6 is ON. L_3 and L_4 are connected in series, and the stored energy is transferred to the main circuit. At the same time, in order to supplement the consumed energy of C_1 and C_2 during this mode, C_1 is charged by V_{in} via the bottom SL cell, and C_2 is charged by V_{in} via the top SL cell. In this mode, the following equations are obtained:

$$v_C = v_L \quad , \quad v_O = 0 \tag{13}$$

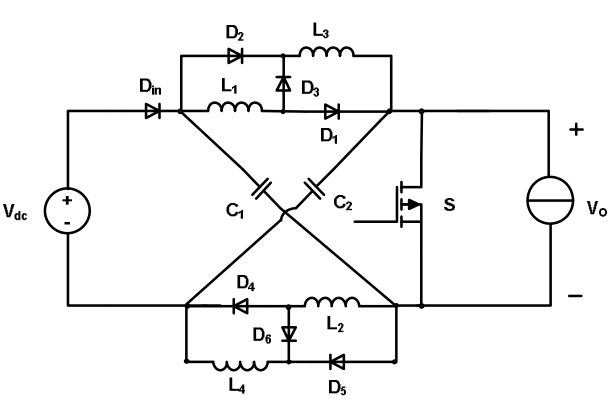

Fig. 12. Equivalent circuit of the SL Z-source ac-dc converter

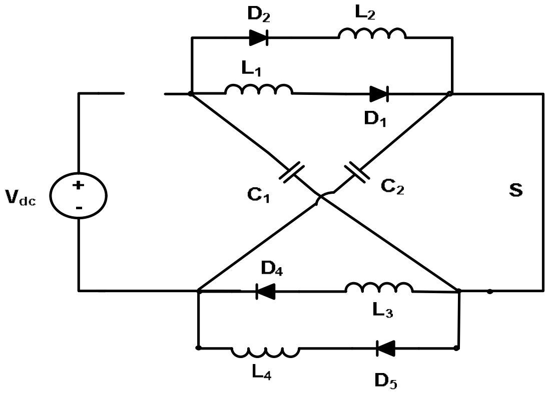

Fig. 13. SL Z-source ac-dc converter mode 1 equivalent circuit

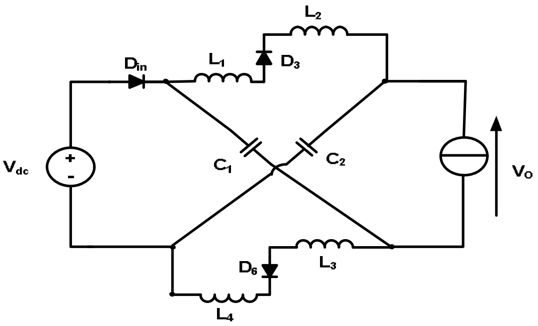

Fig. 14. SL Z-source ac-dc converter mode 2 equivalent circuit

The average voltage of the inductors during one ac line period in the steady state should be zero, if we ignore the fundamental voltage drop. And, from equations (11) to (13), the following is obtained:

$$V_L = \bar{v}_L = \int [V_C.DT + \frac{1}{2}(V_{dc} - V_C).(1-D)T]\ dt \tag{14}$$

This equation results in:

$$\frac{V_C}{V_{dc}} = \frac{1-D}{1-3D} \tag{15}$$

Similarly, the peak output voltage of the converter in a switching cycle can be expressed as follows:

$$\hat{V}_O = 2V_C - V_{dc} \tag{16}$$

The average output voltage of the converter can be expressed as follows:

$$V_O = \frac{1+D}{1-3D} V_{dc} \tag{17}$$

And finally,

$$\frac{V_O}{V_{dc}} = \frac{1+D}{1-3D} \tag{18}$$

As this equation shows, the proposed ac-dc converter has high step-up capacity. Fig. 15 shows the boost factor (B) of the proposed SL Z-source ac-dc converter versus the duty ratio (D).

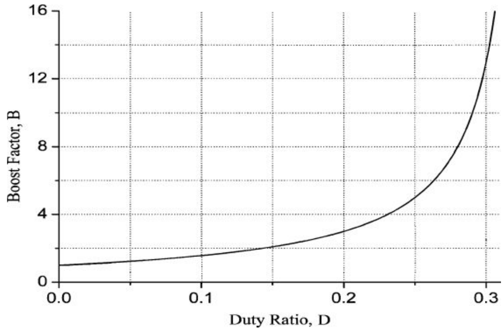

Fig. 15. SL Z-source ac-dc converter voltage gain versus duty cycle

5. Simulation Results

In this section, both proposed Z-source ac-dc converters are simulated by using PSCAD/EMTDC to confirm the above analysis. Simulation is performed in two parts. In part 1, the proposed custom Z-source ac-dc converter simulation results are shown; and in part 2, the proposed SL Z-source ac-dc converter simulation results are presented.

First, in order to simulate the custom Z-source ac-dc converter operation, $L_1=L_2=L=0.5$ mH, $C_1=C_2=C=1000$ µF, $R_{load}=15$ Ω and $L_{load}=0.5$ mH are chosen to be the Z-network, output filter and load parameters. The converter switching frequency is 10 kHz.

Fig. 16 shows the three-phase line-to-line input voltage and Fig. 17 shows the proposed custom Z-source rectifier output dc voltage for the case of 30% duty ratio of switch S. This figure shows the custom Z-source rectifier advantage in boosting the output dc voltage. The proposed rectifier overcomes the limitation of conventional rectifiers in terms of output dc voltage value. Also, the custom Z-source rectifier provides regulated output dc voltage even in voltage sag and undervoltage conditions. Output dc voltage ripple is about 0.39% and this ripple is 24% of the full-bridge diode rectifier output dc voltage ripple under the same conditions. Obviously, one of the major advantages of a good rectifier is its low ripple in the output dc voltage. Fig. 18 shows load current for 30% duty ratio of switch S. Output dc current ripple is about 0.33%.

Fig. 19 shows the proposed custom Z-source rectifier output dc voltage for the case of 85% duty ratio of switch S. This figure shows the proposed rectifier's ability to step down the output dc voltage. As Fig. 17 and Fig. 19 show, the custom Z-source rectifier can both step up and step down the output dc voltage. The inability to do this is one of the limitations of the conventional converters. Output dc voltage ripple is 1.11%. Fig. 20 shows the load current for 85% duty ratio of switch S. Output dc current ripple is about 0.833%.

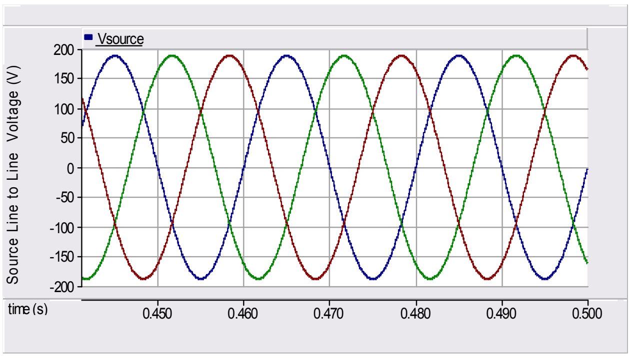

Fig. 16. Three-phase line-to-line input voltage

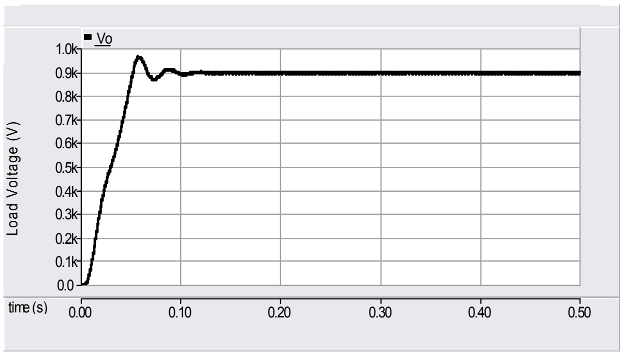

Fig. 17. Z-source rectifier output dc voltage for D=30% for switch S

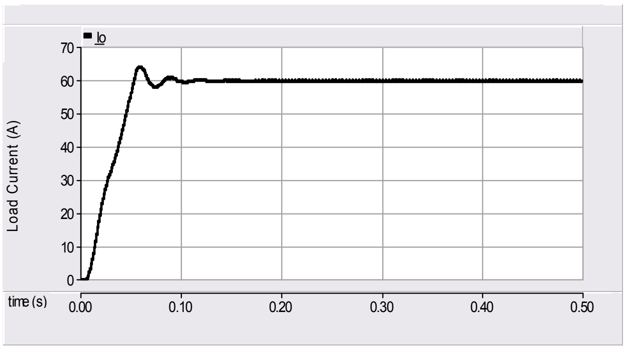

Fig. 18. Z-source rectifier load current for D=30% for switch S

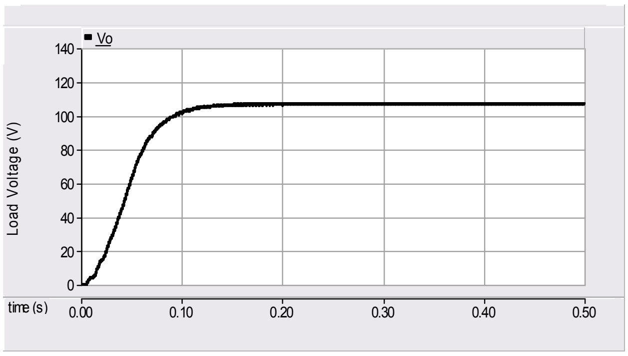

Fig. 19. Z-source rectifier output dc voltage for D=85% for switch S

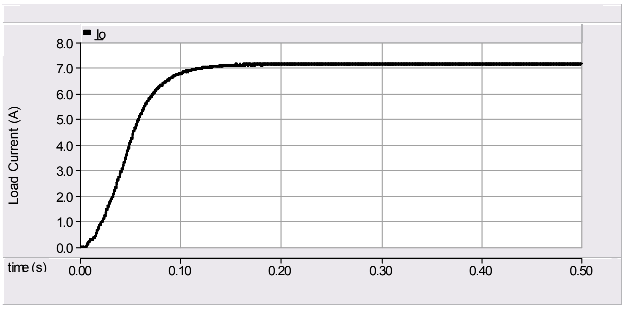

Fig. 20. Z-source rectifier load current for D=85% for switch S

Now, in order to simulate the switched inductor Z-source ac-dc converter, $L_1=L_2=L_3=L_4=L=0.5$mH, $C_1=C_2=C=1000$ μF, $R_{load}=15$ Ω and $L_{load}=0.5$ mH are chosen to be the Z-network, output filter and load parameters. The converter switching frequency is 10 kHz.

Fig. 21 shows the output dc voltage of the SL Z-source rectifier for D=30% duty ratio of the switch S. As this figure shows, the proposed rectifier steps up the input 132 V RMS voltage to 1900 V dc voltage at the converter output. This simulation result confirms the high step-up capability of the SL Z-source ac-dc converter. Fig. 22 shows the load current of the SL Z-source ac-dc converter for 30% duty ratio of switch S. The SL Z-source ac-dc converter output dc voltage ripple is about 0.18% and the output dc current ripple is about 0.15%.

Comparison between the custom Z-source ac-dc converter and the switched inductor Z-source ac-dc converter indicates that the custom Z-source ac-dc converter can both step up and step down the input voltage, but the SL Z-source ac-dc converter can only step up the input voltage. The other drawback of the SL Z-source ac-dc converter is that it uses a larger number of passive elements, as compared to the custom Z-source ac-dc converter. Therefore, the SL Z-source ac-dc converter is larger in size and cost. However, the SL Z-source ac-dc converter has higher step-up capability than the custom Z-source ac-dc converter. So, the SL Z-source ac-dc converter is proper for high power applications. The other advantage of the SL Z-source ac-dc converter is its smaller output dc voltage ripple as compared to the custom Z-source ac-dc converter.

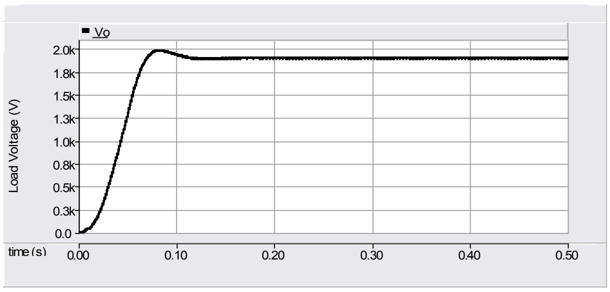

Fig. 21. SL Z-source rectifier output dc voltage for D=30% for switch S

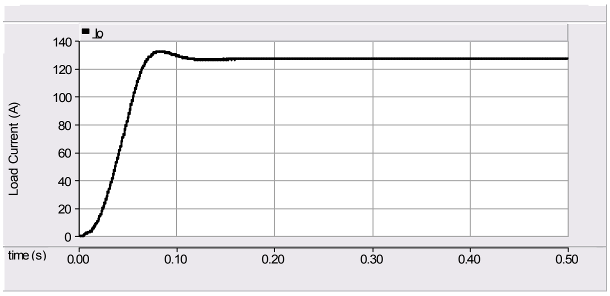

Fig. 22. SL Z-source rectifier load current for D=30% for switch S

6. Conclusion

This paper discussed two types of Z-source ac-dc converters. First, a new Z-source ac-dc converter with custom Z-network was analyzed. The custom Z-source ac-dc converter steady-state operation principle and equivalent circuit were described. Then, a new topology of Z-source converter with switched inductor Z-network was presented. After the steady-state operation principle and equivalent circuit analysis of the SL Z-source converter were discussed, simulation results were presented. Simulation results showed that the proposed Z-source ac-dc converters have some advantages as compared to conventional converters. The main advantages of the proposed converters are their boost capacity, low output dc voltage ripple and output voltage control with less active switch number. Comparison between the custom Z-source ac-dc converter and SL Z-source ac-dc converter indicated that the custom Z-source ac-dc converter can both step up and step down the output voltage, but the SL Z-source ac-dc converter can only step up the input voltage. Also, the SL Z-source ac-dc converter has a larger number of passive elements. However, theoretical analysis and simulation results showed that the SL Z-source ac-dc converter has higher step up capability as compared to the custom Z-source ac-dc converter. This feature of the SL Z-source ac-dc converter makes it a proper choice for high-voltage conversion, renewable energy sources and distributed generation applications.

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