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Simulation and Analysis of Switched-Z-Source/Quasi-Z-Source DC-DC Converters

Harika Kanithi[1], Pawan Putra Pappu[2], Prasanth Kumar Das[3]
[1](Department of Electrical and Electronics, G.V.P.C.O.E, Visakhapatnam
[2] (Department of Electrical and Electronics, G.V.P.C.O.E, Visakhapatnam
[3](Department of Electrical and Electronics, G.V.P.C.O.E, Visakhapatnam

ABSTRACT
This paper presents the performance of three different converters which uses the z-source topology for the boosting of output voltage. The proposed topologies need a smaller duty cycle, and lower values of inductors, which avoids the cause of saturation of inductors. The traditional z-source network is modified with an external switch and diode connected at the end of the terminals, which boosts the voltage gain to 1/(1-4D) at a duty cycle of 0.2 (smaller than 0.25). This technique is also applied to quasi-z-source converters. The quasi-z-source converters are classified as continuous and discontinuous based on the sequence of inductor current and system configuration. The quasi-z-source network features a high voltage gain with reduced voltage stresses. A closed loop control is also applied to the switched-z-source dc-dc converter for the better performance. The simulation of the three converters (SZSC, CSQZSC, DSQZSC) has been done in MATLAB/SIMULINK software and respective waveforms were presented.
***Keywords*-**DC-DC Converter, Z-Source network, Quasi-z-source network.

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I. INTRODUCTION

High step-up dc-dc converters is a type of converter which can boost a low voltage to a high voltage. High voltage gain is necessary and important and the demand of using a high step-up dc-dc converter is increasing for the low voltage suppliers like PV systems, wind turbines and batteries etc. Efficiency, losses, component size etc., are some of the causes which effects the voltage gain. There are many techniques proposed for the improvement of boost ability like cascaded techniques, voltage-lift technique, voltage-multiplier, switched-component techniques, coupled techniques. Boost ability plays an important role for the evaluation of converter. A perfect converter should be analyzed by considering the parameters like efficiency, losses, size etc.

Z-source is one of the topologies used for increasing the voltage gain. Because of its unique structure z-source network has some of the advantages like reduced inrush currents, low harmonics, small component size, can be operated as buck, boost and buck-boost which is not possible in other converters [1]. This makes z-source network one step ahead over the other traditional converters. Inserting an impedance network into a dc-dc converter can make the converter obtain a remarkable high voltage gain.

These Z-source network also has some disadvantages like high voltage stresses on components, and due to the losses power dissipation will achieve. These drawbacks can be overcome by quasi-z-source network [2]. The early modification of the z-source network is the quasi-z-source network. Among the modified z-source topologies, quasi-z-source network is simple and efficient solution. Quasi -Z-source features a high a voltage gain with low voltage stresses. Furthermore, the input source current and the output load current of the quasi-z-source converters are continuous. Based on the sequence of inductor current and system configuration the quasi-z-source converters are classified as continuous switched-quasi z-source converter and discontinuous switched-quasi-z-source converter.

These z-source source topologies are mainly focused on the dc-ac power conversions while these can also be used for other power conversions like dc-dc, ac-ac, ac-dc. Using the correct topology in correct manner can make the converter obtain a high gain, perfect efficiency with low losses. Controller is provided to the switched-z-source dc-dc converter for the better performance. The output dc voltage is regulated and the ripples are minimized by using the PI Controller.

The boost factor for the conventional z-source dc-dc converter is 1/(1-2D) where D is the duty cycle. For the proposed topology the voltage gain is improved to 1/(1-4D) at a duty ratio of 0.2. The conventional z-source dc-dc converter is modified with an extra switch and diode connected at the end of the terminals of traditional z-source converter for the improvement of voltage gain. This topology is also applied to the quasi-z-source dc-dc converter that means an extra switch and diode are added to the end of the conventional quasi-z-source dc-dc converter.

The paper is structured as follows: The configuration of the proposed converters is described in detail in Section II, the operating principle is presented in Section III, the control scheme used for switched z-source dc-dc converter is presented in Section IV, Simulated results of the three converters are presented in Section V and conclusions are shown in Section VI.

II. CONFIGURATION OF THE PROPOSED CONVERTERS (SZSC, CSQZSC, DSQZSC):

The configuration of the three proposed converters are shown in this section, which can be categorized as Switched-Z-Source dc-dc converter, Continuous Switched-Quasi-Z-Source dc-dc converter and Discontinuous Switched-Quasi-Z-Source dc-dc converter. The topologies of these converters are presented in the following sections.

Switched-Z-Source DC-DC Converter:

The circuit configuration of the Switched-Z-Source DC-DC converter is shown in fig.1, which consists of two inductors L_1 and L_2, two capacitors C_1 and C_2 connected in X-shape to form an impedance source network. It can be seen from the figure -1., that the proposed switched-z-source dc-dc converter is obtained by connecting an extra switch and diode to the output terminals of the traditional z-source dc-dc converter. The extra switch is S_2 and the extra diode is D_3. The filter capacitor C_3 is connected across the load in order to avoid the ripples produced in the output voltage and output current. Here the capacitor C_3 has another function other than filtering the ripples that is it charges the inductors when both the switches are turned on simultaneously. The Switched-Z-Source dc-dc converter has a high step up ability with a voltage gain of 1/(1-4D) than that of traditional z-source dc-dc converter.

Continuous Switched Quasi-Z-Source DC-DC Converter:

The circuit configuration of CSQZSC is shown in the fig. 2, which consists of same components as switched-z-source dc-dc converter that is an external switch and diode are added to the end of the terminals of conventional quasi-z-source dc-dc converter. Here the name quasi represents the resembling the circuit with same components looks like same but not exactly. In CSQZSC an inductor, capacitor and diode form an LDC unit. This LDC unit is definitely equivalent to the sequence of X-shaped impedance network and a diode. As mentioned before the output capacitor is not only a filter capacitor it also has another function i.e., this capacitor helps in charging the inductors when both the switches are turned on. As the system configuration is same for both SZSC and CSQZSC the operation principle is also same as that of the SZSC. Continuous and discontinuous current modes are completely depending on the inductor current. Here CSQZSC is said to have a continuous source current if the input voltage source V_i is connected in series with the inductor L_1. The voltage stress of one capacitor in CQZSC is decreased when compared to the SZSC. The voltage stresses are reduced in this CQZSC because of modified circuit with same power components.

Discontinuous Switched-Z-Source DC-DC Converter:

The circuit configuration of discontinuous switched-z-source dc-dc converter is shown in fig.3, which consists the components same as SZSC and DSQZSC. The DSQZSC network also consists of same components as shown in the fig., that is two inductors, two capacitors and a diode. In DSQZSC a common diode is shared by a two LDC cells which is equivalent to the x-shaped impedance network. In order to improve the output voltage an extra switch and diode are connected at the end of general quasi-z-source converter, same as done for the previous converters. The quasi-z-source dc-dc converter is said to have a discontinuous source current if input voltage source is connected in series with the LDC unit. The voltage stresses on both capacitors are reduced in this DSQZSC. This is the advantage of DSQZSC over the other two converters. The voltage gain obtained for the three converters (SZSC, CSQZSC and DSQZSC) is same i.e., 1/(1-4D) but the voltage stresses on quasi-z-source dc-dc converters are reduced when compared to switched-z-source dc-dc converter.

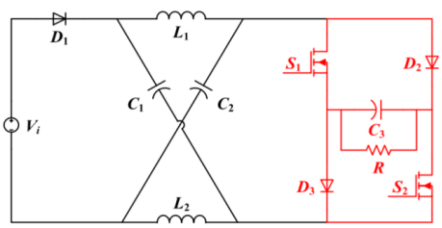

Fig-1: System Configuration of the Switched-Z-Source DC- DC Converter (SZSC)

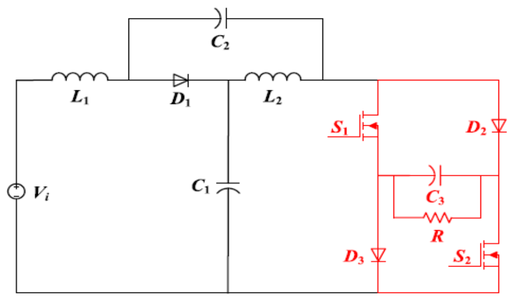

Fig-2: System Configuration of the Continuous Switched Quasi-Z-Source DC- DC Converter (CSQZSC)

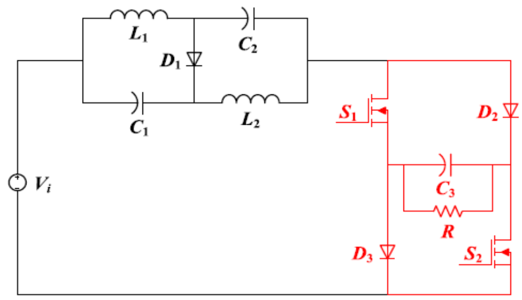

Fig-3: System Configuration of the Discontinuous Switched Quasi-Z-Source DC- DC Converter (DSQZSC)

III. OPERATION OF SZSC:

The switched z-source dc-dc converter can operate in both continuous and discontinuous modes. The continuous and discontinuous current modes are completely based on the current through the inductor. If the inductor current reaches zero for a finite period of time it is said to be discontinuous, if the inductor current doesn't reach zero it is continuous. The modes of operation at different states are explained below.

For our convenience we simply consider the following assumptions:

1) All the power components are ideal
2) $L_1=L_2$ and $C_1=C_2$

Three cases are analyzed based on the sequences of the inductance, load resistance and duty cycle where two cases Case -1 and Case -2 come out in continuous conduction mode and one case, Case -3 in discontinuous conduction mode.

Case -1 in CCM:

We can observe from the waveform shown in the Fig.4 that is in state 1, the two switches S_1 and S_2 together turned on, and when these switches are in on state, diodes D_1, D_2 and D_3 are in reverse biased state that means currents through the diodes is zero. Initially we assume that the capacitors are charging so here when it comes to case-1 the capacitors C_1, C_2 and $C_3$are discharged while inductors $L_1$and L_2 starts storing energy. The energy stored in the filter capacitor is carried to the load. By monitoring the current loop which is shown in the fig., we can say that the current through the capacitor C_1 and current through the inductor L_1 is same where as it can also be observed that current through the capacitor C_2 and inductor L_2 is same. As both the switches are connected in series the switches S and S_2 have same current.

The current through the switch S_1 is equal to the current through the inductors L_1 and L_2.

i.e., $i_{S1} = i_{L1} + i_{L2}$

The current through the capacitor C_3 is equal to the current through the switch S_1 and output current i_o.

i.e., $i_{C3} = i_{S1} + i_o$

In state 2 the switches S_1 and S_2 are together turned off, that means current through the switches S_1 and S_2 is zero and the diodes D_1, D_2 and D_3 are conducting state. The input source voltage V_i and the inductor L_1 discharges the energy while the capacitor C_1 stores energy that means capacitor C_1 is in charging state. The capacitor C_2 stores the energy while the input source voltage and the inductor L_1 discharges the energy. The energy stored in the input source voltage and the z-source inductors is transferred to the filter capacitor and the load that means the z-source inductors are in discharging state while the load capacitor is in charging state. Same current is passing through the diodes D_1 and D_2.

The current through the z-source inductors are equal and the current through the z-source capacitors are equal. The voltage across z-source inductors is equal and the voltage across the z-source capacitors is same.

Case -2 in CCM:

The first two states in case -2 are same as that of the states appeared in the case -1. In order to supply the load, the series connected input source voltage and the capacitor C_3 and the z-source inductors are discharged at the end of the state 2 in case -2. So, there is one more state existing in this case -2.

Case -3 in DCM:

The first three states in case -3 are same as that of the states appeared in the case -2. The inductor current reaches zero at the end of the state 3, that means the switched z-source dc-dc converter is operating in discontinuous conduction mode. When the converters enter the DCM, the switches continued in turned off state and the currents through the z-source inductors and capacitors is zero, the diodes are in reverse biased condition so the currents through the diodes are also zero. The output current is equal to the current through the capacitor C_3. The

voltages across the z-source capacitors are same as in the previous state.
The model waveforms of switched z-source dc-dc converter in different states are shown in the fig., below.

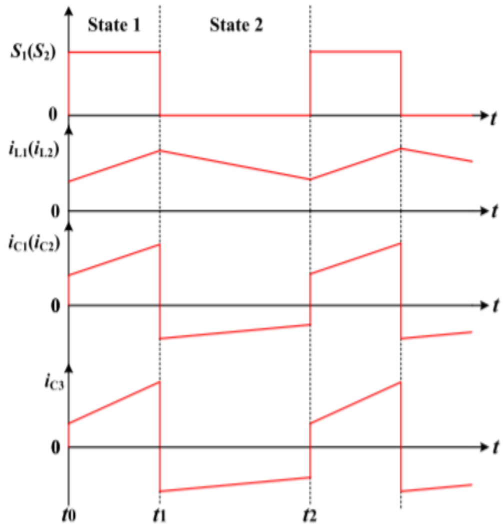

Fig-4: Model waveforms of SZSC showing the charging and discharging states of inductors and capacitors in state-1 and state-2

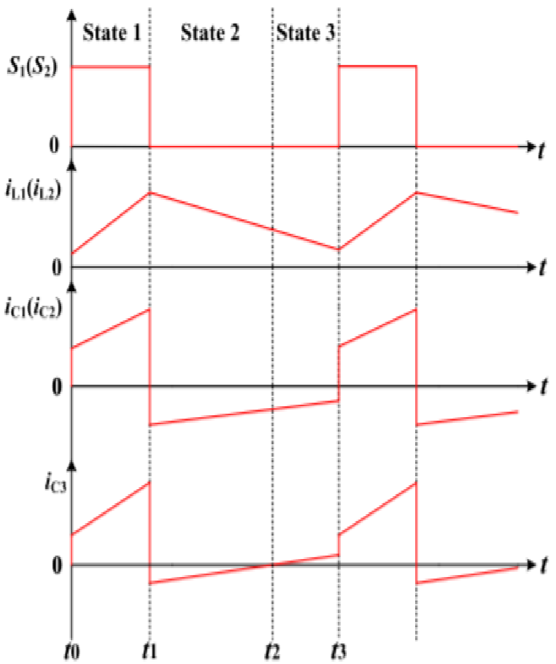

Fig-5: Model waveforms of SZSC when operating in state -3

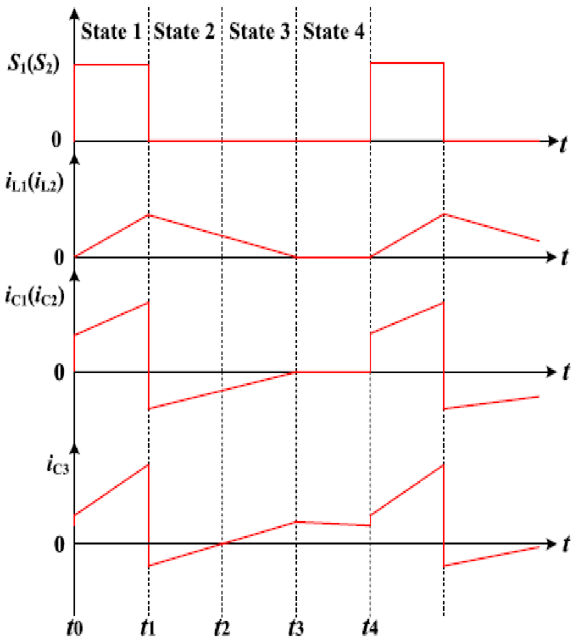

Fig-6: Model waveforms of currents through the z-source inductors and capacitors in state-4 which enters the DCM

IV. CONTROL SCHEME USED FOR SZSC:

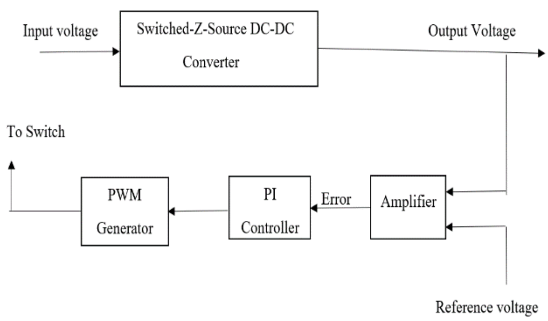

Fig -7: Closed loop diagram of SZSC

The above diagram shows the closed loop operation of Switched-Z-Source dc-dc converter. The output produced from the SZSC is measured and then compared with the reference voltage. The feedback loop measures the output voltage and it subtracts from the reference voltage. PI controller read the error and producing PI output to the PWM generator. Finally, the PWM generator produces PWM according to the input with fixed frequency.
Voltage stresses on capacitors:
SZSC: $V_{C1} = V_{C2} = [(1-2D)/(1-4D)]\ V_i$
CSQZSC: $V_{C1} = [(1-2D)/(1-4D)]\ V_i$
$V_{C2} = [2D/(1-4D)]\ V_i$
DSQZSC: $V_{C1} = V_{C2} = [2D/(1-4D)]\ V_i$
Voltage gain obtained for three converters:
$(V_o/V_i) = [1/(1-4D)]$

Specifications of the devices:

Parameters	Value
Input voltage	45V
Inductors $L_1=L_2$	95µH
Capacitors $C_1=C_2$	300µF
Switching frequency	25kHz
Output voltage	225V
Duty cycle	0.2
Load R	100Ω

V. SIMULATION RESULTS:

The figure shown below represents the output voltage waveform of switched-z-source dc-dc converter. The measured voltage is V_o = 225V

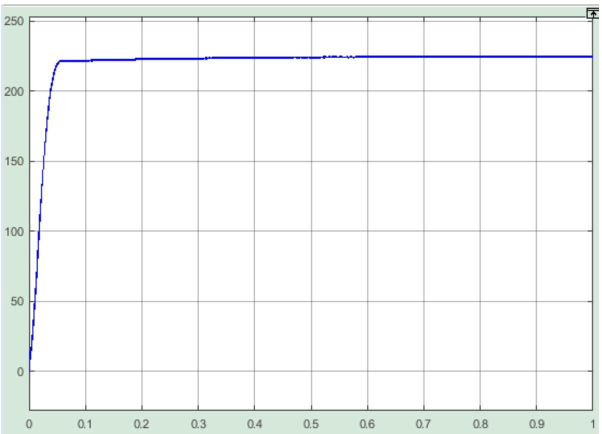

Fig-8: Output voltage waveform of the switched-z-source dc-dc converter

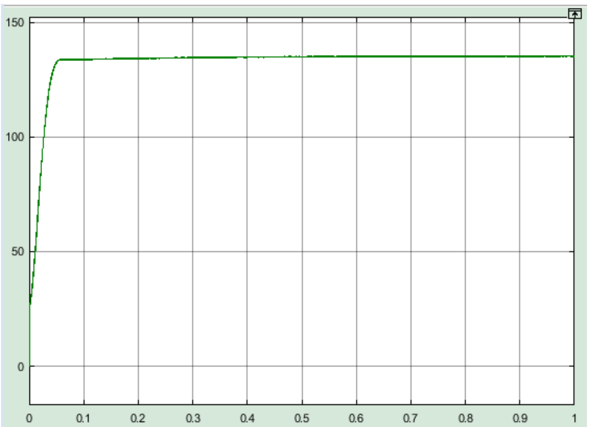

Fig-9: Voltage waveform across the capacitor C_1

The below graph shows the capacitor voltages of CSQZSC. The voltages measured across the capacitors V_{C1} = 135V, V_{C2} = 90V and V_{C3} = 225V. The voltage across the capacitor V_{C3} is equal to the output voltage V_o = 225V with ripple factor of 0.26%, 0.3%, and 0.35%.

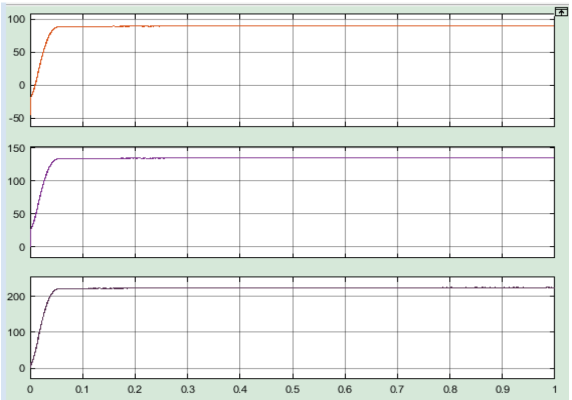

Fig-10: Voltages across the capacitors C_1, C_2 and C_3 in CSQZSC

The below graph shows the voltages across the capacitors. The obtained capacitor voltages are V_{C1} = 82V, V_{C2} = 82V and V_{C3} = 225V. The measured voltage across the capacitor C_3 is equal to output voltage V_o = 225V with a ripple factor of 0.26%, 0.23% and 0.32%.

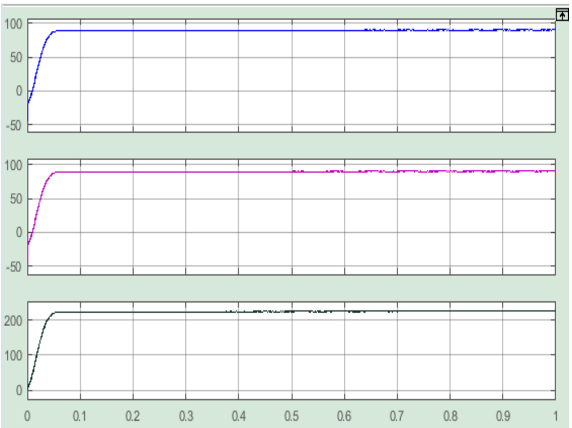

Fig-11: Voltages across the capacitors C_1, C_2 and C_3 in DSQZSC

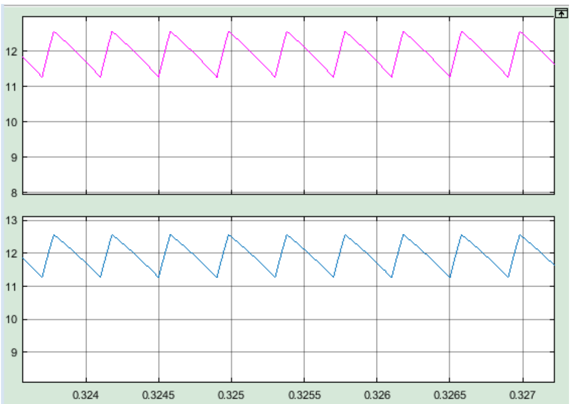

Fig-12: Waveforms of input source current i_i and inductor current i_{L1} in CSQZSC

The above waveforms represent the input source current and the current through the inductor. As input source voltage is connected in series with inductor, the input source current and the current through the inductor will be same. We can observe from the figure that the current through the inductor does not reach zero, so the converter is operating in continuous conduction mode.

The measured component voltages of the three converters (SZSC, CSQZSC and DSQZSC) are shown in table presented below.

Converter Type	$V_o(V_{C3})$	V_{C1}	V_{C2}	V_{S1} (V_{S2})
SZSC	225	135	135	200
CSZSC	225	135	90	200
DSZSC	225	82	82	200

V. CONCLUSIONS:

The performance of the dc-dc converter is mainly evaluated by the boost ability. Better voltage gain is achieved with small duty cycle of 0.2 at a switching frequency of 25kHz for the three converters by using z-source topology. The parameters chosen is same for all the three converters. Simulation of the three different types of converters is done and observed the performances of all the converters. The output voltage of 225v is measured by taking the input voltage as 45v. Lower values of inductors are preferred in order reduce the inductive saturation. By observing the simulated waveforms of the three converters, voltage stresses on the capacitors are reduced in quasi-z-source networks when compared to SZSC. Closed loop control is implemented for the better performance of the Switched-Z-Source DC-DC converter. Simulation results show that the ripple content of SZSC by using PI controller is reduced compared to the ripple content in open loop system.

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