International Journal of Advanced Information in Engineering Technology (IJAIET) ISSN: 2454-6933
Vol.3, No.4, April 2016

Analysis of a Single Input Z-Source DC-DC Converter

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***Abstract*—This paper is related to investigate characteristics and performance of a single input Z-source dc/dc converter which boosts the input voltage to a higher output voltage. Zsourcestructure increases the reliability of the converter. Operating principles of the Z-sourcedc-dc converter is described by current and voltage waveforms of the components and mathematical expressions.Waveforms obtained and mathematical expressions areconfirmed by simulations.**

Keywords—Z-source, Single input Z source dc/dc converter,CCM

I. INTRODUCTION

ThisZ-source structure can be used in all types of power conversions such as ac/dcrectifiers, dc/dc converters, dc/ac inverters and ac/ac converters.The mainoperation principles of Z-source structure and application of Z-source structure toinverter are investigated in detail in [1]. The study discusses the drawbacks oftraditional voltage-fed and current-fed inverters also. In voltage-fed inverter, theoutput ac voltage can not exceed the input dc voltage and upper and lower switchesof the same phase can not be made ‘ON’ at the same time during the operation.Furthermore, in the current-fed inverter, the output ac voltage is always greater thanthe input dc voltage, and one of the upper switches and one of the lower switchesmust be ‘ON’ at any time during the operation. Z-source inverter eliminates theseproblems and gives an opportunity of using the inverter as a step-up or step-downinverter. The single phase ac/ac converter application of Z-source structure is investigated in [2]. The most popular topology for the ac/ac converter for the requirement ofdifferent output voltage level and variable output frequency is the usage of cascaded6diode rectifier and inverter, respectively. However, if only the voltage regulation atthe output side is of concern, the single phase Z-source ac/ac converter can providea cheaper and lower-sized solution, [2]. Also, the proposed single-phase Z-source ac/ac converter in [2] can be used to tackle voltage sags, surges and loadfluctuations.

Moreover, the operating principle of the three-phase Z-source ac/ac converter is investigated in [3].The application of Z-source structure in single-phase rectifier is proposed in [4].Also, the operating principle of the proposed circuit is investigated in that study.Using single phase Z-source rectifier instead of traditional two-stage ac/dc buckrectifier brings some advantages. It gives the opportunity to adjust the output dcvoltage greater or smaller than the input ac voltage. Also, the minimized and singlestage structure of the proposed rectifier provides high efficiency and small size, [4].Furthermore, the three phase rectifier application of Z-source structure is proposed in [5]. In that study, the power-factor of the rectifier is discussed together with theoperating principle.For dc/dc application of Z-source structure, the main studies are [6] and [7]

The objectives of this paper are to present (1) the equivalentcircuits and the associated expressions corresponding to differentstages of operation of the PWM Z-source dc-dc converterin CCM, (2) the dc input-to-output voltage conversion factor for single input Z -source dc-dcconverter.

Section II presents the equivalent circuits and the derivationof relevant equations of the PWM Z-source dc-dc converter [8]. Section IIIpresents an analysis of the Z-source dc-dc converter in CCM mode and presents the derivation of DC voltage conversion factor for CCM . Section IV presents conclusions.

II. CIRCUIT CONFIGURATION

A. Z-Source Converters

Z-source converters are modern group of power electronic converters which can overcome problems with traditional converters. The Z-source converter is a novel topology [1] that overcomes the conceptual and theoretical barriers and limitations of the traditional voltage-source converter and current-source converter. The concept of Z-source was used in direct ac-ac power conversion [2]. Similarly, the concept of source also was extended to dc-dc power conversion [8].

B. Circuit Configuration of Proposed Converter

The schematic circuit diagram of the proposed single input Z-source dc-dc converter is shown in Fig. 1. It consists of one input source, V_s, and the diode, D_1, applied to provide current path . In this paper, permanent connection of input dc source is considered. Energy receiver, converter and transmitter sections are situated in the middle side of the converter. This section is a two-port network that consists of a split-inductor $L_{z1}$and L_{z2} and capacitors C_{z1} and C_{z2} connected in x-shape which is named “Z-network”. An active switch, Q, is situated in output port of Z-network to control input and output power of converter. The final section of converter is a LC filter beside the load in order to reject output signal ripple.

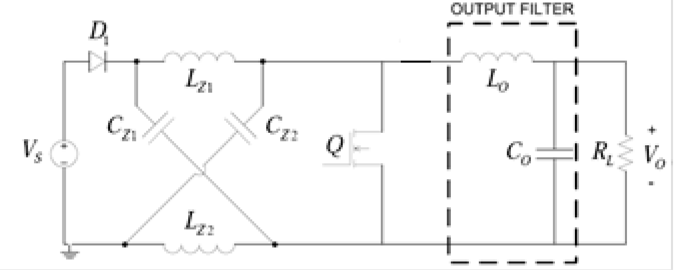

Fig.1. Single Input Z source dc-dc Converter

III. ANALYSIS OF SINGLE INPUT Z SOURCE DC-DC CONVERTER

The analysis of the input voltage to output voltage equation in terms of the dutyfactor,*D*, and other circuit components (inductors, capacitors, load resistance) ismade for CCM operation. To use the symmetrical behavior of Z-source structure, the Z-source capacitors ($C_{Z1}$and C_{Z2}) are set equal to each other and Z-source inductors, ($L_{Z1}$and L_{Z2}) arechosen such as their sizes are same. Then, by the symmetry, voltage waveforms onZ-source inductors come out identical. The current waveforms through Z-sourcecapacitors are also identical over a period. Dc component and small signalcomponents in Z-source capacitor currents are same which is proven at [6]. Thisfact is same for the inductor voltages as well. So, if

$$L_{Z_1} = L_{Z_2} = L_Z$$
$$C_{Z_1} = C_{Z_2} = C_Z \quad (1)$$

A.Mathematical Analysis of Z-source DC/DC Converter in CCM Operation

The circuit diagram of simplified Z-source dc/dc converter can be represented as inFig.2.

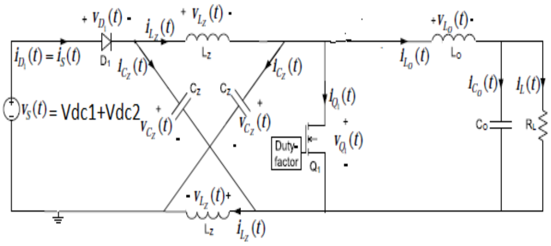

Fig.2. Circuit diagram of the Z-source dc/dc converter

In CCM operation, operation of Z-source dc/dc converter in one period can bedivided into two modes. Mode 1 begins when switch,*Q* , is switched on at t=0.During this time interval $t_1$appearing in Fig.6, the Z-source inductors, $L_Z$areenergized by Z-source capacitors,C_Z.If Kirchhoff’s voltage law is applied aroundLOOP II in Fig.3, it can be resulted that Z-source capacitor voltage,$v_{CZ}(t)$,isequal to Z-source inductor voltage,$v_{LZ}(t)$,at time interval t_1.Also,using Kirchhoff’svoltage law around LOOP I in Fig.3, gives an expression for D_1voltage,$v_{D1}(t)$,is equal to $v_s(t)$ -2$v_{CZ}(t)$ .As $v_{CZ}(t)$ is equal to output voltage, $v_0(t)$, and $v_S(t) < v_0(t)$ because of boosting operation, $v_{D1}(t)$takesnegative value. $D_1$is reverse biased and does not permit current flow towards source. The load meanwhile is fed by the output inductor, L_0, and output capacitor,C_0. Also, output inductorvoltage, $v_{L0}(t)$,is equal to -$v_0(t)$according to LOOP III in Fig.3. The equivalentcircuit for Mode 1 is represented in Fig.3.

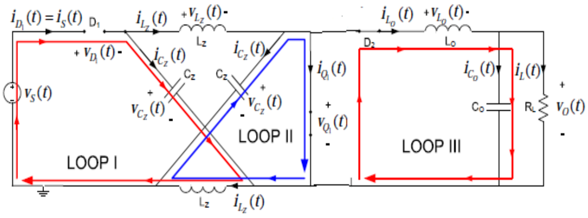

Fig.3 Equivalent circuit for Mode 1 in continuous current mode (CCM) operation ofthe Z-source dc/dc converter

Calling the time elapsed in one cyclic operation of the converter as period,T_S, Mode2 starts at the instant $dT_S$when *Q* switched off at that instant. During the timeperiod in Mode 2, Z-source inductors, L_z, transfer the stored energies on them tothe load. Also, the current drawn from the input is transferred to Z-source capacitors$C_z$and load. Inductor $L_0$is energized during Mode 2. If Kirchhoff’s voltage law isapplied around LOOP I in Fig.4, it can be obtained that the output inductor voltage,$v_{L0}(t)$, is equal to 2$v_{CZ}(t)$ $-v_S(t)$ $-v_0(t)$ in Mode 2 operation. Similarly, applyingKirchhoff’s voltage law at LOOP II brings that Z-source inductor voltage, $v_{LZ}(t)$, isequal to $v_S(t)$- $v_{CZ}(t)$ in Mode 2. The equivalent circuit for Mode 2 is shown inFig.4.

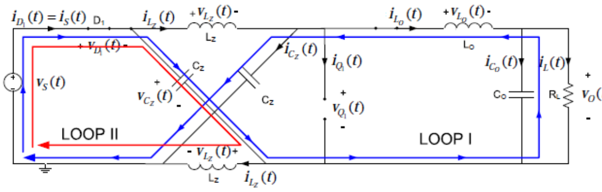

Fig.4 Equivalent circuit for Mode 2 in continuous current mode (CCM) operation ofthe Z-source dc/dc converter

If the capacitor sizes are chosen large enough, the voltage variation across thecapacitors over a period is very small in steady state. Also, the input voltage can bedetermined as constant over a period. Thus, the voltages on capacitors and theinput voltage are only dc.

$$V_{C_Z}(t) = V_{C_Z}$$
$$V_{C_O}(t) = V_{C_O}$$
$$\text{s}V_S(t) = V_S \qquad (2)$$

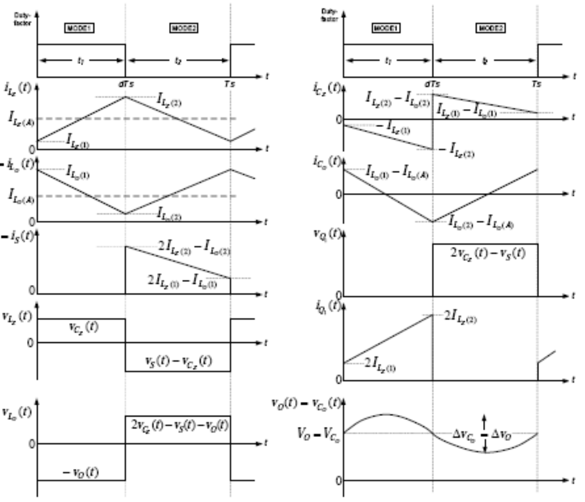

Fig.5Voltage and current waveforms of the inductors ($L_Z$and L_0), the capacitors($C_Z$and C_0) and the nonlinear elements (D_1 and Q) of the Z-source dc/dcconverter in CCM operation

The voltages on inductors can be expressed in terms of capacitor voltages and inputvoltage at any time of period. As the capacitor and input voltages are dc, thevoltages on the inductors are dc at any time of the period so, the slope of inductorcurrent is constant and the current rises and falls linearly at theinductors. If the capacitor sizes are small, than the voltages across them becomestime dependent. As the voltages of capacitors are time dependent, then the voltageson the inductors become time dependent and this leads to complexity in derivations.

The voltage induced in an inductor due to a current, passing through it, is given by,

$$e_L = L\frac{di}{dt} (3)$$

The voltage and current waveforms of inductors, capacitors and nonlinear elements of the circuit for continuous conduction mode are shown in Fig.5.In the figure$I_{LZ(A)}$, $I_{LZ(1)}$and $I_{LZ(2)}$are the abbreviations of average, valley and peak values of Z-source inductors current, respectively. Similarly, $LI_{L0(A)}$, $I_{L0(1)}$and $I_{L0(2)}$are the abbreviations of average, peak and valley values of output inductor current.The voltages appearing on inductors, L_Z, are equal to V_{CZ}in Mode 1 operation,thus considering the differential form of (3)expressed in incremental forms ofvariables then it can be derived;

$$V_{C_Z} = L_Z\frac{I_{L_{Z(2)}} - I_{L_{Z(1)}}}{dT_S} (4)$$

Or

$$dT_S V_{C_Z} = L_Z\left(I_{L_{Z(2)}} - I_{L_{Z(1)}}\right) (5)$$

whose left hand side represents volts-second area developed on $L_z$inductorsduring Mode 1 operation. ‘ d ’ represents the duty-factor in the equations.Similarly, the voltage on the Z-source inductors, L_Z, are V_S-V_{CZ}in Mode 2.

B.DC Voltage Conversion Factor for CCM

$$(1-d) \quad \left(V_S - V_{C_Z}\right) = L_Z\left(I_{L_{Z(1)}} - I_{L_{Z(2)}}\right) \qquad (6)$$

Incremental form of (3) yields;(6)
whose left hand side represents volts-second area developed on $L_Z$inductorsduring Mode 2 operation.Volt-second areas developed on inductors, L_Z, in one complete switching period, T_S, is to be zero. Using this fact, relationship can be obtained between $V_S$and V_{CZ}. Sum (5) and (6) side by side for thepurpose so that result will be;

$$V_{C_Z} = \frac{(1-d)V_S}{1-2d} (7)$$

Applying the same approach to $O\ L$ yields another equation in terms of V_S, V_0andV_{CZ}. The voltage developed on inductor, $v_{L0}(t)$, at time interval $t_1$is

$$V_{L_O(t1)} = -V_O (8)$$

Also, in time interval t_2,

$$V_{L_O(r2)} = 2V_{C_Z} - V_S - V_O (9)$$

Since the volt-second area of output inductor, L_0, in one switching cycle is to bezero, again adding (8) and (9) side by side yields;

$$dT_S(-V_O) + (1-d).T_S.\left(2V_{C_Z} - V_S - V_O\right) = 0 \qquad (10)$$

Substituting V_{CZ}, obtained in (7), into (10) gives;$\left(dT_S(-V_O)\right) + \left[(1-d)T_S\left[2\frac{(1-d)V_S}{1-2d} - V_S - V_O\right]\right] = 0(11)$

and which when simplified yields;

$$V_O = \frac{(1-d)}{1-2d}V_S (12)$$

That is the dc input-to-output voltage conversion factor as

$$\frac{V_0}{V_S} = \frac{(1-d)}{(1-2d)} \qquad (13)$$

IV. SIMULATION ANALYSIS

The main requirements of the Z-source dc/dc converter are listed at Table1. According to these requirements Z-source inductors, L_Z, and output inductor, L_O,values are determined and designed Z-source dc/dc converter is simulated.

Table1Parameters of the Z-source dc/dc converter in CCM

Minimum input voltage	V_S	30	V
Output voltage	V_O	60	V
Output power	P_O	360	W
Peak-to-peak ripple current in Zsource inductor at nominal inputNvoltage (in % of I_{LZ})	$i_{LZ\,D}$	83.3	%
Peak-to-peak ripple current in output inductor at nominal input voltage (in % of I_{LO})	i_{LOD}	66.6	%

Table2 Converter Parameters

Z-source inductors,L_Z	20	µH
Z-source capacitors,C_Z	50	µF
Output inductor,L_O	50	µH
Output capacitor,C_O	400	µF
Switching frequency,f_s	100	kHz
Load resistance,R_L	10	Ω
Input voltage,V_S	30	V
Output voltage,V_O	60	V
Output current	6	A

Fig.6 represents the power stage of the converter. The voltage source, V_S,corresponds to input voltage which is set to 30V . Duty-factor block generates therequired duty-factor and its value is set to 0.333, to get 60V outputvoltage across the load resistance, R_L. The Z-source inductors, $L_{Z1}$and $L_{Z\ 2}$, areset to 20mH , and the Z-source capacitors $C_{Z1}$and $C_{Z\ 2}$, are chosen as 50mF . The output inductance, L_O, is assigned to 50mH . Also, theoutput capacitor, C_O, is chosen as 400mF . The forward voltage drops on diodes,D_1 and D_2, are taken as zero, because the forward voltages of the diodes have notbeen taken into account in development of the converter model. $R_L$is set to 10Wto draw 360W power from the supply, V_S.

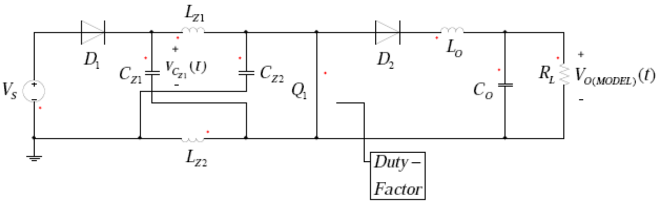

Fig.6.Power stage of the Z-source dc/dc converter in CCM operation

The results obtained in the simulations are shown in figures starting with Fig.7

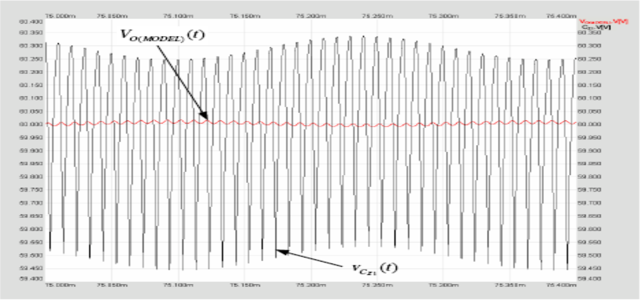

Fig.7.Voltage across the load resistor R_L, $V_{O(MODEL)}$ (t), (red), voltage across the Z-source capacitor C_{Z1}, $v_{CZ1}(t)$, (black) in CCM operation

The graphs display responses beginning from 75*ms* on word in order to discard thestart up transients. The simulation results seen Fig.7 shows that; i. the outputvoltage,$V_{O(MODEL)}$ *(t)*, on R_L is at 60V as desired; ii. and the voltages on Z-sourcecapacitors, $v_{CZ1}(t)$, , are equal to the output voltage, $V_{O(MODEL)}$ *(t)*=60 , as theconverter operation requires it. Fig.8 shows the following variables; Z-source inductor current, i (*t*) *LZ* , Z-sourcecapacitor current, $i_{CZ}(t)$, and diode D_1current, $i_{D1}(t)$graphically for CCM operation. Note that, in Fig.8 that when duty-factor output (in red) is high i.e. theswitchQ_1 is 'ON', Z-source capacitors, $C_{Z1}$and $C_{Z\ 2}$ feed current (and henceenergy) (black for $i_{LZ}(t)$ and green for $i_{CZ}(t)$) through the Z-source inductors, $L_{Z1}$and $L_{Z\ 2}$, respectively. In this time interval, t_1, $D_1$is reverse biased and in blockingmstate, so no energy will be delivered to the rest of the converter by the source. Whenmthe duty-factor output falls to low at zero volts, i.e. the switch is 'OFF' the timeinterval t_2 is entered. In t_2, Z-source inductors transfer the energy they have storedin $t_1$to the load and the output inductor, L_O. $D_1$is now forward biased and Zsourcecapacitors starts charging (green for $i_{CZ}(t)$) from the input source during t_2.

The peak-to-peak magnitude of the current through Z-source inductors is expectedto be 10A as design criteria. Note that, in Fig.8the inductor current, $i_{LZ}(t)$,swings between 7A and 17A in comply with the design criteria. Note also that, theaverage currents through $L_{Z1}$and L_{Z2} are 12A.

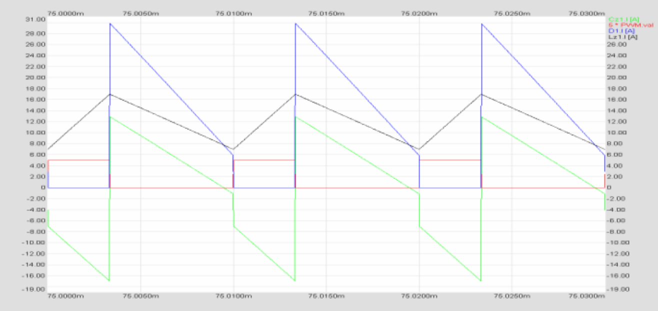

Fig.8Z-source capacitor current, $i_{CZ}(t)$ *, (green), Duty-factor (red), diode* D_1*current,* $i_{D1}(t)$*, (blue), and Z-source inductor current,* $i_{LZ}(t)$ *, (black) in CCMoperation*

For CCM operation, the output inductor current, $i_{LO}(t)$, the output capacitor current,$i_{CO}(t)$ and the Z-source inductor current, $i_{LZ}(t)$, waveforms are displayed in Fig.9 together with duty-factor waveform. When the duty-factor output becomes high, atthe beginning of time interval 1 t time interval i (t) LO starts decreasing. This means,output inductor, L_O, transfers the stored energy in its magnetic medium to theoutput capacitor, C_O, and to the load, R_L.

When the Duty-factor output becomes low, i.e. the switch becomes 'OFF' in timeinterval t_2, $L_O$starts storing energy over inductors $L_{Z1}$and L_{Z2}. The load is fed byC_O in the first half part of the time interval, t_2. Note that the peak-to-peak currentripple on the $L_O$current is 4A due to the inductor current swing from 4A to 8A.Thus, the average value of $L_O$current is 6A.

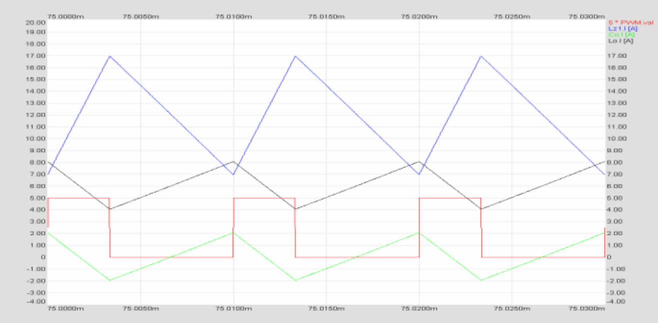

Fig.9 Duty-factor (red), Z-source inductor current, $i_{LZ}(t)$, (blue), output capacitorcurrent, $i_{CO}(t)$, (green), and output inductor current, $i_{LO}(t)$, (black) in CCMoperation

Waveforms seen in Fig.8. and Fig.9. are same with those theoretically expected shown in Fig.5. Also, the peak-to-peak ripple inductor currents are same withthose theoretically calculated. Furthermore, in simulation, taking the duty-factor,$D = 0.333$, leads to 60V output voltage as calculated in (3.3). Thus, Z-source dc/dcconverter simulations for the CCM operation support theoretical results.

V. CONCLUSION

A detailed steady-state analysis of single input Z-source dc-dc converter operating in CCM has been presented. The analysed waveforms are drawn according to the analysed equaions.The dc input-tooutput voltage conversion factor for an ideal single input Z-source dc-dc converter has been derived.Analysis are proven with the help of simulation.

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