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Analysis of Z-Source DC-DC Converter in CCM Using Numerical Technique

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Abstract:- ***Steady-state analysis of Z-source dc-dc converter operating in continuous conduction mode (CCM) is presented. It can operate in voltage-fed and current-fed modes. It has boost and buck-boost characteristics depending on the duty ratio. Analysis and simulation results are presented using the voltage-fed Z-source DC-DC converter as an example. We develop a mathematical model of a single phase Z-source converter in continuous conduction mode. The minimum Z-network inductance required to ensure CCM operation is derived. Voltage gain, Voltage and current waveforms and their corresponding expressions describing the steady-state operation of the Z-source DC-DC converter have been determined by applying numerical techniques. Z-source DC-DC converter is considered, and the simulation results are compared with the analytical model developed.***

Introduction

I. Introduction

A DC-to-DC converter is an electronic circuit which converts direct current (DC) from one voltage level to another. It is a class of power converter. DC to DC converters are important in portable electronic devices such as cellular phones and laptops, which are supplied with power from batteries primarily. Most DC to DC converters also regulate the output voltage.

The impedance-source or Z-source converter was proposed in 2002 [1]. Impedance (Z-) Source networks provide an efficient means of power conversion between source and load in a wide range of electric power conversion applications. Z-source network is a combination of two inductors and two capacitors. It is the energy storage/filtering elements of Z-source inverter [2]. It provides a second-order filter and is more effective to suppress voltage and current ripples. Considering additional filtering and energy storage by the capacitors, the Z-source network should require minimum inductance compared with the traditional I-source inverter. Compared to the existing dc-dc converter circuits [3], this provides a larger range of output dc voltage and improved reliability, minimize component count, increase efficiency, and reduce cost.

Additionally, there has been a renewed interest in isolated and non-isolated voltage step-up dc-dc converters for renewable energy and distributed power generation systems [3]. Typically, the low output voltage energy source, like fuel-cells requires a dc-dc converter to (1) provide a voltage boost and (2) act as a protective buffer between the load and the energy source. Compared to the conventional boost converter, the Z-source dc-dc converter has a higher input-to-output dc voltage boost factor for the same duty ratio, isolates the source and the load in case of a short-circuit at the load side, and has a second-order output filter. This makes Z-source dc-dc converter a potential topology candidate for renewable energy applications. These features prompt the necessity for a detailed investigation of the steady-state behaviour of the Z-source dc-dc converter in CCM.

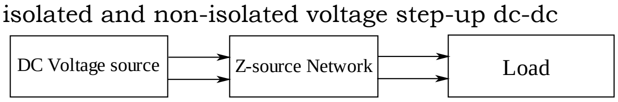

Fig. 1 Block diagram for Z-source dc-dc converter

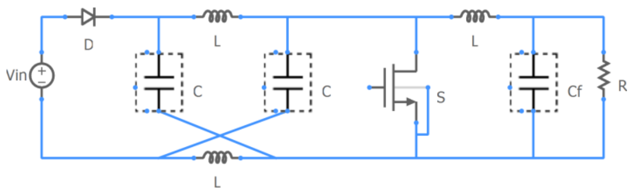

Fig. 2 Z-source DC-DC converter topology

The Z-source dc-dc converter is a buck-boost converter [4]. The Z-source dc-dc converter shown in Fig. 2 consists of a diode D, two identical inductors denoted by L and two identical capacitors denoted by C connected in a manner to obtain the unique impedance or Z-network, an active switch S such as a MOSFET/IGBT, a second order low-pass filter formed by L_f and C_f, and the resistive load R.

The objectives of this paper are to present (1) the equivalent circuits and the associated expressions corresponding to different stages of operation of the Z-source dc-dc converter in CCM [5], (2) the dc input-to-output voltage conversion factor and minimum inductance required to ensure CCM operation, (3) the inductance voltages and current waveforms.

Section II presents the analysis of Z-source dc-dc converter. Section III presents the derivation of DC voltage conversion factor for CCM and the minimum inductance required for CCM operation Section IV presents modelling and simulation results. Section V presents the conclusions and section VI presents acknowledgement.

II. Analysis of Z-source

The following assumptions are used in the present analysis.

1) Inductors, capacitors, and resistors are linear, time-invariant, and frequency independent.
2) Semiconductor switches, i.e., the MOSFET and the diode are ideal.
3) The natural time constant of the converter is much longer than one switching time period.

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Referring to Fig. 2, the MOSFET is switched at a constant frequency $f_s = 1/T$ with the duty ratio of S given by $d = t_{on}/T$, where t_{on} is the duration when is in the ON position. Since the MOSFET S and the diode D have complimentary duty ratios, the duty ratio of the diode D is given by 1-d. Due to the symmetry of the Z-network, and since $L_1 = L_2 = L$ and $C_1 = C_2 = C$, we have $i_{L_1} = i_{L_2} = i_L$, $v_{L_1} = v_{L_2} = v_L$ and $v_{C_1} = v_{C_2} = v_C$.

A. *Time interval:* $0 \le t \le dT$

The equivalent circuit corresponding to this state is shown in Fig. 3. In this state, the voltage across the diode is $V_{in} - 2V_C$, causing the diode to be reverse biased or OFF. Shorting the output terminals results in the diode D being reverse biased, thus isolating the energy source V_{in} from the rest of the circuit. The current through the diode and the voltage across the MOSFET are zero, i.e.,$i_D = 0$ and $v_S = 0$ .The voltage across the inductors L and L_f by applying KVL to the circuit in Fig. 2 we get we get,

$$v_L = L\frac{di_L}{dt} = V_C \quad (1)$$

$$v_{L_f} = L_f\frac{di_{L_f}}{dt} = -V_o \quad (2)$$

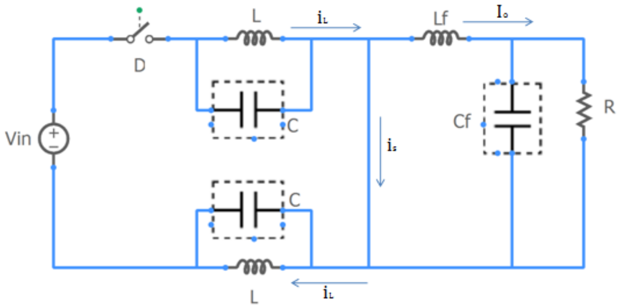

Fig. 3 Equivalent circuit of the Z-source dc-dc converter when S is ON and D is OFF.

The current through the inductors L and L_f is given by,

$$i_L = \frac{V_C}{L}(t) + i_L(0) \quad (3)$$

$$i_{L_f} = \frac{-V_o}{L_f}(t) + i_{L_f}(0) \quad (4)$$

B. *Time interval:* $dT \le t \le T$

The equivalent circuit corresponding to the state when the MOSFET S is OFF and the diode D is forward biased is shown in Fig. 4. In this state, the Z-network acts as the interface between the source and the load. The voltage across the diode v_D and the current through the MOSFET i_S are zero. The voltage across the inductors L and L_f is given by applying KVL to circuit in Fig. 3 we get,

$$v_L = L\frac{di_L}{dt} = V_{in} - V_C \quad (5)$$

$$v_{L_f} = L_f\frac{di_{L_f}}{dt} = V_o - V_{in} \quad (6)$$

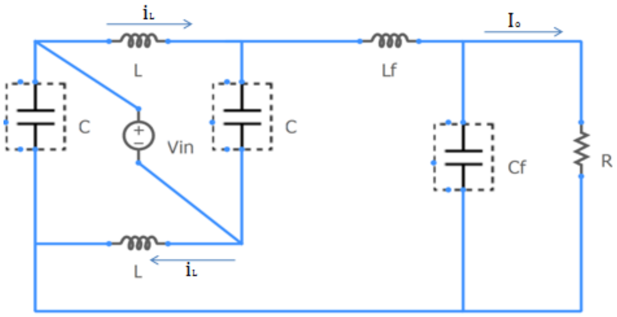

Fig. 4 Equivalent circuit of the Z-source dc-dc converter when S is OFF and D is ON.

The current through the inductors L and L_f is given by,

$$i_L = \frac{V_{in} - V_C}{L}(t - dT) + i_L(0) \quad (7)$$

$$i_{L_f} = \frac{V_o - V_{in}}{L_f}(t - dT) + i_{L_f}(0) \quad (8)$$

III. DC Voltage Conversion Factor And Minimum Inductance for CCM

1. *DC Voltage Conversion Factor for CCM*

By the volt-second balance property of the inductor, the average voltage across an inductor in steady state is zero. From (1) and (5), the volt-second balance for the inductor L can be expressed as

$$\int_0^{dT} v_L(t)dt + \int_{dT}^{T} v_L(t)dt = 0 \quad (9)$$

Thus,

$$V_C dT + (V_{in} - V_C)(1-d)T = 0 \quad (10)$$

which gives

$$\frac{V_C}{V_{in}} = \frac{1-d}{1-2d} \quad (11)$$

Equation (11) is the dc input-to-capacitor voltage conversion factor. Referring to Fig. 1, by applying KVL to the loop containing the Z-network capacitor C, the filter inductor L_f, the parallel combination of $R||C_f$, and the Z-network inductor, we obtain

$$V_C - v_{L_f} - V_o - v_L = 0 \quad (12)$$

Since the average values of $v_{L_f} = 0$ and $v_L = 0$, (12) leads to

$$V_C = V_o \quad (13)$$

Using (11) and (13), we derive the dc input-to-output voltage conversion factor as

$$\frac{V_o}{V_{in}} = \frac{1-d}{1-2d} \quad (14)$$

Fig. 5 shows the voltage gain as a function of duty ratio. Shows the buck-boosting capability of Z-source dc-dc converter.

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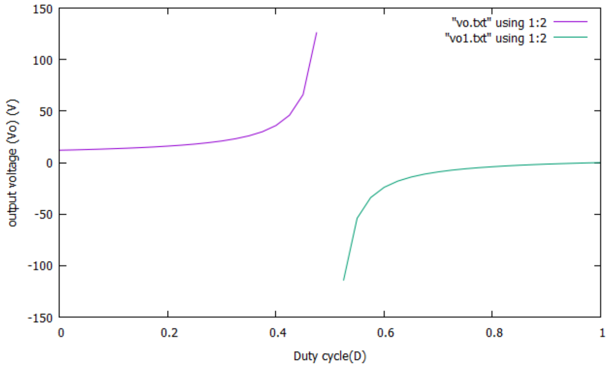


Fig. 5 Voltage gain as a function of d

2. *Minimum Inductance for CCM*

The peak inductor current is given by:

$$i_L = \frac{\Delta i_L}{2} \tag{15}$$

Substituting the values of i_L and Δi_L we have,

$$\frac{V_C(1-d)}{(1-2d)R} = \frac{V_C dT}{2L} \tag{16}$$

On solving we get,

$$\frac{2L}{RT} = \frac{d(1-2d)}{(1-d)} \tag{17}$$

Let, $K = \frac{2L}{RT}$ and $K_{critical} = \frac{d(1-2d)}{(1-d)}$ when,

$$K > K_{critical} \rightarrow \text{CCM}$$
$$K < K_{critical} \rightarrow \text{DCM}$$

Fig. 6 shows the normalized load current as a function of duty ratio for CCM/DCM boundary.

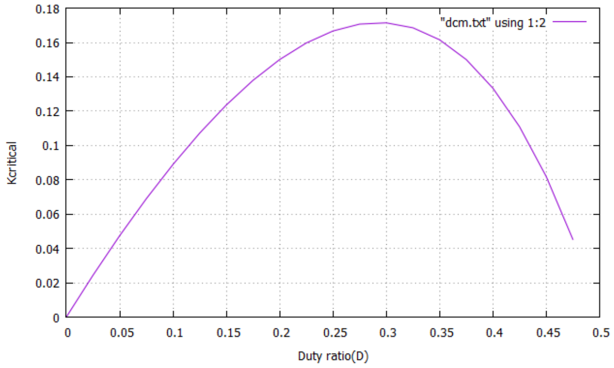


Fig. 6 Normalized load current as a function of d

IV. Modelling and Simulation Results

To find the inductor currents we use Implicit Euler method. Consider the ordinary differential equation

$$\frac{dy}{dt} = f(t, y) \tag{18}$$

with initial value $y(t_0) = y_0$ Here the function f and the initial data t_0 and y_0 are known; the function y depends on the real variable t and is unknown. A numerical method produces a sequence y0, y1, y2 . . . such that y_k approximates $y(t_0 + kh)$, where h is called the step size.

The Euler's implicit method [6] computes the approximations using

$$y_{k+1} = y_k + hf(t_{k+1}, y_{k+1}) \tag{19}$$

Using (19) we calculate the instantaneous inductor currents. Data structure is used to simulate and verify the modelled results.

An example of Z-source dc-dc converter with specifications input voltage V_{in}=12 V, frequency f=10 kHz, duty ratio D=0.3, inductor L=10 mH, filter inductor L_f=1 mH.

Fig. 7 Current through the inductor of the Z-network

Fig. 8 Current through the filter inductor

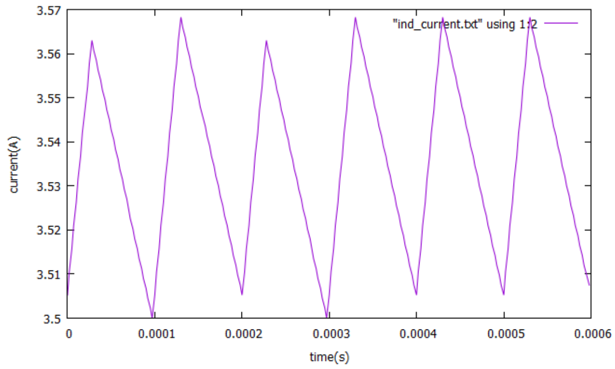
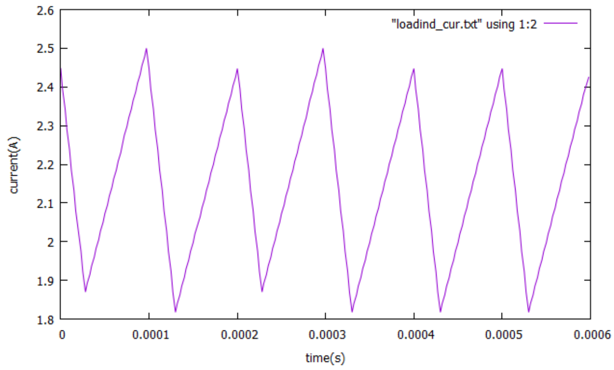
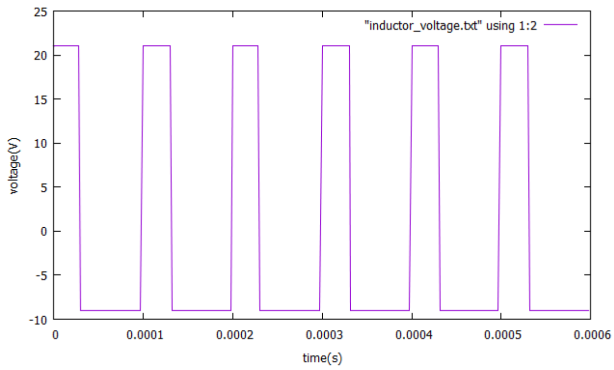


Fig. 9 Voltage across the inductor of the Z network





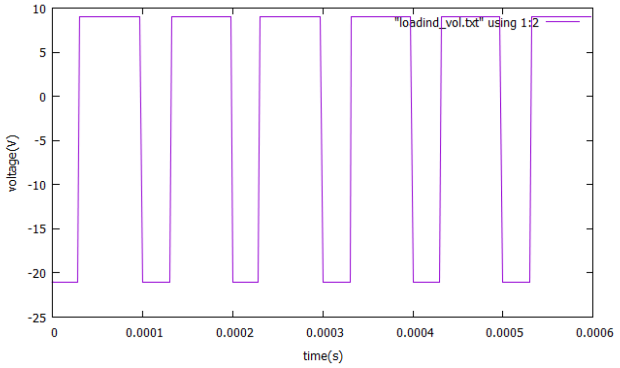


Fig. 10 Voltage across the filter inductor

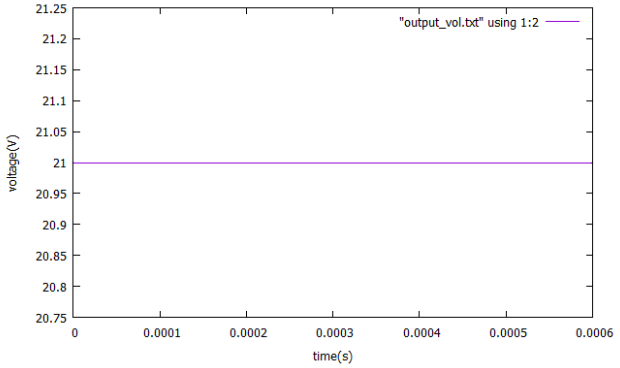


Fig. 11 Z-source DC-DC converter output voltage waveform

I.CONCLUSIONS

A detailed steady-state analysis of Z-source dc-dc converter operating in CCM has been presented. The dc input-to output voltage conversion factor for an ideal Z-source dc-dc converter has been derived. The minimum Z-network inductance required to ensure CCM operation has been derived. Now the disadvantage of the Z-source dc-dc converter as compared to conventional boost converter topology is its higher part count. However, the merits of the Z-source dc-dc converter are:

- For the same duty ratio and input voltage, Z-source dc-dc converter offers a higher output voltage.
- Since the diode is turned OFF when the MOSFET is ON, if there is a short on the load side, the source is isolated from the load. This provides inherent immunity to disturbances at the load side. This can be critical if the fuel or energy source is expensive and is to be protected.
- Since the input-to-output voltage conversion factor is for, the output voltage is inverted. It can be employed, where such a feature is desired.

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