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Closed Loop Control of Bi-Directional Soft Switched Quasi Z-Source DC-DC Converter

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Abstract

Quasi Z-source converter is a single stage soft switched power converter derived from Z-source converter topology, employing an impedance network coupling the source with the converter. The quasi Z-source source converter can buck or boost the voltage and current flow is bidirectional. The duty cycle of the switch can be adjusted to maintain constant voltage during load change. To obtain constant output voltage, proper controller design is a must. This paper presents closed loop control of quasi Z-source converter using PI controller where controller parameters are estimated using the small signal model of the entire system. The transfer function of the system with AC sweep is used to obtain appropriate proportional and integral gain constants to reduce transient dynamics and to reduce steady state error.

Keywords

Quasi Z-Source Network, PSIM, Soft Switching, Switching Losses, Smart Control, PI Controller Design

1. Introduction

Many DC-DC converters can either buck or boost the voltages. The voltage fed converters can only buck the voltage and current fed converters can boost the voltages. There are applications which demands both buck and boost operation, for example battery charging and discharging. During batter charging, the voltage has to be stepped down whereas during battery discharge, the voltage has to be stepped up. The converters which can perform both the operations are Z-source converters which were first proposed by F. Z. Peng [1]. Z-source or impedance source network consists of cross connected L and C elements. Z-source inverters find wide applica-

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tions in electric drive systems, as active filters for power quality improvement. The desired AC output can be obtained by controlling the shoot-through duty cycle of the Z-source. The output voltage can also be boosted; therefore Z-source converters can be used to mitigate the voltage sags and also they add on the other benefits like reliability, less harmonics and can have wider range of output voltages [2]-[4].

By controlling the shoot through period, the duty cycle of Z-source converter can be controlled. The Z-source converter can produce any desired output ac voltage, even greater than the line voltage by controlling the shoot through period. Therefore Z-source inverters can be used to compensate the voltages when voltage sag occurs in power systems.

The concept of the Z-source network can be applied to DC-DC power conversion. Z-source dc-dc converter (ZSC) is proposed in [2]. H-bridge has been used to operate in four-quadrant operation for motor drives for many years, but it utilizes four active switches which are expensive and large. Z-source converter for DC motor speed control was proposed in [4]. To improve on the traditional ZSIs, quasi-Z-source inverters (qZSIs), have been developed in [5]. DC-DC switched power converters such as Buck, Boost and Buck/Boost converters have been widely used in industry. They can be divided according to their output characteristics: single-quadrant converters, two-quadrant converters, and four-quadrant converters. Single-quadrant dc-dc converters have been studied for a long time since this type of converter has wide spread applications. Two-quadrant converters also have been discussed in bidirectional current and motor control applications [6]. Four-quadrant converters have been discussed in [7]. The efficiency of multi stage cascaded converter is poor because of losses in every stage. This problem can be overcome in Quadratic converters which was proposed in [8]. The design of Buck, Boost, Buck/Boost, Sepic converters is discussed in [9]-[11]. The four-order converter was taken; both continuous conduction mode and discontinuous conduction mode operations were performed [12]. Along with the advantages of ZSC, qZSC has the above advantages of quasi-Z-source network. Also, the voltage gain of qZSC is the same with that of ZSC. The design of PI controller by using ACSWEEP is discussed in [13] [14]. Quasi Z-source DC-DC converter with switched capacitor was proposed in [15] for higher gain with less voltage stress.

2. Conventional Z-Source DC-DC Converters

Z-source network has both the current-fed topology and the voltage-fed topology. This paper focuses on voltage-fed power conversion circuit which is represented in **Figure 1**. The input part is composed of the input voltage source V_{in} and the diode D_0. The Z-source network part is composed of the inductors L_1, L_2 and the capacitors C_1, C_2. The inductors L_1, L_2 have the same inductance value. Also, the capacitors C_1, C_2 have the same capacitance value. In the case of ZSC, the output part is composed of the switch S, the low pass filter L_f-C_f, and the load resistance R_0.

ZSC has two operation modes; state 0 and state 1. During the term of state 0, the switch S is on. The Z-source inductors L_1, L_2 are magnetized, and the capacitors C_1, C_2 of Z-source are discharged. During the state 1 cycle,

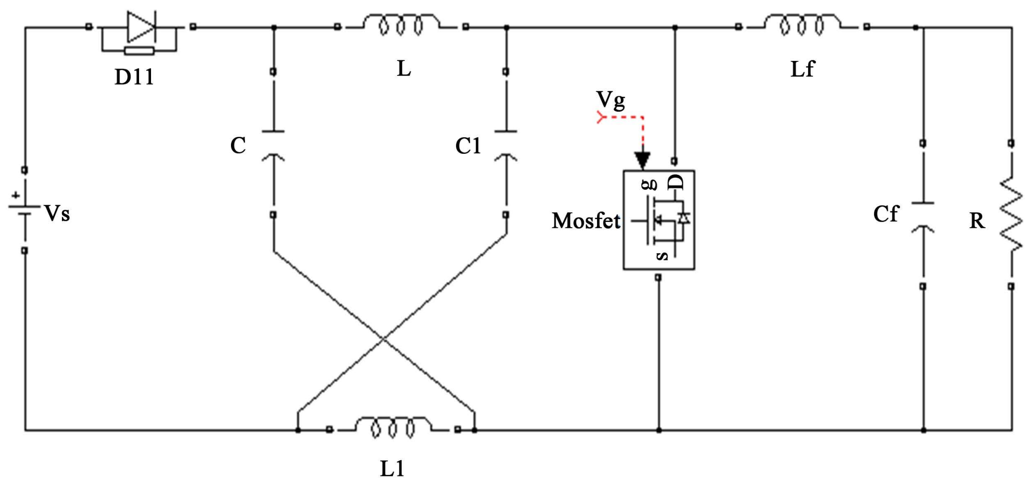


Figure 1. Voltage-fed Z-source DC-DC converter.

the switch S is off. The Z-source inductors L_1, L_2 and input voltage source V_{in} provide the energy to the output part and the Z-source capacitors C_1, C_2. By repeating these two operation modes, ZSC can output positive polar boost voltage. The equivalent circuits and the associated expressions corresponding to different stages of operation of the PWM Z-source dc-dc converter in CCM, the dc input-to-output voltage conversion factor and minimum inductance required to ensure CCM operation for power losses in the components of the PWM Z-source dc-dc converter and the overall efficiency, output voltage ripple across the filter capacitor and experimental results to validate the theoretical analysis [3]. Z-Source dc-dc converter used in applications like solar and fuel cell with high voltage gain and low ripple input current.

3. Open Loop Quasi Z-Source Converter

In common with Z-source network, quasi-Z-source network has both the current-fed topology and the voltage-fed topology. This paper focuses on voltage-fed power conversion circuit which is shown in **Figure 2**. In analogy with Z-source network, the dc-dc converter output part can be added to quasi-Z-source network, and quasi-Z-source network can be applied to the dc-dc converter. ZSC has some disadvantages; the discontinuity of input current, high voltage stress on Switch is more. The L_f-C_f output filter is used to smoothen the output current and load voltage respectively.

To overcome the above problems of ZSC, quasi-Z-source converter is proposed in [3]. Quasi Z-source converter has an LC impedance network, which is the improved Z-source network. The operation of qZSC is similar to the opeartion of ZSc, along with the advantages of Z-source network topology, quasi-Z-source network has some advantages, such as continuous input current, low voltage stress on capacitors, and sharing the input and output grounds. In common with Z-source network, quasi-Z-source network can be applied to dc-dc power conversion. Quasi-Z-source dc-dc converter (qZSC) is proposed in [4]. Along with the advantages of ZSC, qZSC has the above advantages of quasi-Z-source network. Also, the voltage gain of qZSC is the same as that of ZSC.

4. Modes of Operation

qZSC has two operation modes, state 0 and state 1. During the term of state 0, the switch s is on and the diode D_1 is off. The inductor L_1 is magnetized by the input voltage source V_{in} and the capacitor C_2. Also, the inductor L_2 is magnetized by the capacitor C_1. During the term of State 1, the switch is off and the diode D_1 is on. The input voltage source V_{in} and the inductor L_1, L_2 provide the energy to the load resistance R_0. Moreover, the capacitor C_1 is charged by the input voltage source V_{in} and the inductor L_1, and the capacitor C_2 is charged by the inductor L_2. By repeating these two operation modes, qZSC can boost the voltage.

1) State $0(t_o \le t \le t_{on})$ when the switch is ON.

During the term of state 0, the switch s is on and the diode D_1 is off. The inductor L_1 is magnetized by the input voltage source V_{in} and the capacitor C_2. Also, the inductor L_2 is magnetized by the capacitor C_1.

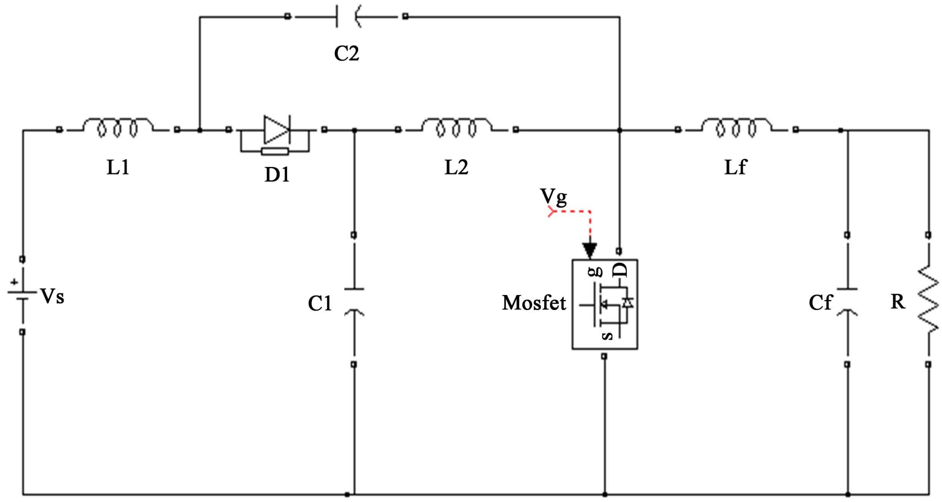


Figure 2. Voltage-fed quasi Z-source DC-DC converter.

As shown in **Figure 3**, the following equations are derived in state 0.

$$V_{in} + V_{L_1} + V_{C_2} = 0 \tag{1}$$

$$V_{C_2} + V_{L_2} = 0 \tag{2}$$

$$V_{Cf} = V_0 \tag{3}$$

2) State 1($t_{on} \le t \le t_{off}$) when the is switch OFF.

During the term of State 1, the switch is off and the diode D_1 is on. The input voltage source V_{in} and the inductor L_1, L_2 provide the energy to the load resistance R_0. Moreover, the capacitor C_1 is charged by the input voltage source V_{in} and the inductor L_1, and the capacitor C_2 is charged by the inductor L_2.

As shown in **Figure 4**, the following equations are derived in state 1.

$$V_{in} + V_{L_1} - V_{C_2} = 0 \tag{4}$$

$$V_{L_2} = V_{C_2} \tag{5}$$

$$V_{C_1} + V_{L_2} + V_{L_f} = V_0 \tag{6}$$

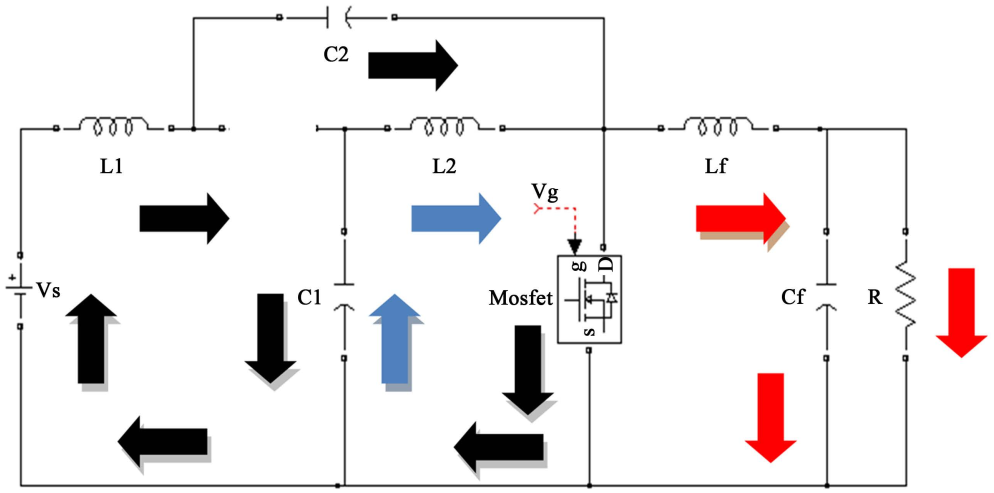


Figure 3. Quasi Z-source DC-DC converter when the switch on.

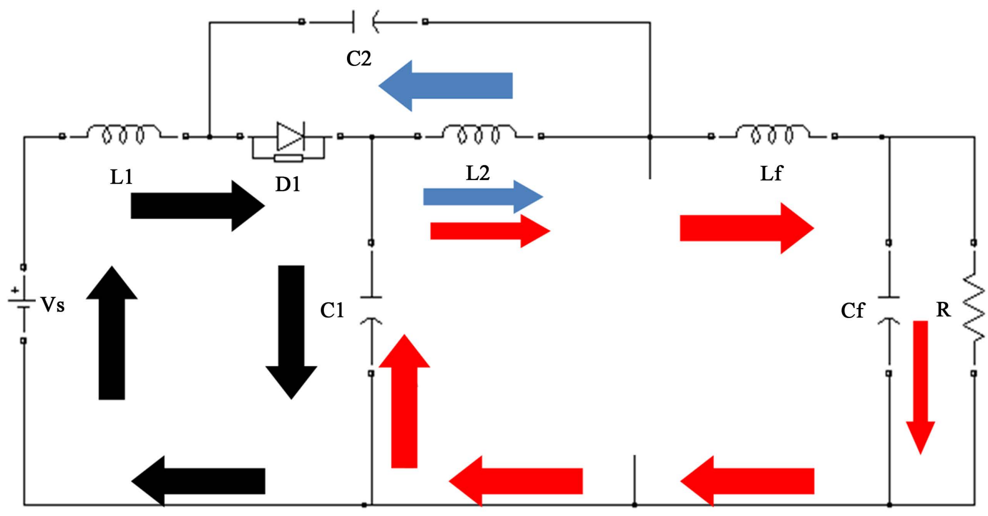


Figure 4. Quasi Z-source DC-DC converter when the switch off.

D—duty ratio.
T_s—total time period.
T_{on}—switch ON period.
T_{off}—switch OFF period.
Where V_{in} is the supply voltage.
V_{C_1} is the capacitor C_1 voltage.
V_{C_2} is the capacitor C_2 voltage.
V_{C_f} is the filter capacitor C_f voltage.
V_{L_1} is the voltage across the inductor L_1.
V_{L_2} is the voltage across the inductor L_2 with reference to **Figure 2**.

$$T_{ON} = DT_S \tag{7}$$

$$T_{off} = (1-D)T_S \tag{8}$$

where D—duty ratio.
T_s—total time period.
T_{on}—switch ON period.
T_{off}—switch OFF period.

In steady-state, the averaged voltages of L_1, L_2 are zero for one switching cycle T_S. Therefore, the following equations are satisfied.

$$\frac{1}{T_S}\left[\int_{t_0}^{t_{on}} V_{L_1}\mathrm{d}t + \int_{t_{on}}^{t_{off}} V_{L_1}\mathrm{d}t\right] = 0 \tag{9}$$

$$\frac{1}{T_s}\left[\int_{t_0}^{t_{on}} V_{L_2}\mathrm{d}t + \int_{t_{on}}^{t_{off}} V_{L_2}\mathrm{d}t\right] = 0 \tag{10}$$

Substitute (1) and (4) in (9)

$$\frac{1}{T_s}\left[\int_{t_0}^{t_{on}} \left(-V_{in} - V_{c_1}\right)\mathrm{d}t + \int_{t_{on}}^{t_{off}} \left(V_{c_1} - V_{in}\right)\mathrm{d}t\right] = 0. \tag{11}$$

Substitute (2) and (5) in (10)

$$\frac{1}{T_s}\left[\int_{t_0}^{t_{on}} \left(-V_{c_1}\right)\mathrm{d}t + \int_{t_{on}}^{t_{off}} \left(V_{c_2}\right)\mathrm{d}t\right] = 0. \tag{12}$$

Since the voltages across C_1, C_2, increase and decrease linearly in two operation modes, the averaged voltages V_{c_1}, V_{c_2}, across C_1, C_2, are expressed as follows in steady state.

$$V_{c_1} = \frac{1}{T_0}\int_{t_0}^{t_{on}} \left(V_{c_1}\right)\mathrm{d}t = \frac{1}{T}\int_{t_{on}}^{t_{off}} \left(V_{c_1}\right)\mathrm{d}t \tag{13}$$

$$V_{c_2} = \frac{1}{T_0}\int_{t_0}^{t_{on}} \left(V_{c_2}\right)\mathrm{d}t = \frac{1}{T}\int_{t_{on}}^{t_{off}} \left(V_{c_2}\right)\mathrm{d}t \tag{14}$$

Substitute (7), (8), (13) and (14) in (11) we will get

$$V_{c_2} = \left[V_{c_1}(1-D) - V_{in}\right]/D. \tag{15}$$

Substitute (7), (8), (13) and (14) in (12) we will get

$$V_{c_2} = \frac{V_{c_1}D}{(1-D)}. \tag{16}$$

Equating Equations (15) and (16) we will get

$$V_{c_2} = \frac{V_{in}(1-D)}{(1-2D)}. \tag{17}$$

In steady-state, the averaged voltages of L_f are zero for one switching cycle T_S. Therefore, the following equations are satisfied.

$$\frac{1}{T_s}\left[\int_{t_0}^{t_{on}}\left(V_{Lf}\right)\mathrm{d}t+\int_{t_{on}}^{t_{off}}\left(V_{Lf}\right)\mathrm{d}t\right]=0 \tag{18}$$

Substitute (3), (6) in (18) we will get

$$V_0=\left[V_{in}\left(1-D\right)/1-2D\right]. \tag{19}$$

In steady-state, the input power is equal to output power

$$P_{in}=P_0 \tag{20}$$

$$I_{L_1}=\frac{I_0\left(1-D\right)}{\left(1-2D\right)}. \tag{21}$$

The ripple Current allowed to the inductance

$$\Delta I_L=I_L*\delta\% \tag{22}$$

δ—allowed Ripple.

5. PI Controller Design

Smart Control is a general-purpose controller design software specifically for power electronics applications. To design the controller of a dc-dc converter with a single control loop using the Smart Control software. Before going to Smart control find bode plot of the Plant. The converter selected in this example is a quasi Z-source converter with voltage model control, as shown in **Figure 5**. The voltage regulator to be designed is highlighted in the red box. Before going to the design define the converter and Select the sensor, regulator type, crossover frequency and phase margin. Given a particular design, the attenuation given by the sensor and the regulator at the switching frequency is calculated and displayed in the edit box |K(s)*R(s)| at Fsw. The PI controller parameters are shown in **Table 1**.

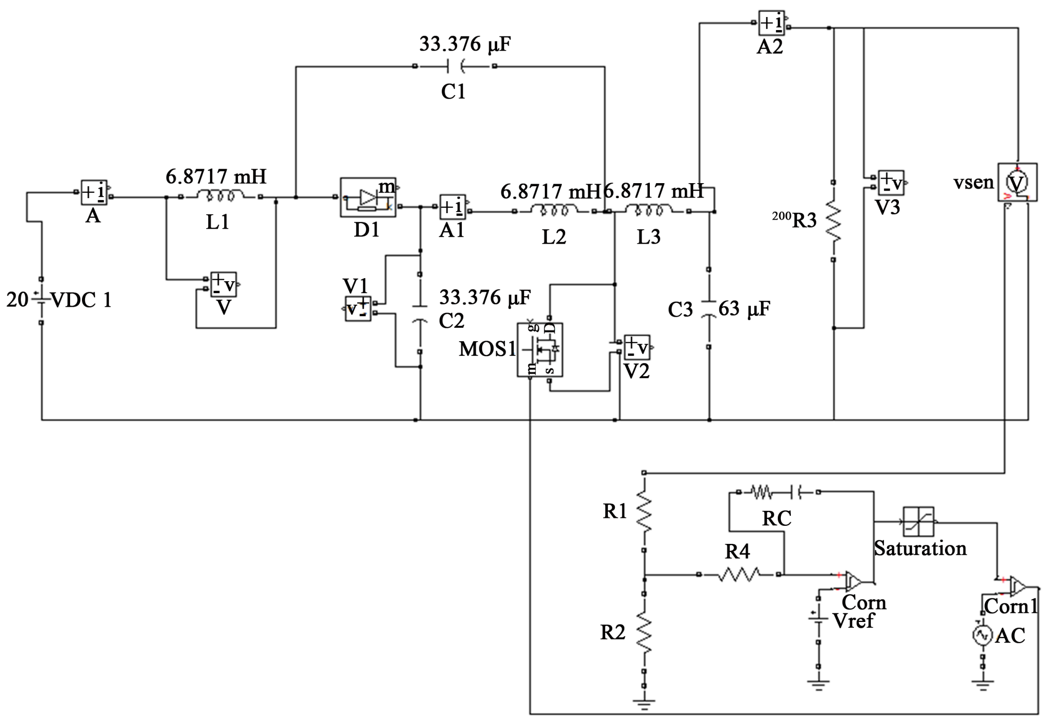


Figure 5. Quasi Z-source DC-DC converter closed loop controlled circuit diagram.

Note that if there is not enough attenuation at the switching frequency, the system will likely oscillate in the high frequency region. Also, if a design is not proper, the edit boxes will be change to the red color, warning users to re-select the design. After the design is completed, Smart Control provides the component values for the sensor and the regulator.

6. Simulation Results

In this paper the simulation model is developed with Psim software. The simulation is carried out for closed loop control of converter shown in **Figure 3**. The simulation circuit of proposed method and output waveform is shown in figure below. The proposed converter has to boost the voltage from 20 V to 120 V with the switching frequency $f_s = 20\text{ kHz}$ and load Resistance R_0 = 200 Ω. V_{in} and V_0 are the input and output voltage while I_{in} and I_0 are the input and output current which are all positive. The Gating Pulses, Voltage across the switch and the current through MOSFET switch is shown in **Figure 6**. **Figure 7(a)** and **Figure 7(b)** shows the capacitor voltage C_1 and C_2 of qZSC. Current through inductor of L_1 and L_2 of qZSC is shown in **Figure 8(a)** and **Figure 8(b)**. **Figure 9** and **Figure 10** shows the output voltage and current of closed loop control. On the other hand **Figure 11** and **Figure 12** shows the output voltage and current of losed loop control when there is a change in load. The circuit parameters are listed in **Table 2**.

As observed from **Figure 11** and **Figure 12**, whenever there is load change, the closed loop control action maintains the output voltage at desired value, whereas the current decreases due to increase in load resistance. Hence proposed closed loop control helps in regulating load voltage during load variation.

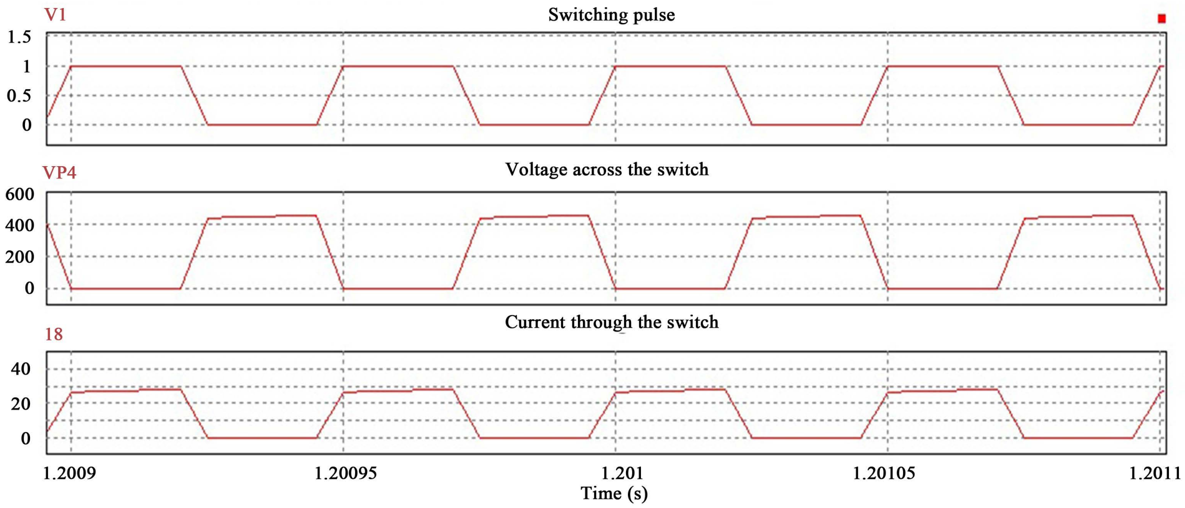
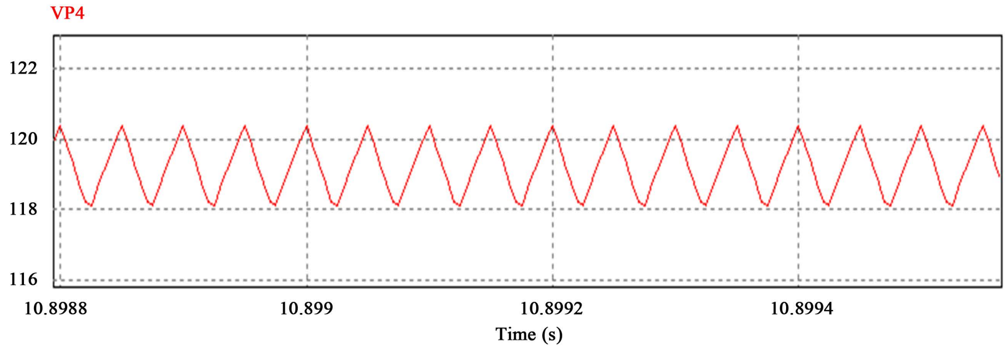


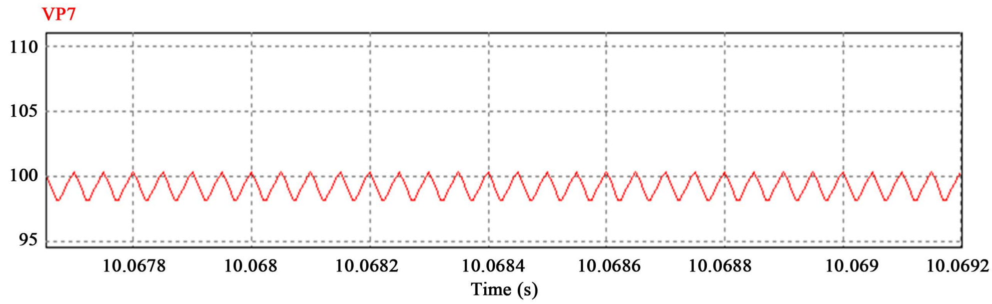
Figure 6. Gating pulses, voltage across the switch and the current through the switch.

Table 1. PI controller parameters.

Component	Values
f_{sw}	20 kHz
R_a	23.5 KΩ
R_b	500 Ω
V_{ref}	2.5 V
R_2	87.752 KΩ
R_{11}	10 KΩ
C_2	24.5036 nF
G_{mod}	0.2

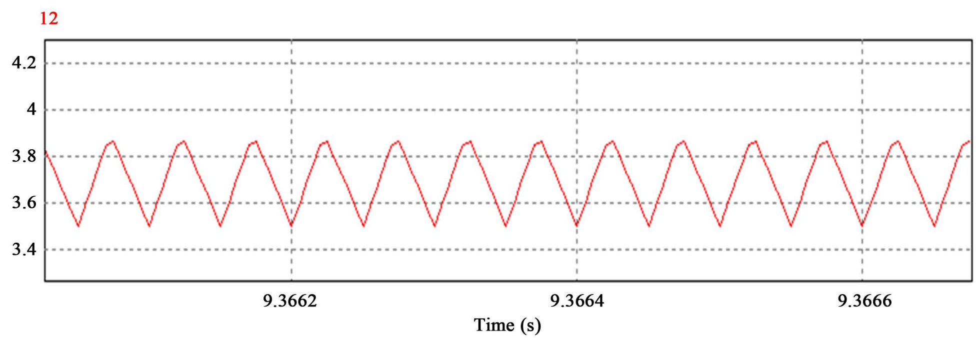


(a)

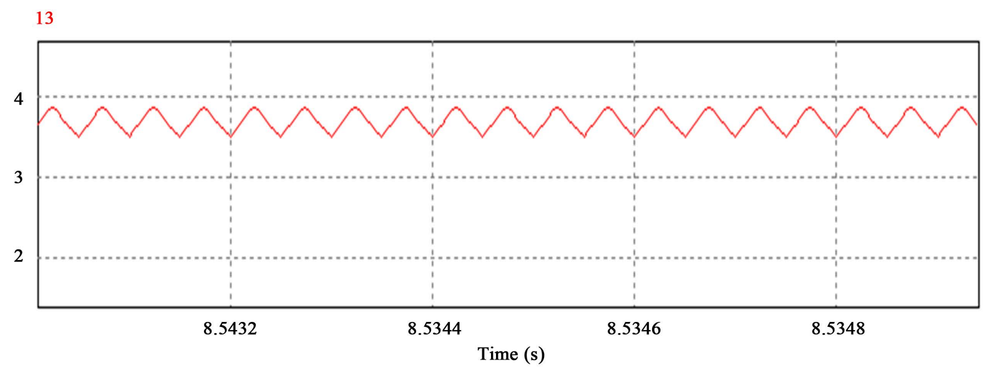


(b)

Figure 7. (a) Quasi Z-source DC-DC converter capacitor voltage C_1; (b) Quasi Z-source DC-DC converter capacitor voltage C_2.



(a)



(b)

Figure 8. (a) Quasi Z-source DC-DC converter inductor current L_1; (b) Quasi Z-source DC-DC converter inductor current L_2.

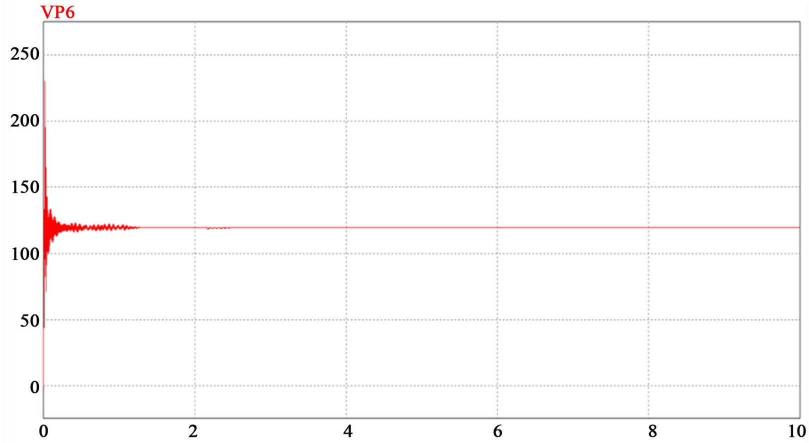


Figure 9. Closed loop controlled output voltage.

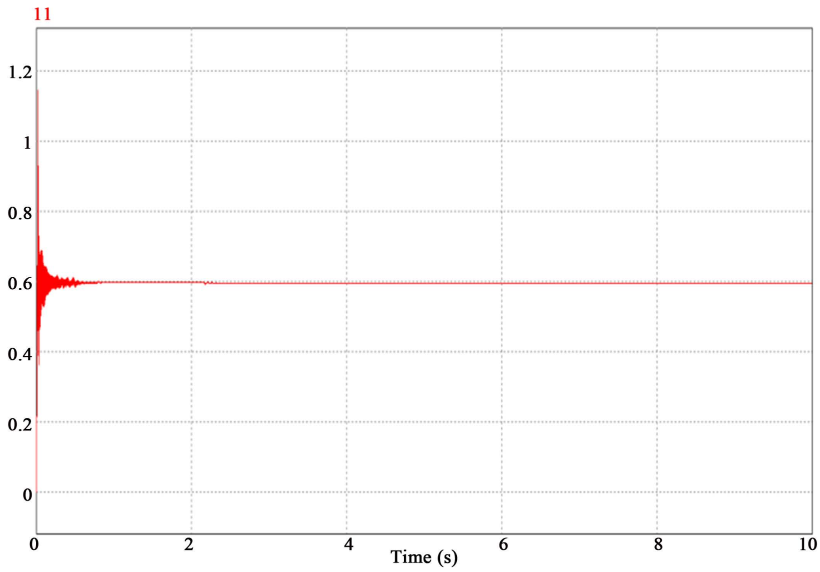


Figure 10. Closed loop controlled output current.

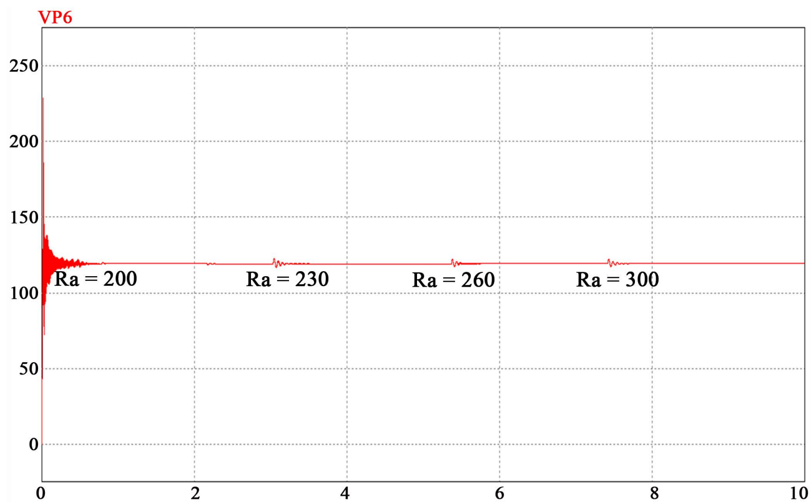


Figure 11. Closed loop controlled output voltage while change in load.

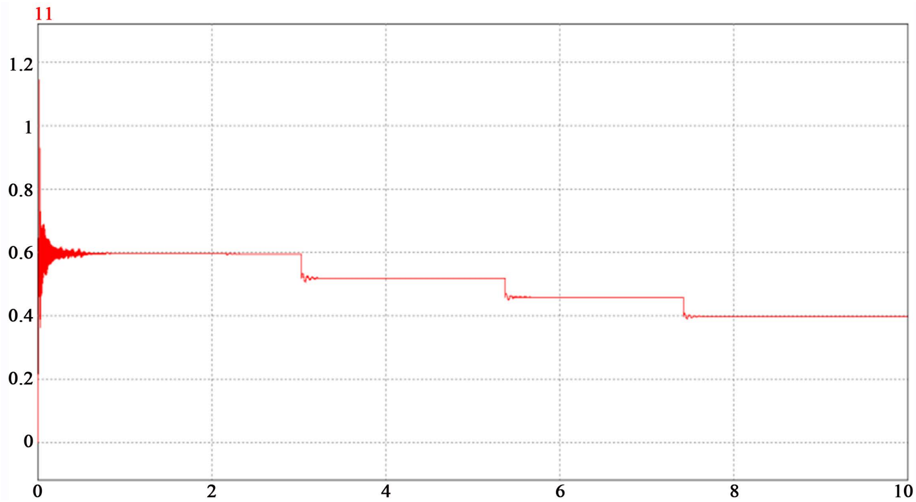


Figure 12. Closed loop controlled output current while change in load.

Table 2. Circuit parameters.

	Component	Values
Quasi Z-source network	Inductor L_1	6.8717 mH
	Inductor L_2	6.8717 mH
	Capacitor C_1	33.763 µF
	Capacitor C_2	33.763 µF
Low passfilter	Inductor L_f	6.87 mH
	Capacitor C_f	0.4815 µF
	Switching frequency	20 kHz
	Load resistance	200 Ω
	Duty cycle	0.47
	Output power	392 W

7. Conclusion

In this paper, the PI controller is designed by using smart control and the closed loop control performance of quasi Z-source dc-dc converter was analyzed for step change in load. By PWM duty ratio control, it can boost the input voltage. It can reduce cost and improve reliability. Quasi-Z-source dc-dc converter has been proposed with low pass filter. The quasi Z-source converter draws continuous current from supply and the input current ripple is also less compared to Z-source converter. By the circuit analysis and experiment, the operation of the proposed circuit has been confirmed.

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