DC-DC and AC-DC Zeta and Buck Converter Design and Analysis for High Efficiency Application

A Thesis Submitted to the Academic Faculty in Partial Fulfillment of the Requirements for the Degree of

BACHELOR OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING

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We hereby declare that this thesis has been prepared in partial fulfillment of the requirement for the degree of Bachelor of Science in Electrical and Electronic Engineering at the Islamic University of Technology (IUT), Boardbazar, Gazipur-1704 and has not been submitted anywhere else for any other degree.

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List of Acronyms

PWM	Pulse Width Modulation
CCM	Continuous Conduction Mode
PF	Power Factor
THD	Total Harmonic Distortion
AC	Alternating Current
DC	Direct Current
SMPS	Switching Mode Power Supply

Acknowledgements

All the praises are for Allah for blessing us with the knowledge and ability to do the present study. Our indebt gratitude must be to the most benevolent and merciful for everything that we have from Him.

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Abstract

The thesis work is carried out to design and analyze DC-DC and AC-DC converters. Two types of DC-DC converters, buck and zeta, are presented in this book with dc steady state analysis at continuous conduction mode, ac small signal analysis and simulation results. The analysis of DC-DC buck converter includes a switched capacitor buck converter and a switched inductor buck converter. These two converters have been proposed in a previously published article. But, the article did not show the detailed analysis. So, the detailed mathematical model has been developed for these two buck circuits. Another type of buck converter, based on switched inductor-capacitor, is presented briefly in chapter 5. This buck converter has been accepted in an IEEE conference. Two types of zeta converter, switched inductor and modified conventional, are shown in this book. The modified conventional zeta circuit is a new design while the other circuit is taken from a previously published article. The newly developed modified conventional zeta circuit improves the performance of conventional zeta circuit by increasing the efficiency above 95%. A two stage AC-DC converter based on switched inductor zeta circuit is designed and analyzed. The proposed AC-DC circuit improves the power quality compared to the conventional circuit. It raises the efficiency above 95%, increases the power factor (PF) by 6% compared to the conventional circuit and improve the total harmonic distortion (THD) by 2-3% with respect to the conventional circuit.

Chapter 1

Introduction

1.1 Overview

Development in the field of power electronics has constituted one of the great success stories of the 20th century. As manufacturing technology has improved, the cost of the semiconductor devices has decreased. It is often said that solid-state electronics brought in the first electronics revolution, whereas solid-state power electronics is the second electronics revolution. It is interesting to note that power electronics blends the mechanical, electrical and electronic era.

A high-level productivity of the industries and product quality enhancement is not possible by using non-power electronic systems. Today, power electronics is an indispensable tool in any country's industrial economy. It is necessary that some converters are to be used to improve the quality of power supply. Power semiconductor devices are making it possible for utilities to use a variety of power control equipment to raise power quality level and enhance performance and efficiency [1, 2].

The continuous development of communication technologies requires high performance communication power. High efficiency, high power density, high reliability of the communication power module becomes the inevitable trend of the development of communication power [3, 4].

The above mention applied field necessary involves the requirement of highly efficient regulation of system voltage and current. This regulation of voltage can be achieved through the use of transformers and converters. DC-DC & AC-DC power converter have grown popular over the years, and become an integral part of the power supply system in recent year

Power electronic circuits are used to control the power conversion from one or more AC or DC sources to one or more AC or DC loads, and sometimes with bidirectional capabilities [4, 5]. The converter, handles the power transfer from the input to

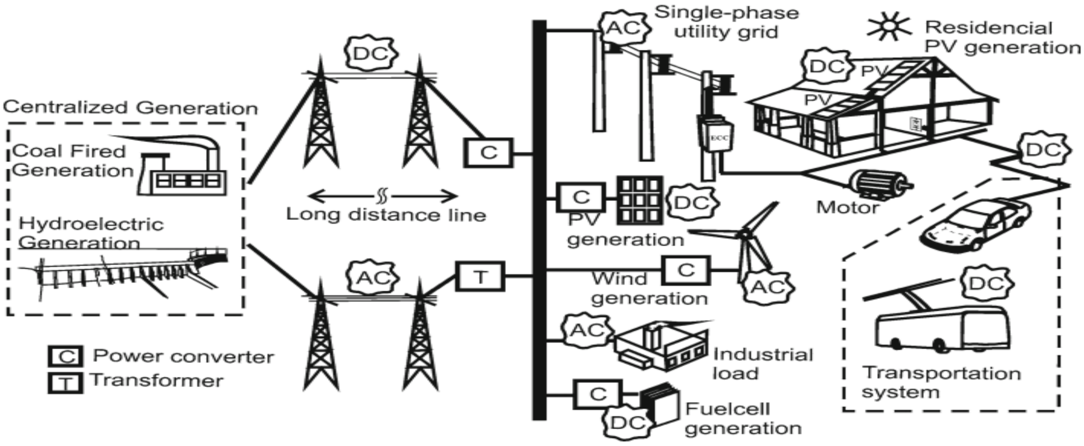


Fig. 1 A schematic of Power electronics and electrical energy generation transmission, storage and distribution

output,

or vice versa, and is constituted of power semiconductor devices acting as switches, plus passive devices (inductor and capacitor) [6-8].

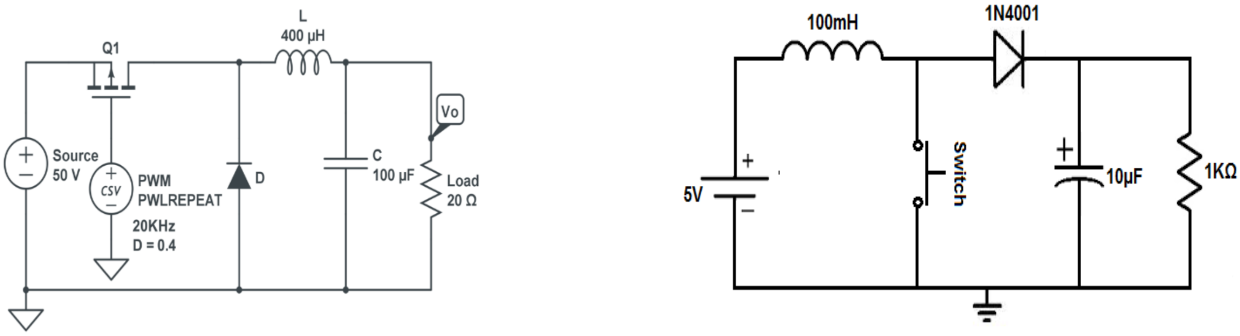
1.2 DC-DC Converter

The DC– DC converter, also known as chopper, is a converter which transforms a D.C. signal to another D.C. value. The average value of a converter output voltage can be modified between zero and the full voltage. This can be done using the “Pulse Width Modulation (PWM)” principle of constant frequency pulses [9-13].

The charge carriers in DC supply travel in a single direction. Solar cells, batteries and thermocouples are the sources of DC supply. A DC voltage can produce a certain amount of constant electricity, which becomes weak when it travels further longer. Semiconductor devices developed in recent years often consist of power supply ratings of lower voltages.

Based on this factor, over the years basically two types of DC-DC converter have been developed.

1. A DC-DC converter that can provide higher voltage at the output than input, or in other sense, a converter that can step up (like a transformer) DC voltage known as step up converter [14-17].
2. A DC-DC converter that can provide lower voltage at the output than input, a converter that can step down DC voltage is known as step down converter [18-21].



(a) (b)

Fig. 2 Schematic of (a) step down converter (b) step up converter

Buck converter is the primary example of DC-DC step up converter, for step down it is buck converter. A buck converter (step-down converter) is a DC-to-DC power converter which steps down voltage (while stepping up current) from its input (supply) to its output (load). It is a class of switched-mode power supply (SMPS) typically containing at least two semiconductors (a diode and a transistor, although modern buck converters frequently replace the diode with a second transistor used for synchronous rectification) and at least one energy storage element, a capacitor, inductor, or the two in combination [22-25]. To reduce voltage ripple, filters made of capacitors (sometimes in combination with inductors) are normally added to such a converter's output (load-side filter) and input (supply-side filter). Zeta, or ‘inverse sepic’, is another one of those DC-DC converters that have a capacitor in series with the power path.

1.3 AC-DC Converter

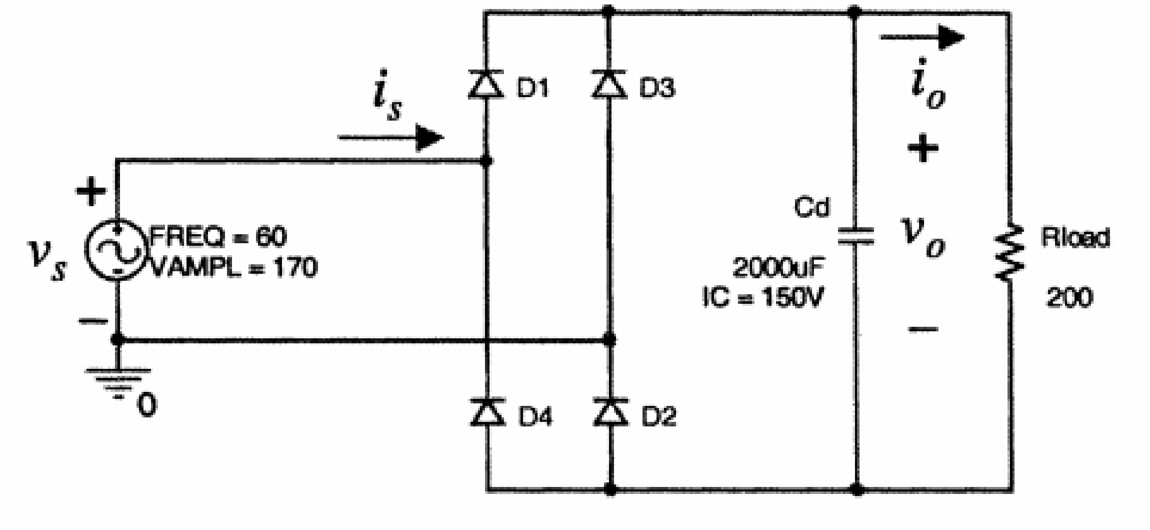


Fig. 3 Circuit of a single-phase diode bridge rectifier with a purely capacitive output filter

AC-dc converters, or rectifiers are used at the input of almost all line connected electronic equipment.

Electronic devices that are powered directly from line and do not have regulation requirements use single- and 3-phase diode bridge rectifiers for converting line frequency ac to an uncontrolled dc voltage [26-28].

Due to its simplicity and low cost this circuit is preferred for low-power applications such as input stages of ac-dc adapters and computer power supplies. Diodes conduct in pairs to transfer energy from the input to the output when the input line voltage exceeds the output dc voltage in magnitude [29-31].

Diodes *D*1 and *D*4 conduct when s$_1$, while *D*2 and *D*4 conduct when s_0. The capacitor C_d gets charged by high current pulses during these small intervals near the peak of *s*, and discharges with the almost constant load current during the rest of the line cycle [32-35].

The output dc voltage is approximately equal to the peak of the line voltage minus the forward voltage drop of two diodes. The capacitor value is chosen on the basis of the maximum load current and allowable output voltage ripple [36-38]. The line current has significant harmonic content. Source inductance of the line, common for regular utility supply, leads to lower peak input current, larger conduction times for the diodes, and reduced magnitude of the output voltage [39-41].

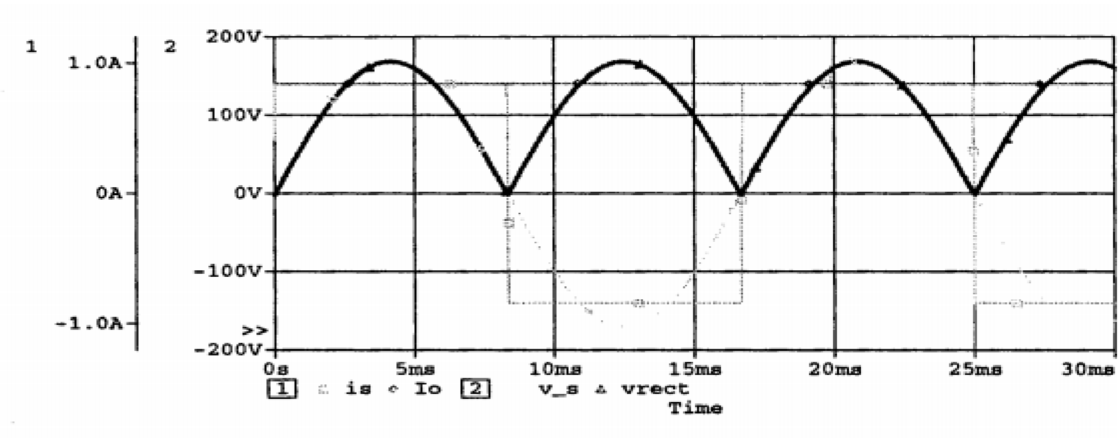


Fig. 4 Current waveform for AC-DC converter

To quantify the line current distortion, the following definitions are commonly used:

Total Harmonic Distortion. THD is the ratio of rms values of the distortion component to the fundamental component, expressed as a percentage.

$$\text{THD} = \frac{I_{dist}}{I_1} \times 100 = \frac{\sqrt{(I^2 - I_1^2)}}{I_1} \times 100$$

Real Power. This is the actual value of power consumed computed as an average over one-line cycle.

$$P_{real} = \frac{2\pi}{\omega} \int_{0}^{2\pi/\omega} v_s(t) i_s(t)\, dt = VI_1 \cos(\phi_1)$$

Apparent Power. It is the product of the rms values of the input voltage and current.

$$P_{app} = V \cdot I$$

Power factor. Power factor (PF) is defined as the ratio of real power to apparent power.

$$PF = \frac{P_{real}}{P_{app}} = \frac{VI_1 \cos(\phi_1)}{VI} = \frac{I_1}{I} \cdot \cos(\phi_1)$$

where V, I, and I_1 denote the rms value of the voltage, current, and fundamental component of the current, respectively, 1 is the phase angle of the fundamental component of the current with respect to the input voltage (assumed sinusoidal), and *Idist* is the rms value of the distortion component of the input current. The term cos (1) is called the *displacement power factor*, while the term I_1/I is called the *distortion power factor*

1.4 Zeta Converter

The ZETA converter topology provides a positive output voltage from an input voltage that varies above and below the output voltage. The ZETA converter also needs two inductors and a series capacitor, sometimes called a flying capacitor. Unlike the SEPIC converter, which is configured with a standard boost converter, the ZETA converter is configured from a buck controller that drives a high-side MOSFET [42-44]. The ZETA converter is another option for regulating an unregulated input-power supply, like a low-cost wall wart. To minimize board space, a coupled inductor can be used [45-47].

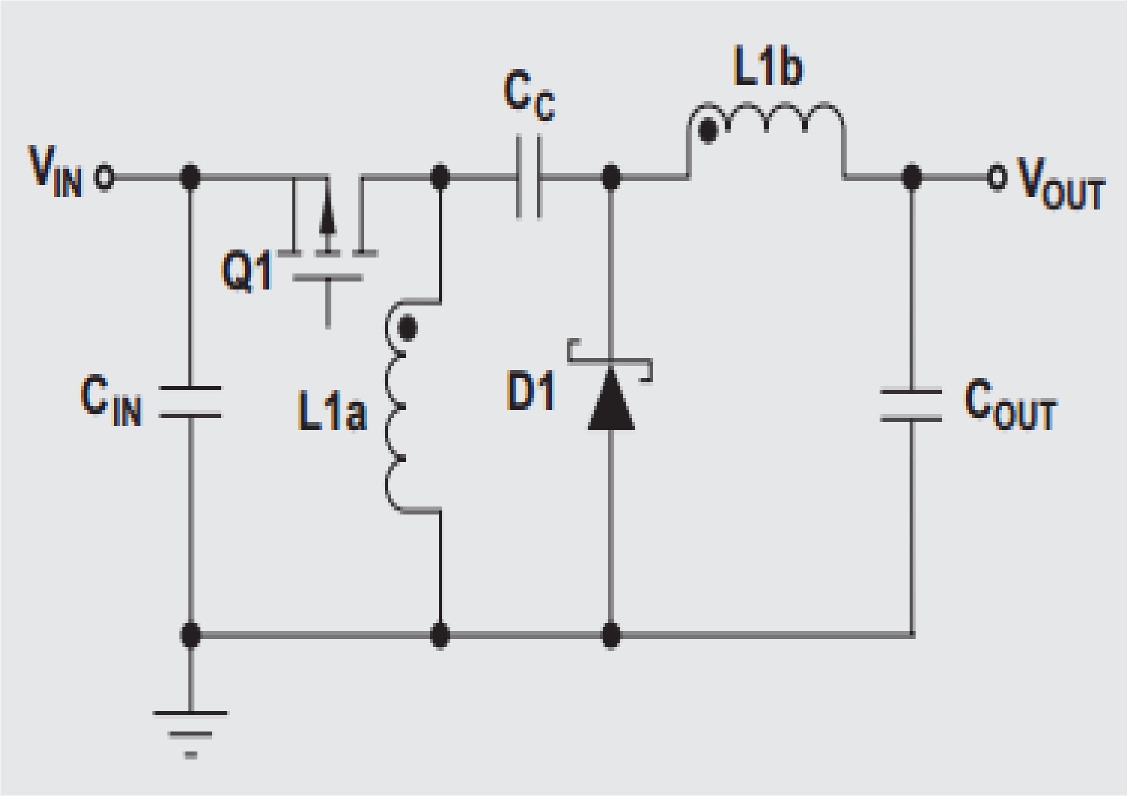
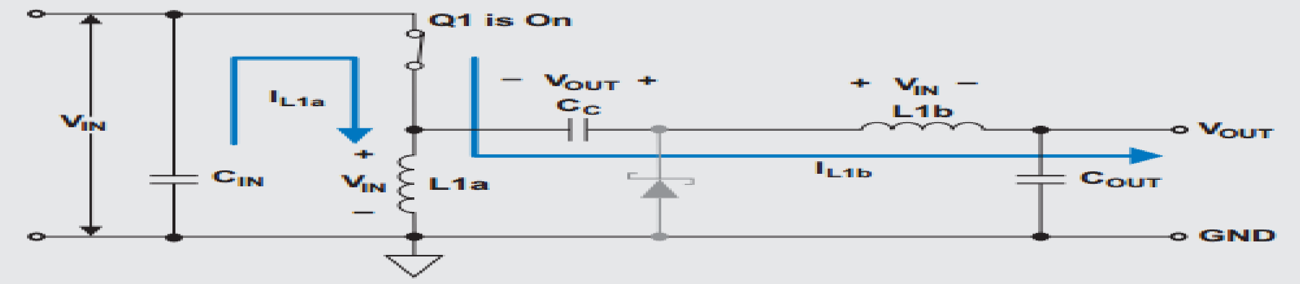
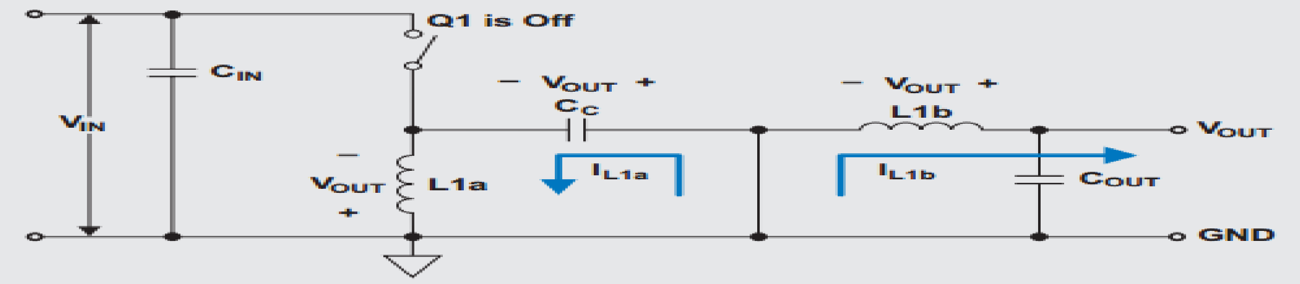


Fig. 5 Schematic of a Zeta Converter

Basic Operation is described in Fig. 5, shows a simple circuit diagram of a ZETA converter is shown, consisting of an input capacitor, C_{IN}; an output capacitor, C_{OUT}; coupled inductors L_{1a} and L_{1b}; an AC coupling capacitor, C_C; a power PMOS FET, Q1; and a diode, D1. Fig. 6 shows the ZETA converter operation in CCM when Q1 is on and when Q1 is off. To understand the voltages at the various circuit nodes, it is important to analyze the circuit at DC when both switches are off. Capacitor C_C will be in parallel with C_{OUT}, so C_C is charged to the output voltage, V_{OUT}, during steady-state CCM. Fig. 6 shows the voltages across L_{1a} and L_{1b} during CCM operation. When Q1 is off, the voltage across L_{1b} must be V_{OUT} since it is in parallel with C_{OUT}. Since C_{OUT} is charged to V_{OUT}, the voltage across Q1 when Q1 is off is $V_{IN} + V_{OUT}$; therefore, the voltage across L_{1a} is $-V_{OUT}$ relative to the drain of Q1. When Q1 is on, capacitor C_C, charged to V_{OUT}, is connected in series with L_{1b}; so the voltage across L_{1b} is $+V_{IN}$, and diode D1 sees $V_{IN} + V_{OUT}$.



(a) When Q1 is on



(b) When Q1 is off

Fig. 6 Converter CCM operation for zeta

1.5 Motivation

Conventional AC-DC converters utilize diode bridge rectifier to rectify the input AC signal. Some limitations are imposed because of using such bridge. Due to charging & discharging of capacitor, current flow into the system becomes discontinuous. This introduces high harmonic current & degrades the power factor.

Duty ratio for conventional zeta converter is,

$$\frac{V_o}{V_{in}} = \frac{D}{(1-D)}$$

Efficiency of conventional zeta topology ranges within 85-90% [48]. Duty ratio for conventional buck converter is, $\frac{V_o}{V_{in}} = D$. In buck converter to get low output voltage extremely low duty cycle is needed. In extremely low duty cycle (5-20%) overall efficiency of the system decreases, fast & expensive comparator circuit is necessary to generate desired duty ratio, designing stable control system becomes difficult as it imposes obstacles in transient response [47, 49, 50].

1.6 Thesis Outline

An alternative topology of AC-DC zeta converter has been proposed to increase the overall power quality. The proposed topology is a two stage switched inductor based zeta converter with duty ratio,

$$\frac{V_o}{V_{in}} = \frac{D}{2(1-D)}$$

We have also proposed a DC-DC converter, an alternative DC-DC zeta converter topology to increase efficiency over 90%.

In chapter-2, a DC-DC switched capacitor buck converter proposed in has been discussed. Circuit operation for both half cycle has been shown. CCM DC steady state analysis and AC small signal analysis has been done. The relevant simulation results have been shown. MATLAB has used to obtain output voltage transfer function.

Then, a DC-DC switched inductor buck converter proposed in has been simulated using PSIM. Like the previous circuit, an output voltage transfer function has been obtained. Mathematical model is also obtained.

In chapter 3, a DC-DC zeta converter proposed in and a modified version of zeta converter has been simulated. A comparison between conventional zeta converter and modified zeta converter has been discussed in details.

In chapter 4, a AC-DC two stage switched inductor has been simulated. The conventional circuit and modified circuit has been compared by considering quality factors.

In chapter 5, a published work on DC-DC buck modified topology has been briefly introduced.

Chapter 2

DC-DC Buck Converter Design and Analysis

2.1 Introduction

DC-DC buck converter works to step down a supply voltage. The output to input voltage conversion ratio for a DC-DC buck converter is D, where D refers to the duty ratio. The switch shown below, may be implemented using MOSFET, BJT or IGBT technology. The switch turns on or off according to the duty ratio, D. Thus, the desired output voltage can be achieved by tuning the duty ratio.

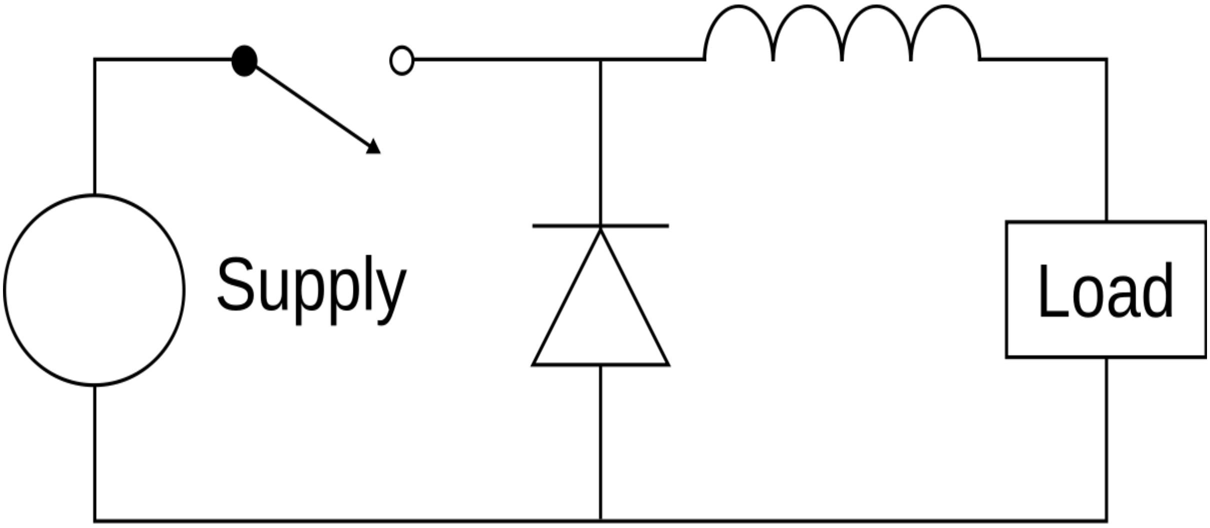


Fig. 7 Basic Buck Converter

In this chapter, we have shown two modified versions of the conventional DC-DC buck topologies with detailed mathematical analysis and simulation result. One of the modified version is based on switched inductor and the other one is based on switched capacitor. MATLAB is used in some parts of mathematical modelling. Whereas, the PSIM is used for circuit simulation.

2.2 DC-DC Switched Capacitor Buck Converter

The DC-DC switched capacitor buck converter circuit is made up of a switched capacitor branch, an input inductor an output inductor and an output capacitor. The capacitors C_1 and C_2 and the diodes D_1, D_2 and D_3 make the switched capacitor branch. The voltage across both the capacitors of the switched capacitor branch are equal during both the on and off time of the MOSFET. The load is simulated using the resistor R. The circuit is shown in Fig 8.

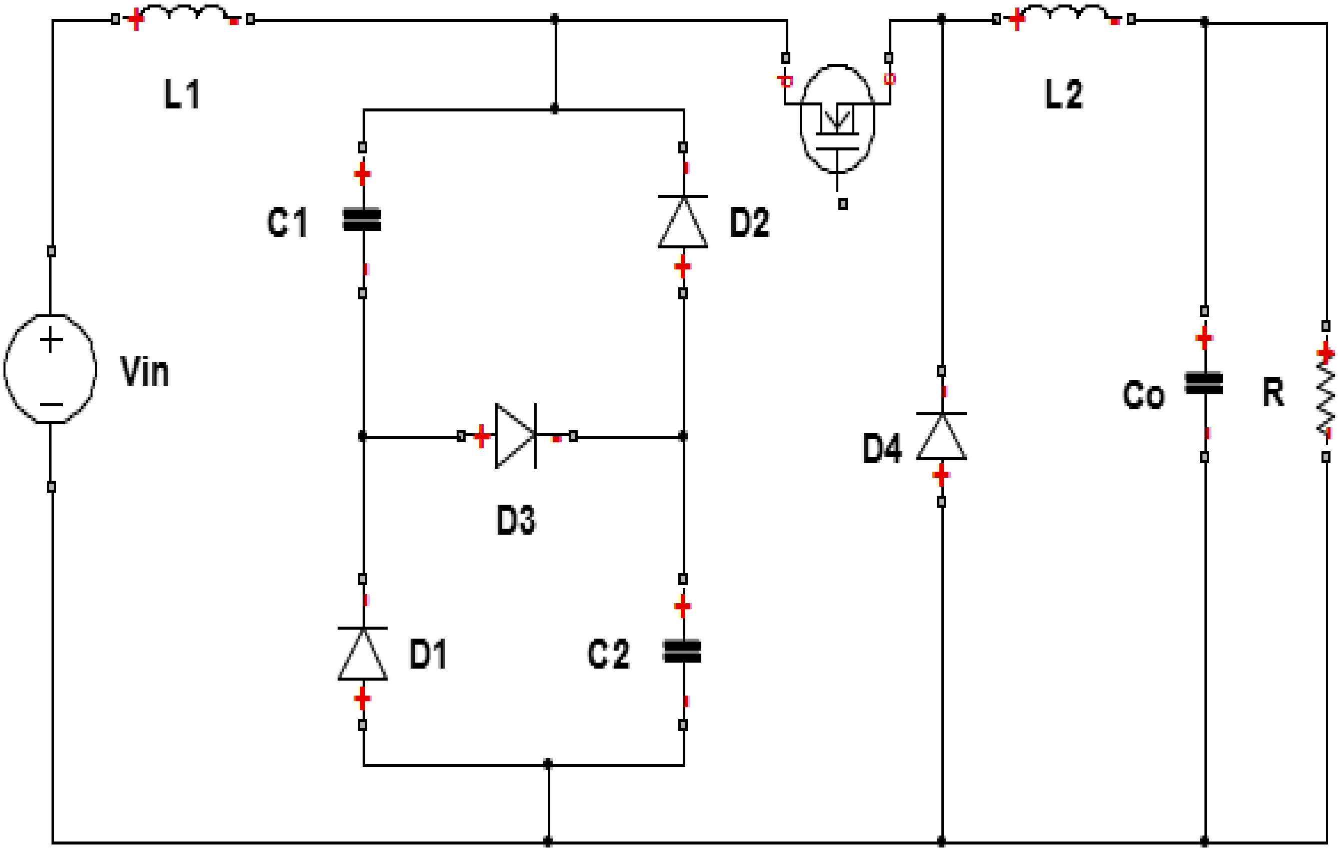


Fig. 8 DC-DC Switched Capacitor Buck Converter

2.2.1 Operation Analysis

The circuit operation during on time of the MOSFET is shown in Fig. 9. During this time, current flows through the MOSFET. The diodes D_1 and D_2 of the switched capacitor branch are on and the diodes D_3 and D_4 are off. So, the capacitors C_1, C_2 of the switched capacitor branch are connected in parallel. So, they get discharged in parallel during this time.

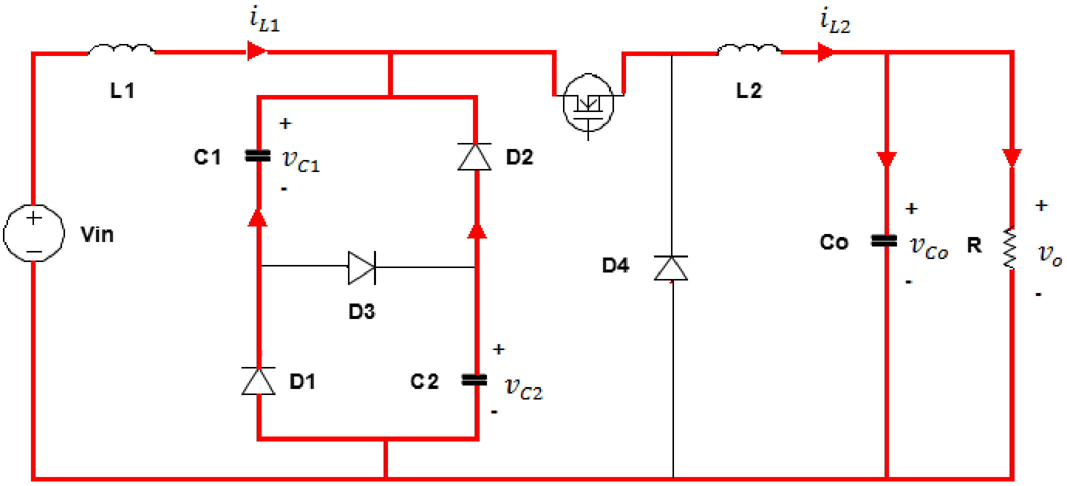


Fig. 9 On time operation of DC-DC Switched Capacitor Buck Converter

The circuit operation during off time of the MOSFET is shown in Fig. 10. During this time, current does not flow through the MOSFET. The diodes D_1 and D_2 of the switched capacitor branch are off. But, the diode D_3 is operates. So, the capacitors C_1, C_2 of the switched capacitor branch are in series connected. So, they are charged series during this time.

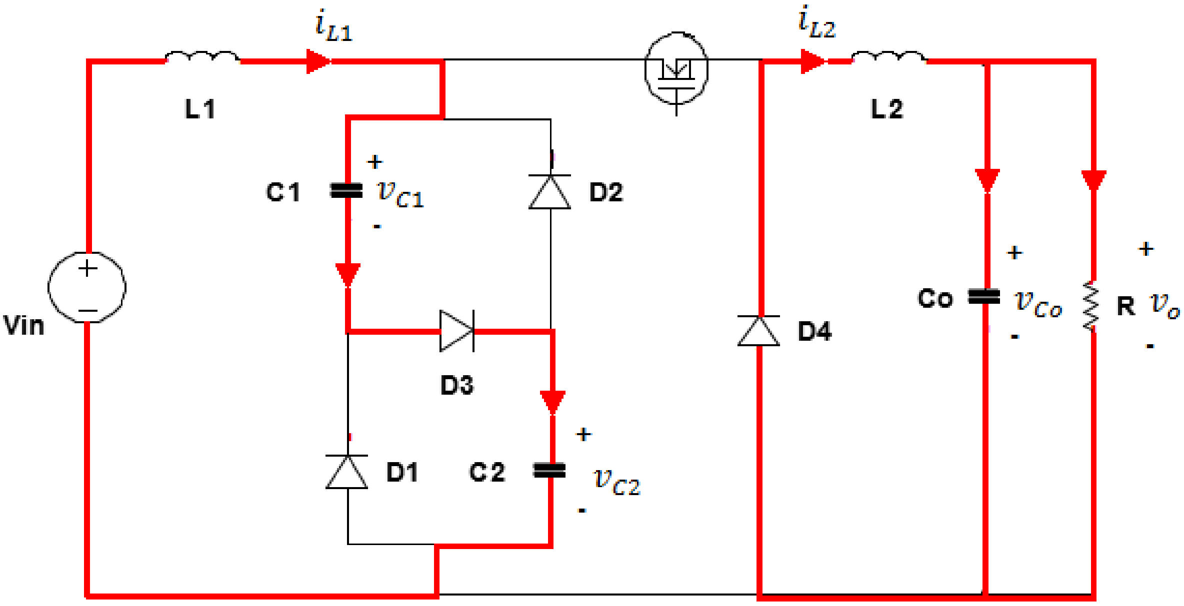


Fig. 10 Off time operation of DC-DC Switched Capacitor Buck Converter

2.2.2 CCM DC Steady State Analysis

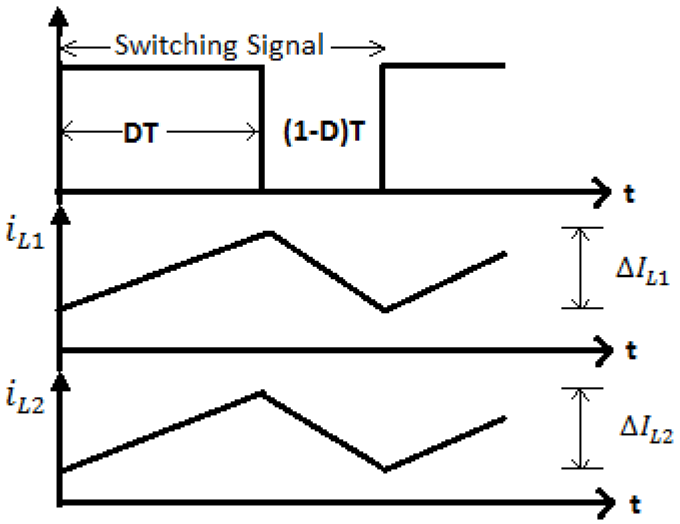


Fig. 11 Inductor current waveform in switched capacitor Buck Converter

During on time, the inductor current increases. So, the curves during on time have positive slope as shown in Fig. 11.

$$L_1 \frac{\Delta I_{L1}}{t_{on}} = V_{in} - V_{C1}$$

$$\text{Or, } \Delta I_{L1} = \frac{DT}{L_1}(V_{in} - V_{C1}) \tag{1}$$

$$L_2 \frac{\Delta I_{L2}}{t_{on}} = V_{C1} - V_{CO}$$

$$\text{Or, } \Delta I_{L2} = \frac{DT}{L_2}(V_{C1} - V_{CO}) \tag{2}$$

During off time

$$L_1 \frac{\Delta I_{L1}}{t_{off}} = 2V_{C1} - V_{in}$$

$$\text{Or, } \Delta I_{L1} = \frac{(1-D)T}{L_1}(2V_{C1} - V_{in}) \tag{3}$$

$$L_2 \frac{\Delta I_{L2}}{t_{off}} = -V_{Co}$$

$$\text{Or, } \Delta I_{L2} = \frac{(1-D)T}{L_2}(-V_{Co}) \tag{4}$$

From equations (1), (2), (3) and (4), it is found that

$$\frac{V_{C2}}{V_{in}} = \frac{D}{2-D}$$

Or, $\frac{\mathrm{V_o}}{\mathrm{V_{in}}} = \frac{\mathrm{D}}{2-\mathrm{D}}$ $[\because \mathrm{V_{CO}} = \mathrm{V_o}]$

2.2.3 AC Small Signal Analysis

The state-space equations of the switched capacitor buck converter for the on and off time of the switch can be written as

$$\mathrm{L_1}\frac{\mathrm{di_{L1}}}{\mathrm{dt}} = \mathrm{D}(\mathrm{v_{in}} - \mathrm{v_{C1}}) + (1-\mathrm{D})(2\mathrm{v_{C1}} - \mathrm{v_{in}}) \tag{5}$$

$$\mathrm{L_2}\frac{\mathrm{di_{L2}}}{\mathrm{dt}} = \mathrm{D}(\mathrm{v_{C1}} - \mathrm{v_{co}}) + (1-\mathrm{D})(-\mathrm{v_{Co}}) \tag{6}$$

$$\mathrm{C_1}\frac{\mathrm{dv_{C1}}}{\mathrm{dt}} = \mathrm{D}\frac{\mathrm{i_{L2}} - \mathrm{i_{L1}}}{2} + (1-\mathrm{D})\mathrm{i_{L1}} \tag{7}$$

$$\mathrm{C_o}\frac{\mathrm{dv_{Co}}}{\mathrm{dt}} = \mathrm{D}(\mathrm{i_{L2}} - \frac{\mathrm{v_{co}}}{\mathrm{R}}) + (1-\mathrm{D})(i_{L2} - \frac{v_{Co}}{R}) \tag{8}$$

When D=1 the circuit in Fig. operates at on time and the opposite is for off time.

The state space matrices for on time are found as

$$A_{on} = \begin{bmatrix} 0 & 0 & -1/L1 & 0 \\ 0 & 0 & 1/L2 & -1/L2 \\ -1/(2*C1) & 1/(2*C1) & 0 & 0 \\ 0 & 1/Co & 0 & -1/(R*Co) \end{bmatrix}$$

$$B_{on} = \begin{bmatrix} 1/L1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad C_{on} = [0\ 0\ 0\ 1] \quad D_{on} = [0\ 0\ 0\ 0]$$

The state space matrices for off time operation are written below

$$A_{off} = \begin{bmatrix} 0 & 0 & -2/L1 & 0 \\ 0 & 0 & 0 & 1/L2 \\ 1/C1 & 0 & 0 & 0 \\ 0 & -1/Co & 0 & -1/(R*Co) \end{bmatrix}$$

$$B_{off} = \begin{bmatrix} -1/L1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad C_{off} = [0\ 0\ 0\ 1] \quad D_{off} = [0\ 0\ 0\ 0]$$

The averaged matrices for the steady-state equations are found from,

$$\mathrm{A} = \mathrm{A_{on}D} + \mathrm{A_{off}}(1 - \mathrm{D})$$

$$\mathrm{B} = \mathrm{B_{on}D} + \mathrm{B_{off}}(1 - \mathrm{D})$$

$$\mathrm{C} = \mathrm{C_{on}D} + \mathrm{C_{off}}(1 - \mathrm{D})$$

$$\mathrm{D_e} = \mathrm{D_{on}D} + \mathrm{D_{off}}(1 - \mathrm{D})$$

$$\mathrm{E} = (\mathrm{A_{on}} - \mathrm{A_{off}})\mathrm{X} + (\mathrm{B_{on}} - \mathrm{B_{off}})\mathrm{V_{in}} \quad ;\ \text{where}\ \mathrm{X} = -\mathrm{A^{-1}BV_{in}}$$

$$\mathrm{F} = (\mathrm{C_{on}} - \mathrm{C_{off}})\mathrm{X} + (\mathrm{D_{on}} - \mathrm{D_{off}})\mathrm{V_{in}}$$

Control to output voltage transfer function can be found by,

$$\mathrm{G_1(s)} = \mathrm{C(sI - A)^{-1}E + F}$$

where I is an identity matrix.

The transfer function is found using MATLAB, is written below

$$\mathrm{G_1(s)} = \frac{\widetilde{\mathrm{v_o}}(\mathrm{s})}{\tilde{\mathrm{d}}\,(\mathrm{s})} = \frac{\mathrm{a_1s^2 + a_2s + a_3}}{\mathrm{b_1s^4 + b_2s^3 + b_3s^2 + b_4s + b_5}}$$

Here, $\widetilde{v_o}(s)$ is small signal perturbation of output voltage and $\tilde{d}(s)$ is small signal perturbation of duty cycle.

$$\mathrm{a_1} = -\,\mathrm{V_{in}} * \frac{2 * \mathrm{C1} * \mathrm{L1} * \mathrm{R} - 3 * \mathrm{D} * \mathrm{C1} * \mathrm{L1} * \mathrm{R}}{\mathrm{C1} * \mathrm{C2} * \mathrm{L1} * \mathrm{L2} * \mathrm{R} * (3 * \mathrm{D^2} - 8 * \mathrm{D} + 4)}$$

$$\mathrm{a_2} = \frac{\mathrm{D^2} * \mathrm{V_{in}}}{\mathrm{C1} * \mathrm{C2} * \mathrm{L2} * \mathrm{R} * (3 * \mathrm{D^2} - 8 * \mathrm{D} + 4)}$$

$$\mathrm{a_3} = -\frac{\mathrm{V_{in}} * (-18 * \mathrm{R} * \mathrm{D^3} + 33 * \mathrm{R} * \mathrm{D^2} - 20 * \mathrm{R} * \mathrm{D} + 4 * \mathrm{R})}{\mathrm{C1} * \mathrm{C2} * \mathrm{L1} * \mathrm{L2} * \mathrm{R} * (3 * \mathrm{D^2} - 8 * \mathrm{D} + 4)}$$

$$\mathrm{b_1} = 1 \quad \mathrm{b_2} = \frac{1}{\mathrm{C2} * \mathrm{R}}$$

$$\mathrm{b_3} = \frac{-(2*\mathrm{C1}*\mathrm{L1}*\mathrm{R} - 4*\mathrm{C2}*\mathrm{L2}*\mathrm{R} + \mathrm{D}\hat{}2*\mathrm{C2}*\mathrm{L1}*\mathrm{R} - 3*\mathrm{D}\hat{}2*\mathrm{C2}*\mathrm{L2}*\mathrm{R} - 4*\mathrm{D}*\mathrm{C1}*\mathrm{L1}*\mathrm{R} + 8*\mathrm{D}*\mathrm{C2}*\mathrm{L2}*\mathrm{R})}{2*\mathrm{C1}*\mathrm{C2}*\mathrm{L1}*\mathrm{L2}*\mathrm{R}}$$

$$b_4 = \frac{4 * L2\ -\ 8 * D * L2\ -\ D^2 * L1\ +\ 3 * D^2 * L2}{2 * C1 * C2 * L1 * L2 * R}$$

$$b_5 = -\frac{-\ 6 * R * D^3 +\ 19 * R * D^2 -\ 16 * R * D\ +\ 4 * R}{2 * C1 * C2 * L1 * L2 * R}$$

Table 1 Circuit Parameters of DC-DC Switched Capacitor Buck Converter

Circuit parameter	Values
V_{in}	100V
L1/L2	5uH/200uH
C1/C2	5uF
Co	220uF
R	10 ohm
Switching frequency	10kHz
V_m	1

Using the values shown in Table 1, the control to output voltage transfer function is found as

$$G_1(s) = \frac{-4e08\ s^2 + 4e13\ s}{s^4 + 1000\ s^3 + 3.738e11\ s^2 + 3.738e14\ s}$$

Poles of the above transfer function $G_1(s)$ are 0, (±)(105)* 6.1135i, -1000. The zeros are found 0, 105. DC gain is .1070 dB. Gain margin is -19dB at 6.11*105 rad/s and phase margin is 9.39^0 at 6.11*105 rad/s

So, the uncompensated system is marginally stable and the closed loop uncompensated system will be unstable.

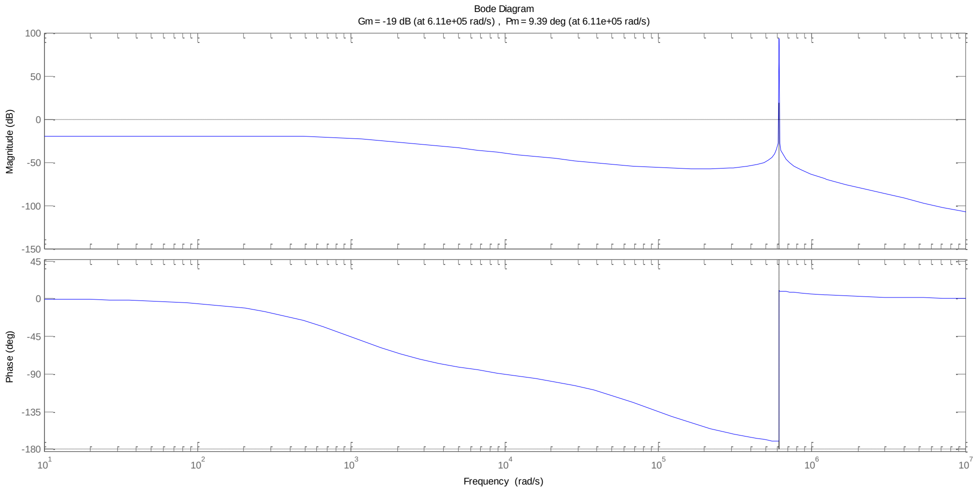


Fig. 12 Bode Plot for DC-DC switched capacitor zeta converter

2.2.4 Simulation Result

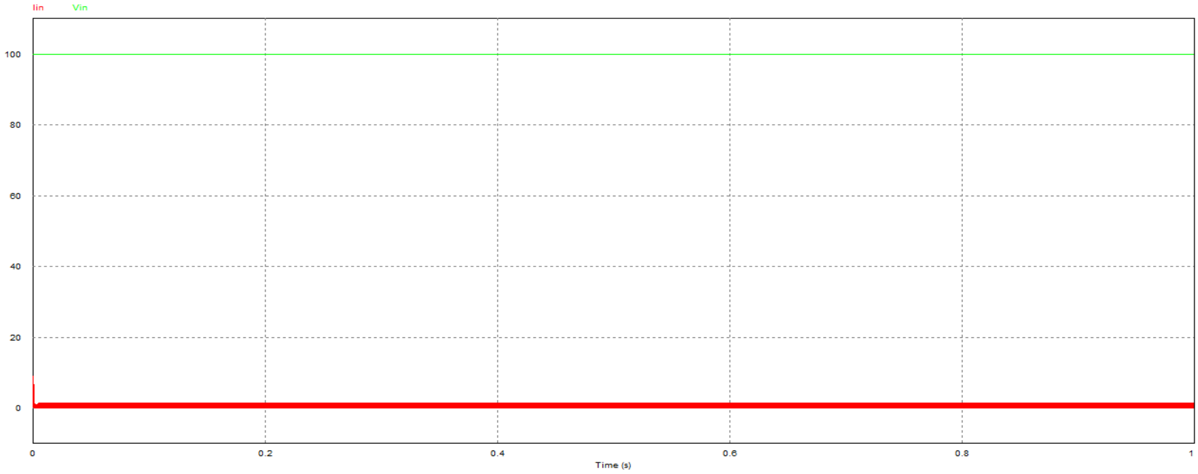


Fig. 13 Input signal for switched capacitor zeta converter

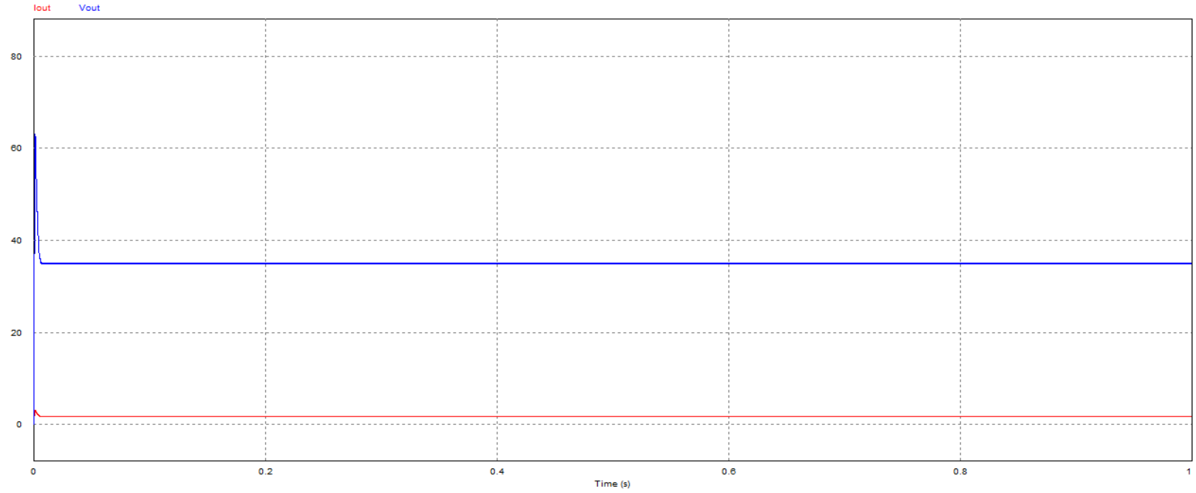


Fig. 14 Output signal for switched capacitor zeta converter

According to the simulation done using PSIM software, a step down conversion system has been developed. The system provides a lower output (nominal 37 volts) for an input DC signal (100 volts) at a duty ratio of 0.4. The output current doesn’t necessarily become zero, so this imposes some complication during system transient because of harmonic effects.

2.3 DC-DC Switched Inductor Buck Converter

The DC-DC switched inductor buck converter circuit is made up of a switched inductor branch, a MOSFET and an output capacitor Co. The inductors L_1 and L_2 and the diodes D_1, D_2 make the switched inductor branch. The current through both the inductors of the switched inductor branch are equal. So, the voltage-drop across the inductors during both the on and off time of the MOSFET are equal. The load is simulated using the resistor R. The circuit is shown in Fig.15.

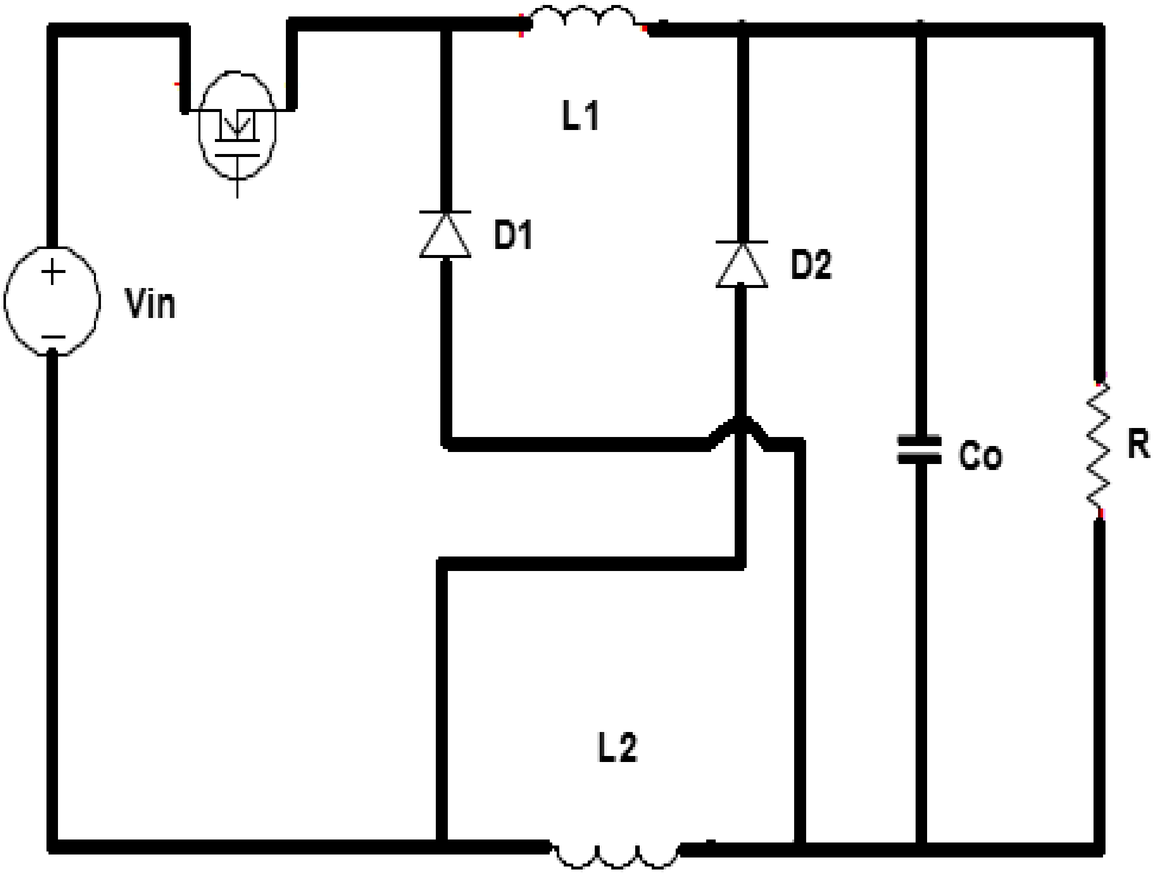


Fig. 15 DC-DC switched inductor Buck Converter

2.3.1 Operation Analysis

The on-time operation is shown in Fig. 16. During this time, the MOSFET switch is on. The inductors L_1 and L_2 conducts in series because the diodes D_1 and D_2 are off. So, the inductors are charged in series.

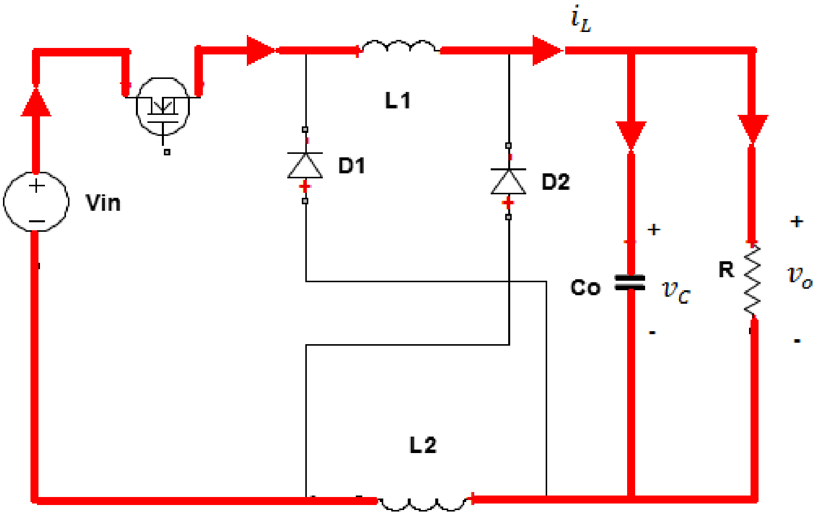


Fig. 16 On time operation of a DC-DC switched inductor Buck Converter

The off-time operation is shown in Fig. 17. During this time, the MOSFET switch is off. The inductors L_1 and L_2 conducts in parallel because the diodes D_1 and D_2 are on. So, the inductors are discharged in parallel.

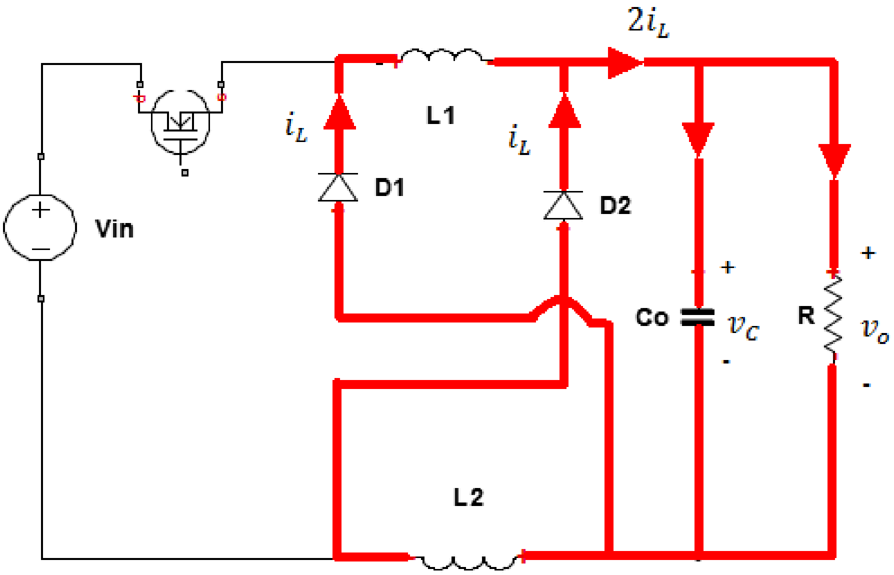


Fig. 17 Off time operation of a DC-DC switched inductor Buck Converter

2.3.2 CCM DC Steady State Analysis

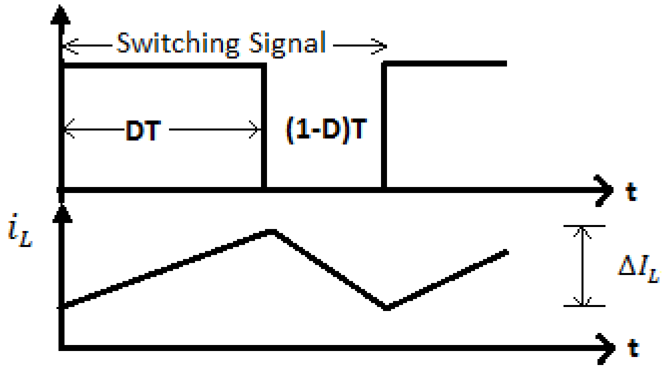


Fig. 18 Inductor Current waveform for DC-DC switched inductor buck converter

During on time inductor current increases

$$\frac{\Delta I_L}{t_{on}} = \frac{1}{2L}(V_{in} - V_C)$$

$$\text{Or, } +\Delta I_L = \frac{DT}{2L}(V_{in} - V_C) \tag{9}$$

During off time inductor current decreases,

$$\frac{\Delta I_L}{t_{off}} = -\frac{V_C}{L}$$

$$\text{Or, } \Delta I_L = \frac{(1-D)T}{L}(-V_C) \tag{10}$$

From equation (9) and (10), we find,

$$\frac{V_C}{V_{in}} = \frac{D}{2-D}$$

$$\text{Or, } \frac{V_O}{V_{in}} = \frac{D}{2-D} \quad [\because V_O = V_C]$$

2.3.3 AC Small Signal Analysis

The state-space equations of the switched inductor buck converter for the on and off time of the switch can be written as

$$\frac{di_L}{dt} = D\frac{(v_{in} - v_C)}{2L} + (1-D)(-v_C/L) \tag{11}$$

$$\frac{dv_C}{dt} = D\left(\frac{i_L}{C} - \frac{v_C}{R*C}\right) + (1-D)\left(\frac{2*i_L}{C} - \frac{v_C}{R*C}\right) \tag{12}$$

When D=1 the circuit in Fig. operates at on time and the opposite is for off time.

The state space matrices for on time are found as

$$A_{on} = \begin{bmatrix} 0 & -1/(2L) \\ 1/C & -1/(RC) \end{bmatrix} \quad B_{on} = \begin{bmatrix} 1/(2L) \\ 0 \end{bmatrix}$$

$C_{on} = [0\ 0\ 0\ 1]$ $\qquad D_{on} = [0\ 0\ 0\ 0]$

The state space matrices for off time operation are written below

$$A_{off} = \begin{bmatrix} 0 & -1/L \\ 2/C & -1/(RC) \end{bmatrix} \quad B_{off} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

$C_{off} = [0\ 0\ 0\ 1]$ $\qquad D_{off} = [0\ 0\ 0\ 0]$

The averaged matrices for the steady-state equations are found from,

$\mathrm{A} = \mathrm{A_{on}D} + \mathrm{A_{off}}(1 - \mathrm{D})$

$\mathrm{B} = \mathrm{B_{on}D} + \mathrm{B_{off}}(1 - \mathrm{D})$

$\mathrm{C} = \mathrm{C_{on}D} + \mathrm{C_{off}}(1 - \mathrm{D})$

$\mathrm{D_e} = \mathrm{D_{on}D} + \mathrm{D_{off}}(1 - \mathrm{D})$

$\mathrm{E} = (\mathrm{A_{on}} - \mathrm{A_{off}})\mathrm{X} + (\mathrm{B_{on}} - \mathrm{B_{off}})\mathrm{V_{in}}$; where $\mathrm{X} = -\mathrm{A}^{-1}\mathrm{BV_{in}}$

$\mathrm{F} = (\mathrm{C_{on}} - \mathrm{C_{off}})\mathrm{X} + (\mathrm{D_{on}} - \mathrm{D_{off}})\mathrm{V_{in}}$

Control to output voltage transfer function can be found by,

$\mathrm{G_1(s)} = \mathrm{C}(s\mathrm{I} - \mathrm{A})^{-1}\mathrm{E} + \mathrm{F}$

where I is an identity matrix.

The transfer function is found using MATLAB, is written below

$$G_1(s) = \frac{\widetilde{v_o}(s)}{\tilde{d}\,(s)} = \frac{a_1 s + b_1}{a_2 s^2 + b_2 s + c_2}$$

Here, $\widetilde{v_o}(s)$ is small signal perturbation of output voltage and $\tilde{d}(s)$ is small signal perturbation of duty cycle.

Where $a_1 = -\frac{\mathrm{DVin}}{\mathrm{CR(D-2)^2}}$, $b_1 = \frac{Vin(RD^2 - 4RD + 4R)}{CLR(D-2)^2}$

$a_2 = 1$, $b_2 = \frac{1}{RC}$, $c_2 = \frac{Vin(RD^2 - 4RD + 4R)}{CLR(D-2)^2}$

Table 2 Circuit Parameters of DC-DC Switched Inductor Buck Converter

Circuit parameter	Values
V_{in}	12V
Vo	3V
Duty cycle, D	0.4
L	100uH
C	200uF
Load, R	10 ohm
ΔV_C	.05V
ΔI_L	.5A
Switching frequency	10kHz
V_m	1V

Using the parameters shown in table (2), the control to output voltage small signal transfer function $G_1(s)$ is

$$G_1(s) = \frac{-2500\,s\ +\ 2.382 * 10^9}{s^2\ +\ 680.6\,s\ +\ 1.945 * 10^8}$$

From MATLAB, different parameters of this transfer function are found as

Poles: 10^3 *(-0.500 ±7.4958i)

zeros: 45000, DC gain = 10.667

Gain margin = -11.3 dB at $2.9036*10^4$rad/s, Phase margin = -2.2215^0 at $5.0795*10^4$

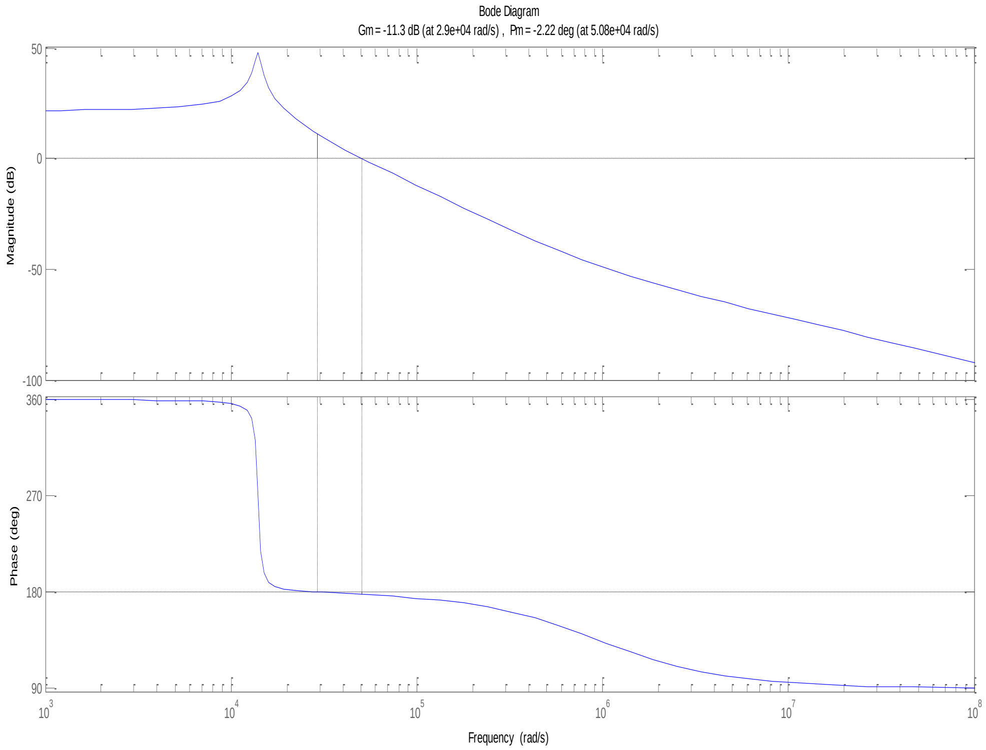


Fig. 19 Bode plot for switched inductor buck converter

So, the uncompensated system is stable as the 2 poles are in the left half plane. But the closed loop uncompensated system will be unstable. The bode plot of the transfer function $G_1(s)$ is shown in Fig. 19.

2.3.4 Simulation

The simulation is done using PSIM using the parameters shown in Table 2. The input voltage is 12V dc. The input current has average value of 1.5A. The duty ratio is 0.4. So, the average output voltage is 6.2V dc and the average output current is 0.62A. The input voltage and input current waveforms are shown in Fig. 20. The output voltage and current waveforms are shown in Fig. 21.

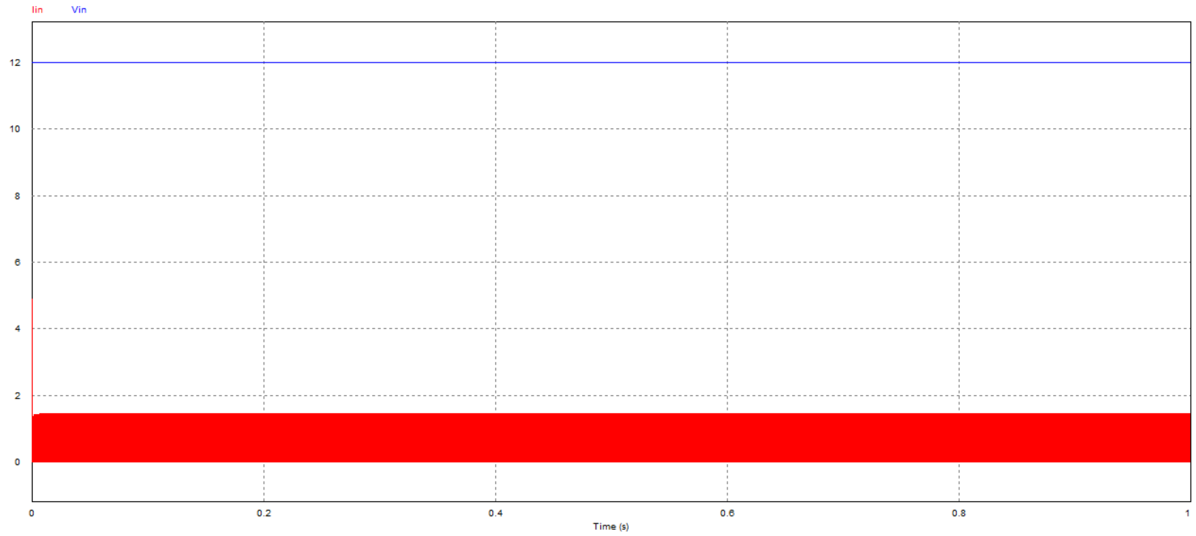


Fig. 20 Input signal for switched inductor buck converter

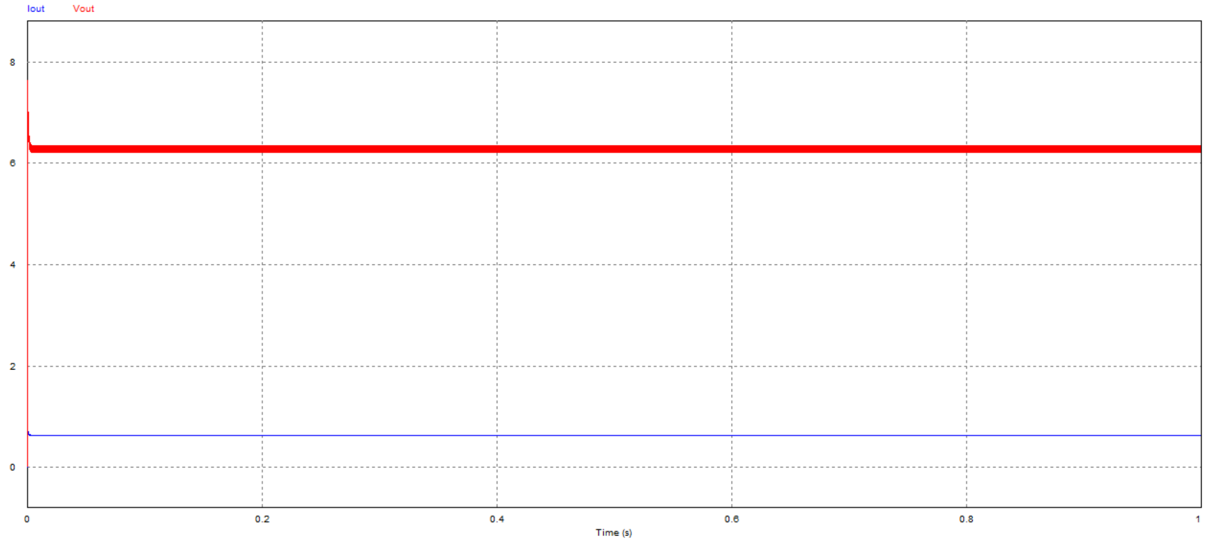


Fig. 21 Output signal for switched inductor buck converter

Chapter 3

DC-DC Zeta Converter Design and Analysis

3.1 Introduction

The zeta converter is a type of buck-boost converter. So, it can step up or step down the supply voltage according to the duty ratio. The output voltage is always positive. It is fourth order converter as there are four energy storing device. The output voltage has less ripple. The conventional zeta converter is shown in Fig. 22.

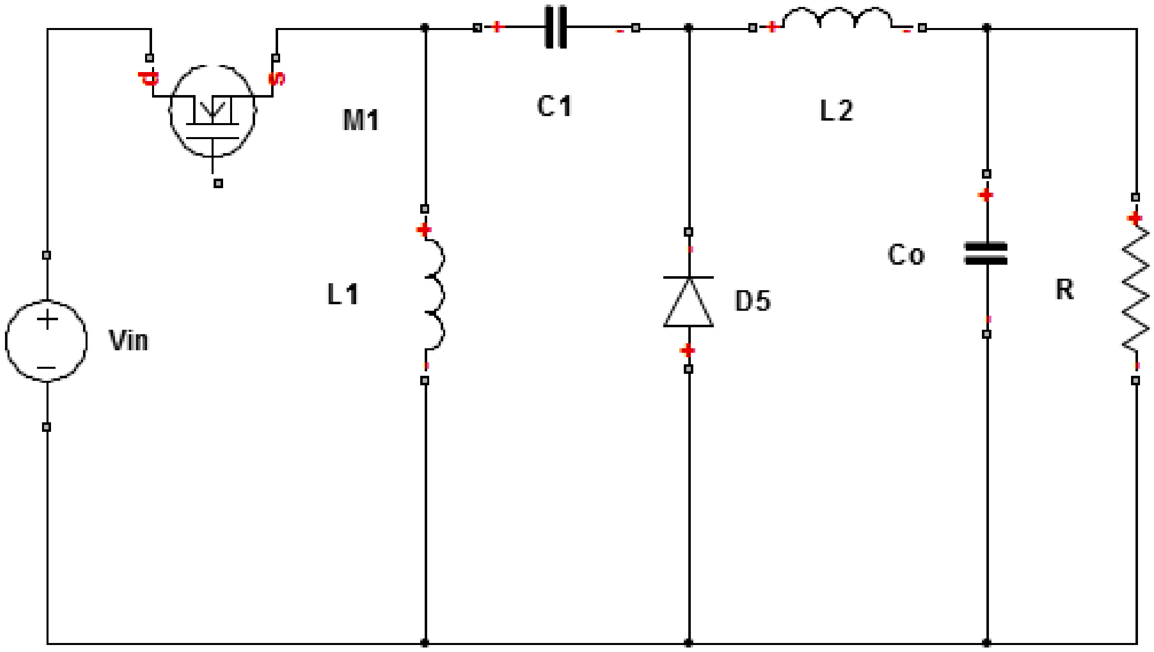


Fig. 22 Conventional Zeta Converter

In this chapter, a modified version of the zeta converter and a switched inductor zeta converter topology are presented with detailed mathematical analysis and simulation result. In the modified version of the zeta converter, the inductor L_2 of the conventional zeta converter is replaced with a step up switched inductor. The other one circuit is based on switched inductor which is proposed in . MATLAB is used in some parts of mathematical modelling. Whereas, the PSIM was used for circuit simulation.

3.2 Modified DC-DC Zeta Converter

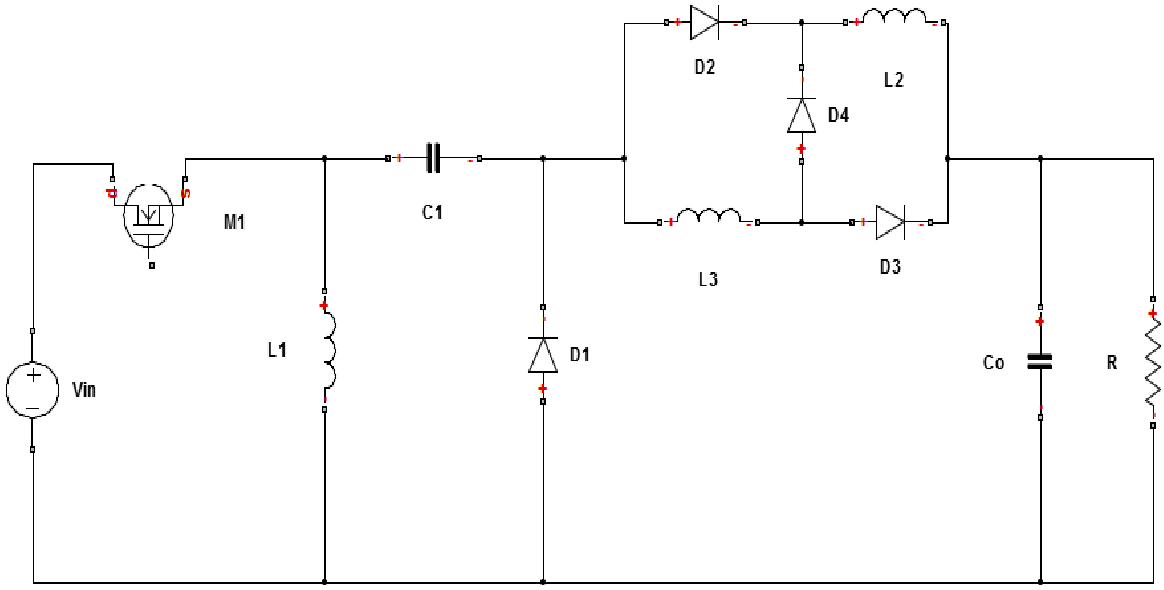


Fig. 23 Schematic of modified DC-DC zeta converter

The modified zeta circuit is made up of a switched inductor branch, an inductor L1, and an output capacitor Co. The switched inductor branch is made up of inductors L2 and L3 and diodes D2, D3 and D4. The inductors L2 and L3 have equal value.

3.2.1 Operation Analysis

During the on time, the MOSFET switch is on. The L_2 and L_3 of the switched inductor branch are connected in parallel. So, they are charged during this time as the diodes D_2 and D_3 are conducting. The inductor L_1 is also charged during this time. The on time operation is shown in Fig. 24.

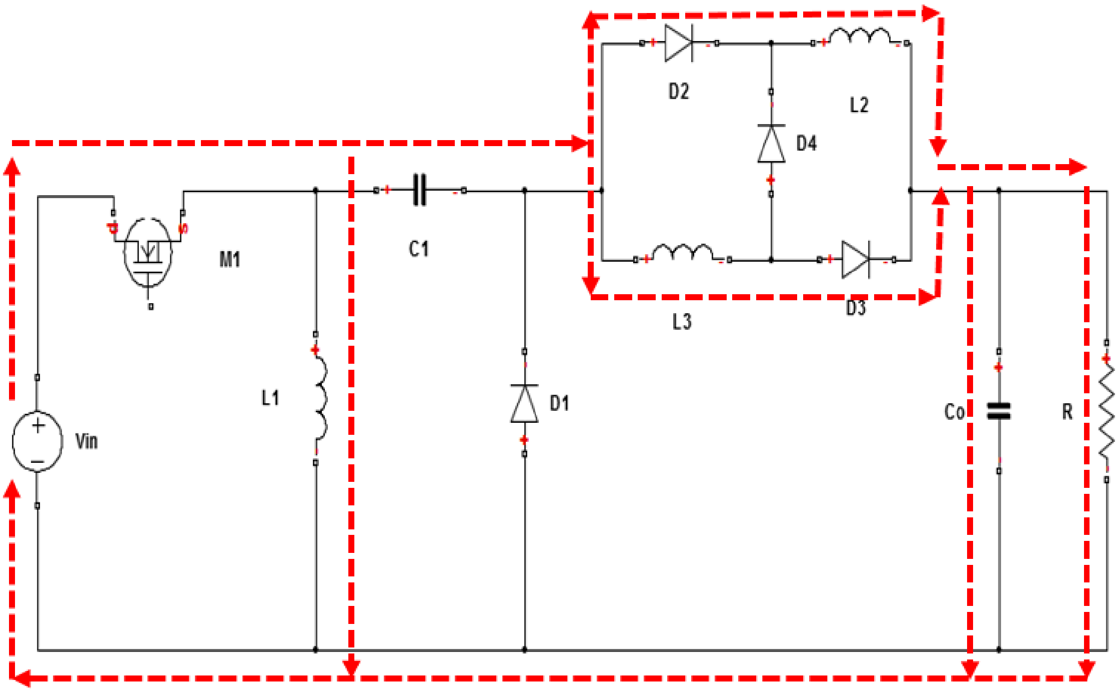


Fig. 24 On time operation of the modified DC-DC zeta converter

The off time operation is shown in Fig. 25. The L_2 and L_3 of the switched inductor branch are connected in series. So, they are discharged during this time as the diode D_4 is on. The inductor L_1 is also discharged during this time.

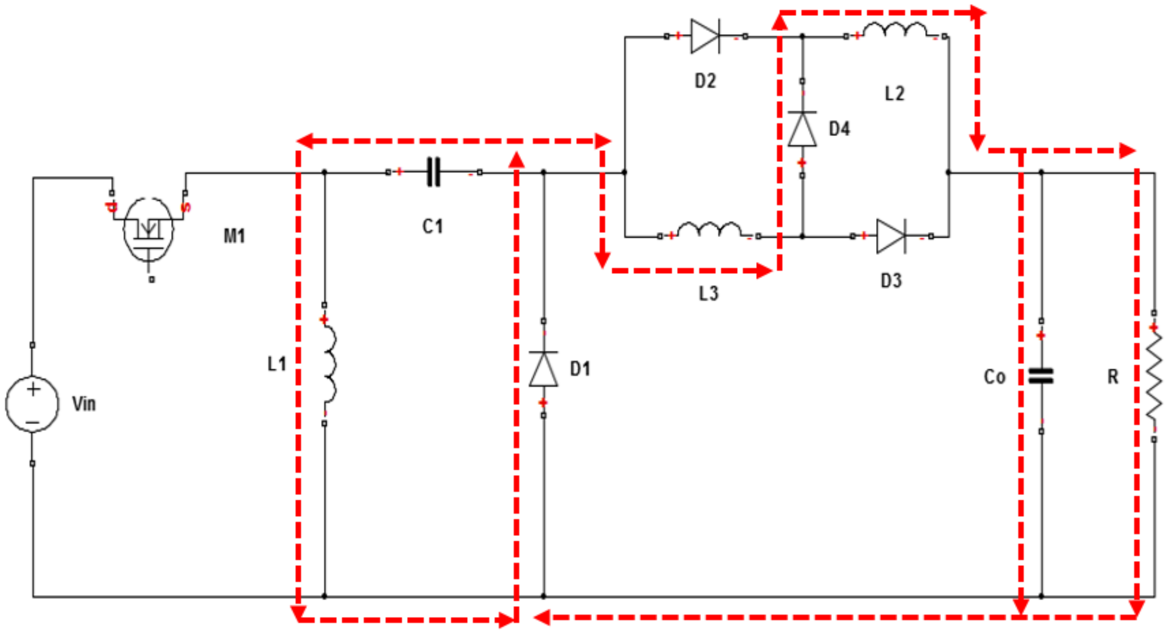


Fig. 25 Off time operation of the modified DC-DC zeta converter

3.2.2 CCM DC Steady State Analysis

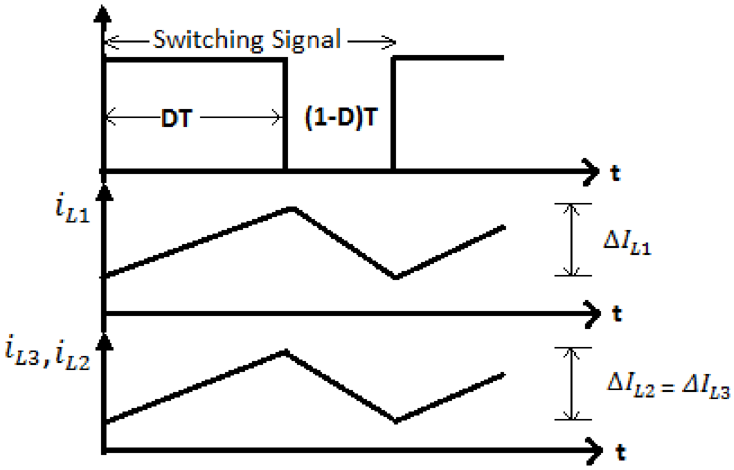


Fig. 26 Inductor Current waveform for modified zeta converter

During on time

$$L_1 \frac{\Delta I_{L1}}{t_{on}} = V_{in}$$

$$\text{Or, } \Delta I_{L1} = \frac{DT}{L_1}(V_{in}) \tag{13}$$

$$L_2 \frac{\Delta I_{L2}}{t_{on}} = V_{C1} - V_{CO}$$

$$\text{Or, } \Delta I_{L2} = \frac{DT}{L_2}(V_{C1} - V_{CO}) \tag{14}$$

During off time

$$L_1 \frac{\Delta I_{L1}}{t_{off}} = -V_{C1}$$

$$\text{Or, } \Delta I_{L1} = \frac{(1-D)T}{L_1}(-V_{C1}) \tag{15}$$

$$L_2 \frac{\Delta I_{L1}}{t_{off}} = -V_{CO}$$

$$\Delta I_{L2} = \frac{(1-D)T}{L_2}(-V_{CO}) \tag{16}$$

By equations (13), (14), (15) and (16), the DC steady state equation is found as,

$$\frac{V_O}{V_{in}} = \frac{2D}{1-D^2}$$

3.2.3 AC Small Signal Analysis

The state-space equations of the modified zeta converter for the on and off time of the switch can be written as,

$$L_1 \frac{di_{L1}}{dt} = DV_s - (1-D)(V_{C_1}) \tag{17}$$

$$L_2 \frac{di_{L2}}{dt} = D(v_{C1} - v_{c2}) - \frac{(1-D)V_{C_2}}{2} \tag{18}$$

$$C_1 \frac{dv_{c1}}{dt} = 2Di_{L2} - (1-D)i_{l1} \tag{19}$$

$$C_2\frac{dv_{co}}{dt} = D(i_{L2} - \frac{v_{co}}{R}) + (1-D)(i_{L2} + \frac{v_{co}}{R}) \tag{20}$$

When k=1 the circuit in Fig. operates at on time and the opposite is for off time.

The state space matrices for on time are found as

$$A_{on} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1/L2 & -1/L2 \\ 0 & -1/(C1) & 0 & 0 \\ 0 & 1/Co & 0 & -1/(R*Co) \end{bmatrix}$$

$$B_{on} = \begin{bmatrix} 1/L1 \\ 1/L2 \\ 0 \\ 0 \end{bmatrix} \quad C_{on} = [0\ 0\ 0\ 1] \quad D_{on} = [0\ 0\ 0\ 0]$$

The state space matrices for off time operation are written below

$$A_{off} = \begin{bmatrix} 0 & 0 & -1/L1 & 0 \\ 0 & 0 & 0 & 1/(2*L2) \\ 1/C1 & 0 & 0 & 0 \\ 0 & -1/Co & 0 & -1/(R*Co) \end{bmatrix}$$

$$B_{off} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad C_{off} = [0\ 0\ 0\ 1] \quad D_{off} = [0\ 0\ 0\ 0]$$

The averaged matrices for the steady-state equations are found from,

$\mathrm{A} = \mathrm{A_{on}D} + \mathrm{A_{off}}(1-\mathrm{D})$

$\mathrm{B} = \mathrm{B_{on}D} + \mathrm{B_{off}}(1-\mathrm{D})$

$\mathrm{C} = \mathrm{C_{on}D} + \mathrm{C_{off}}(1-\mathrm{D})$

$\mathrm{D_e} = \mathrm{D_{on}D} + \mathrm{D_{off}}(1-\mathrm{D})$

$\mathrm{E} = (\mathrm{A_{on}} - \mathrm{A_{off}})\mathrm{X} + (\mathrm{B_{on}} - \mathrm{B_{off}})\mathrm{V_{in}}$; where $\mathrm{X} = -\mathrm{A}^{-1}\mathrm{BV_{in}}$

$\mathrm{F} = (\mathrm{C_{on}} - \mathrm{C_{off}})\mathrm{X} + (\mathrm{D_{on}} - \mathrm{D_{off}})\mathrm{V_{in}}$

Control to output voltage transfer function can be found by,

$$G_1(s) = C(sI - A)^{-1}E + F$$

where I is an identity matrix.

The transfer function is found using MATLAB, is written below

$$G_1(s) = \frac{\widetilde{v_o}(s)}{\tilde{d}\,(s)} = \frac{a_1 s^3 + a_2 s^2 + a_3 s + a_4}{b_1 s^4 + b_2 s^3 + b_3 s^2 + b_4 s + b_5}$$

$$a_1 = \frac{V_{in}(4C_1L_1L_2D^2 - 4C_1L_1L_2D)}{C_1C_2L_1L_2R(D - 1)^2(D + 1)}$$

$$a_2 = \frac{V_{in}(C_1L_1R - DC_1L_1R)}{C_1C_2L_1L_2R(D - 1)^2(D + 1)}$$

$$a_3 = \frac{V_{in}(2D^2L1 - 4Dl2 + 12D^2L2 - 8D^3L_1 - 12D^3L_2 + 4D^4L_1 + 4D^4L_2)}{C_1C_2L_1L_2R(D - 1)^2(D + 1)}$$

$$a_4 = \frac{V_{in}(RD^4 - 2RD^3 + 2RD^2 - 2RD + R)}{C_1C_2L_1L_2R(D - 1)^2(D + 1)}$$

$$b_1 = 1$$

$$b_2 = -\frac{2C_1L_1L_2 - 4DC_1L_1L_2}{2C_1C_2L_1L_2R}$$

$$b_3 = \frac{C_1L_1R + 2C_2L_2R + 2D^2C_2L_1R + 2D^2C_2L_2R + DC_1L_1R - 4DC_2L_2R}{2C_1C_2L_1L_2R}$$

$$b_4 = -\frac{2L_2 - 8DL_2 + 2D^2L_1 + 10D^2L_2 - 4D^3L_1 - 4D^3L_2}{2C_1C_2L_1L_2R}$$

$$b_5 = \frac{RD^3 - RD^2 - RD + R}{2C_1C_2L_1L_2R}$$

Table 3 Modified Zeta Converter Simulation Parameters

Circuit parameter	Values
V_{in}	100V
L1/L2	5uH/200uH
C1/C2	5uF
Co	220uF
R	10 ohm
Switching frequency	10kHz
V_m	1

Using the values shown in Table 1, the control to output voltage transfer function is found as

$$\mathrm{G}_1(\mathrm{s}) = \frac{-1.172 * 10^5\, s^3 \;+\; 4.88 * 10^8\, s^2 \;-\; 7.85 * 10^{13}\, s \;+\; 2.6510^{17}}{s^4 \;+\; 62.5\, s^3 \;+\; 5.22 * 10^8\, s^2 \;+\; 3.25 * 10^1\, s \;+\; 4 * 10^{14}}$$

Poles of the above transfer function $G_1(s)$ are (±) (10^4) * 2.2841i, (10^4) * (-0.0031 ± 0.0875i).

The zeros are found 10^4(0.0385± 2.5831i), 10^4(0.3396).

DC gain is 664.0625 dB.

Gain margin is 1.6128 dB at 2.5885e+04 rad/s and phase margin is 51.7233^0 at 2.5465e+04 rad/s

So, the uncompensated open loop system is marginally stable and the closed loop uncompensated system will be unstable. So, a compensator will be required to make the closed loop system stable.

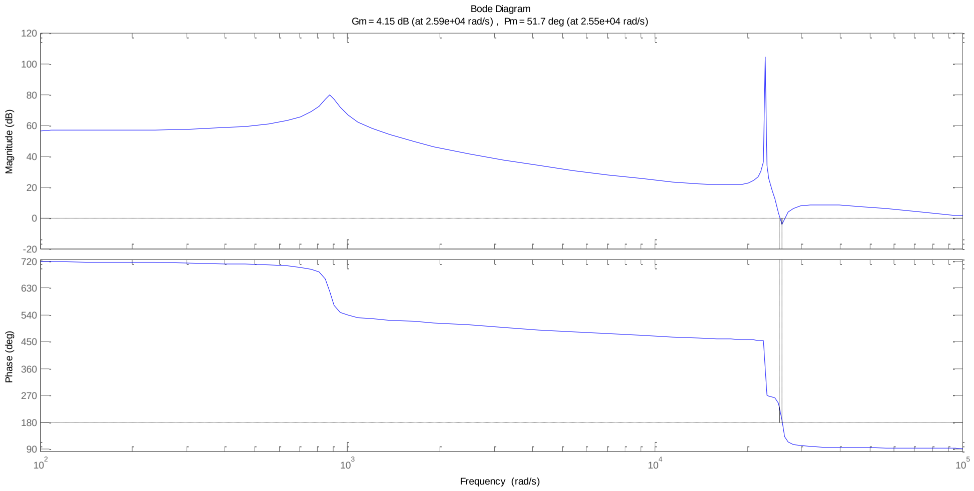


Fig. 27 Bode plot of the modified DC-DC zeta converter

3.2.4 Simulation

The simulation is done using PSIM using the parameters shown in Table 3. The input voltage is 100V dc. The input current has average value of 4.5A. The duty ratio is 0.5. So, the average output voltage is 62V dc and the average output current is 6.2A. The input voltage and input current waveforms are shown in Fig. 28. The output voltage and current waveforms are shown in Fig. 29.

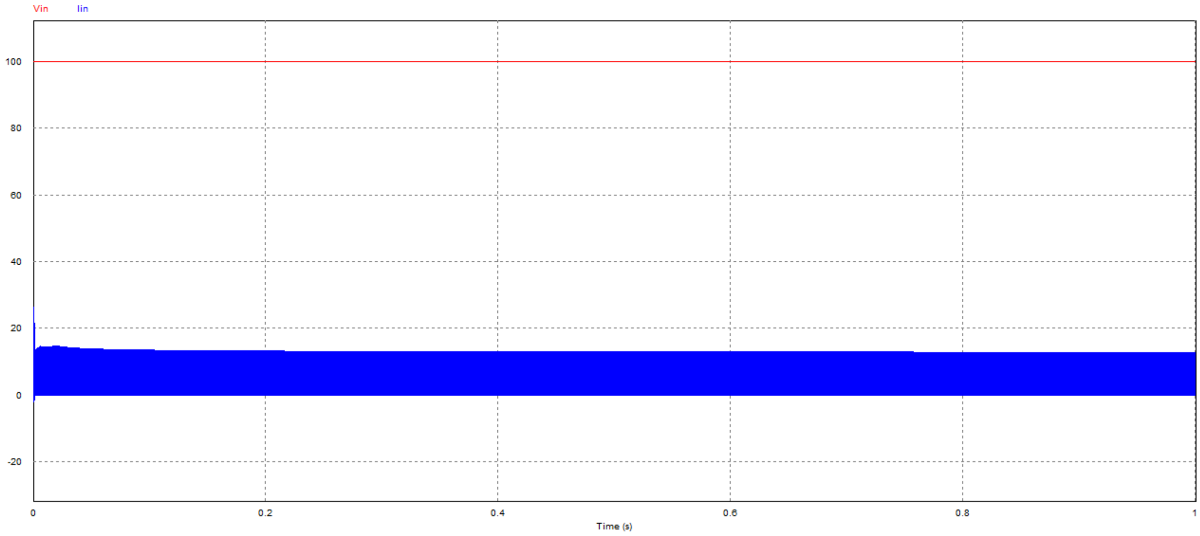


Fig. 28 Input signal for modified zeta converter

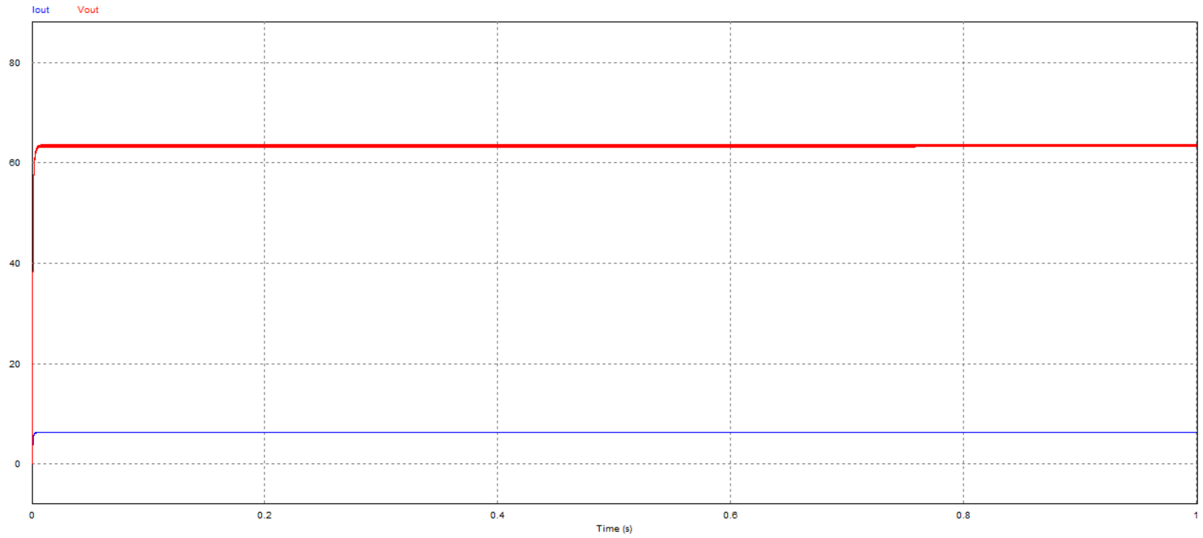


Fig. 29 Output signal for a modified zeta converter

A comparative graph between simulated data and mathematically obtained data is shown in Fig 30. Voltage gain deviation between simulated circuit and the mathematical model is very little.

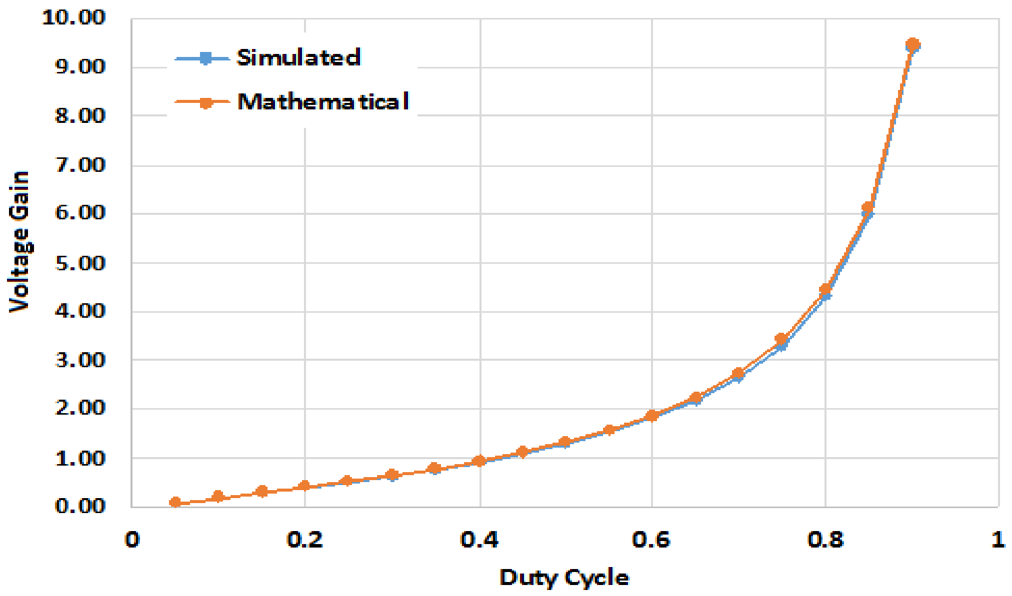


Fig. 30 Voltage gain Vs Duty Cycle for modified zeta converter

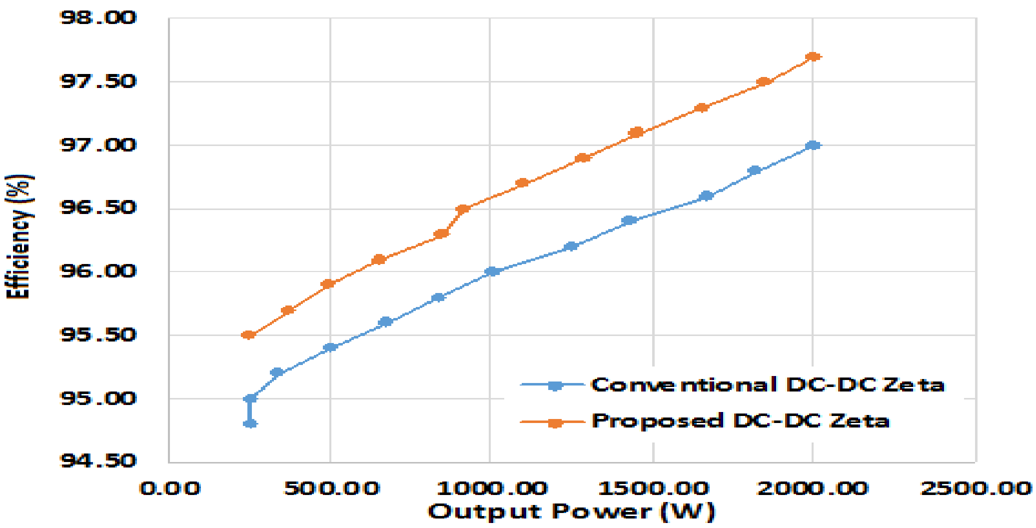


Fig. 31 Efficiency comparison between conventional & proposed zeta converter

A relative comparison between conventional zeta topology and modified zeta topology proposed in case of efficiency is shown in Fig. 31. In this figure we can see that, approximately 1.5-2.0% improvement in efficiency is achieved in case of modified zeta converter.

3.3 Switched Inductor Zeta Converter

This circuit is made up of a switched inductor branch, an output capacitor Co and the load R. The switched inductor branch is made up of inductors L_2 and L_3 and diodes D_2, D_3. The inductors L_2 and L_3 have equal value.

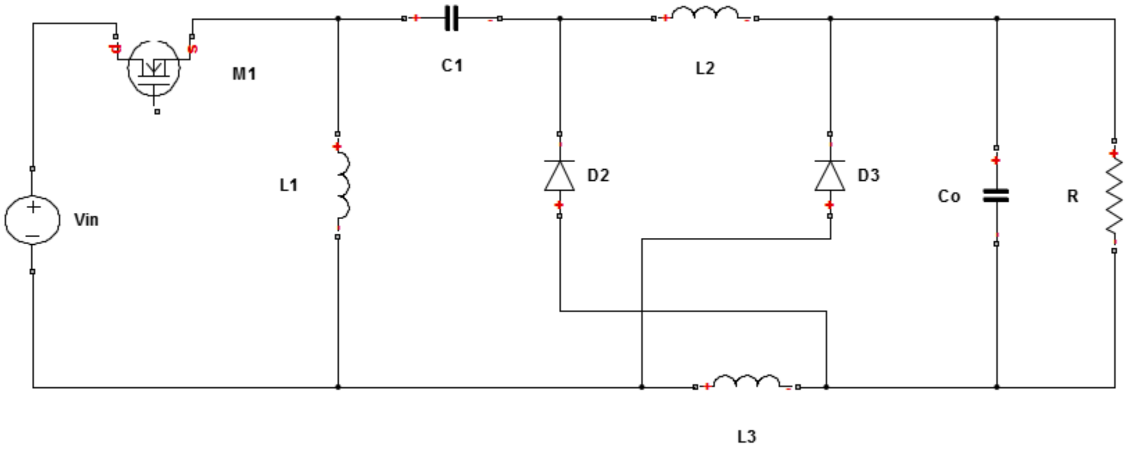


Fig. 32 Schematic of a switched inductor zeta converter

3.3.1 Operation Analysis

The on-time operation is shown in Fig. 33. The inductors L2 and L3 are charged in series as the diodes D2 and D3 are off. The MOSFET switch conducts during this time.

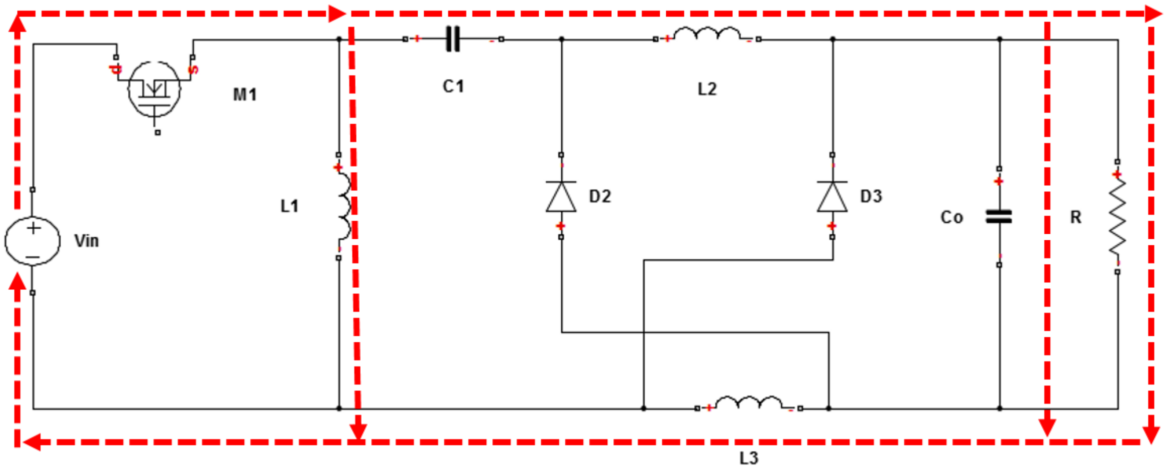


Fig. 33 On time operation of a switched inductor zeta converter

The off time operation is shown in Fig. 34. The inductors L2 and L3 are discharged in parallel as the diodes D2 and D3 are conducting. The MOSFET switch is off during this time.

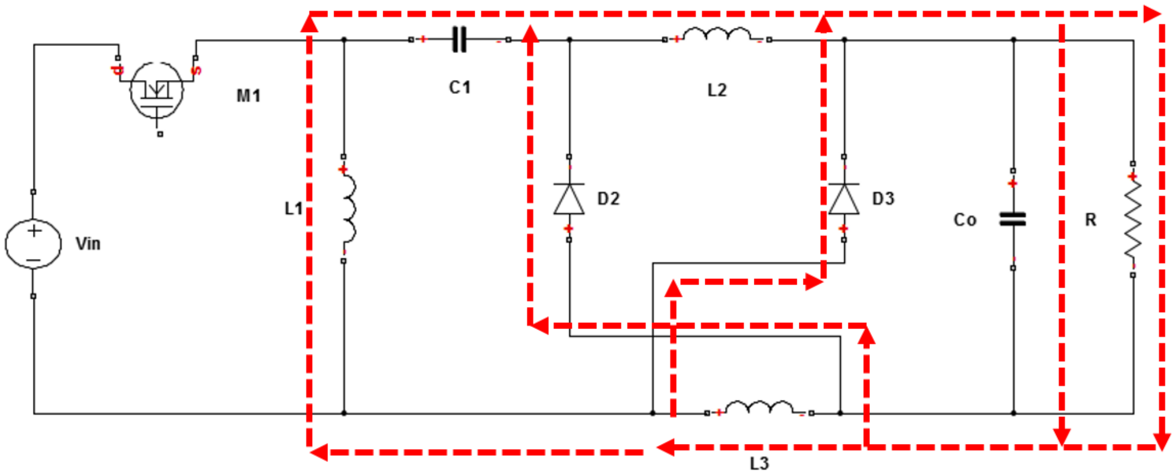


Fig. 34 Off time operation of a switched inductor zeta converter

3.3.2 CCM DC Steady State Analysis

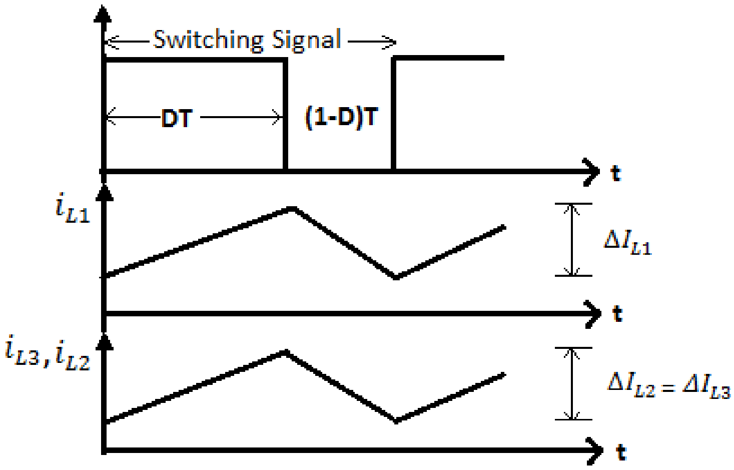


Fig. 35 Inductor current waveform for switched inductor zeta converter

During on time,

$$L_1 \frac{\Delta I_{L1}}{t_{on}} = V_{in}$$

$$\text{Or, } \Delta I_{L1} = \frac{DT}{L_1}(V_{in}) \qquad (21)$$

$$2L_2 \frac{\Delta I_{L2}}{t_{on}} = V_{C1} - V_{CO} + V_{in}$$

$$\text{Or, } \Delta I_{L2} = \frac{DT}{2L_2}(V_{C1} - V_{CO} + V_{in}) \qquad (22)$$

During off time,

$$L_1 \frac{\Delta I_{L1}}{t_{off}} = -V_{C1} - V_{C2}$$

$$\text{Or, } \Delta I_{L1} = \frac{(1-D)T}{L_1}(-V_{C1} - V_{CO}) \qquad (23)$$

$$L_2 \frac{\Delta I_{L1}}{t_{off}} = -V_{CO}$$

$$\Delta I_{L2} = \frac{(1-D)T}{L_2}(-V_{CO}) \qquad (24)$$

By equations (13), (14), (15) and (16), the DC steady state equation is found as,

$$\frac{V_o}{V_{in}} = \frac{D}{2(1-D)}$$

3.3.3 AC Small Signal Analysis

The state-space equations of the switched inductor zeta converter for the on and off time of the switch can be written as

$$L_1 \frac{di_{L1}}{dt} = DV_s - (1-D)(V_{C_1} + V_{C_2}) \tag{25}$$

$$L_2 \frac{di_{L2}}{dt} = D(\frac{V_{C_1}}{2} - \frac{V_{C_2}}{2}) - (1-D)V_{C_2} \tag{26}$$

$$C_1 \frac{dv_{c1}}{dt} = Di_{L2} - (1-D)i_{l1} \tag{27}$$

$$C_2 \frac{dv_{c2}}{dt} = D(i_{L2} - \frac{v_{c2}}{R}) - (1-D)(i_{l1} + i_{L2} - \frac{v_{c2}}{R}) \tag{28}$$

When D=1 the circuit in Fig. operates at on time and the opposite is for off time.

The state space matrices for on time are found as

$$A_{on} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1/(2*\mathrm{L2}) & \text{-}1(2*/\mathrm{L2}) \\ & 1/C1 & 0 & 0 \\ 0 & 1/\mathrm{Co} & 0 & \text{-}1/(\mathrm{R}*\mathrm{Co}) \end{bmatrix}$$

$$B_{on} = \begin{bmatrix} 2/L1 \\ 2/L2 \\ 0 \\ 0 \end{bmatrix} \quad C_{on} = [0\ 0\ 0\ 1] \quad D_{on} = [0\ 0\ 0\ 0]$$

The state space matrices for off time operation are written below

$$A_{off} = \begin{bmatrix} 0 & 0 & -1/L1 & -1/L1 \\ 0 & 0 & 0 & 1/(L2) \\ 1/C1 & 0 & 0 & 0 \\ 1/Co & 2/Co & 0 & -1/(R*Co) \end{bmatrix}$$

$$B_{off} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad C_{off} = [0\ 0\ 0\ 1] \quad D_{off} = [0\ 0\ 0\ 0]$$

The averaged matrices for the steady-state equations are found from,

$$\mathrm{A} = \mathrm{A_{on}D} + \mathrm{A_{off}}(1 - \mathrm{D})$$

$$\mathrm{B} = \mathrm{B_{on}D} + \mathrm{B_{off}}(1 - \mathrm{D})$$

$$\mathrm{C} = \mathrm{C_{on}D} + \mathrm{C_{off}}(1 - \mathrm{D})$$

$$\mathrm{D_e} = \mathrm{D_{on}D} + \mathrm{D_{off}}(1 - \mathrm{D})$$

$$\mathrm{E} = (\mathrm{A_{on}} - \mathrm{A_{off}})\mathrm{X} + (\mathrm{B_{on}} - \mathrm{B_{off}})\mathrm{V_{in}} \quad ; \text{ where } \mathrm{X} = -\mathrm{A}^{-1}\mathrm{BV_{in}}$$

$$\mathrm{F} = (\mathrm{C_{on}} - \mathrm{C_{off}})\mathrm{X} + (\mathrm{D_{on}} - \mathrm{D_{off}})\mathrm{V_{in}}$$

Control to output voltage transfer function can be found by,

$$\mathrm{G_1(s)} = \mathrm{C(sI - A)^{-1}E + F}$$

where I is an identity matrix.

The transfer function is found using MATLAB, is written below

$$\mathrm{G_1(s)} = \frac{\widetilde{\mathrm{v_o}}(\mathrm{s})}{\tilde{\mathrm{d}}\,(\mathrm{s})} = \frac{\mathrm{a_1 s^3} + \mathrm{a_2 s^2} + \mathrm{a_3}s + a_4}{\mathrm{b_1 s^4} + \mathrm{b_2 s^3} + \mathrm{b_3 s^2} + \mathrm{b_4 s} + \mathrm{b_5}}$$

$$\mathrm{a_1} = -V_{in}\frac{2D^2C_1L_1L_2 - DC_1L_1L_2}{4C_1C_2L_1L_2R(D - 1)^3}$$

$$a_2 = -vin * \frac{4C_1L_1R + 4C_1L_2R + 8D^2C_1L_1R + 12D^2C_1L_2R - 2D^3C_1L_1R - 4D^3C_1L_2R - 10DC_1L_1R - 12DC_1L_2R}{4C_1C_2L_1L_2R(D - 1)^3}$$

$$\mathrm{a_3} \quad = V_{in}\frac{2DL_2 - D^2L_1 - 6D^2L_2 + 6D^3L_2 + D^4L_1 - 2D^4L_2}{4C_1C_2L_1L_2R(D - 1)^3}$$

$$a_4 = -\frac{V_{in}(4RD^4 - 16RD^3 + 24RD^2 - 16RD + 4R)}{4C_1C_2L_1L_2R(D - 1)^3}$$

$$\mathrm{b_1} = 1$$

$$\mathrm{b_2} = \frac{1}{c2*r}$$

$$\mathrm{b_3} = \frac{4C_1L_1R + 2C_1L_2R + 2C_2L_2R + D^2C_1L_1R + 2D^2C_1L_2R - D^2C_2L_1R + 2D^2C_2L_2R - 4DC_1L_1R - 4DC_1L_2R - 4DC_2L_2R}{2C_1C_2L_1L_2R}$$

$$b_4 = \frac{2L_2 - 4DL_2 - D^2L_1 + 2D^2L_2}{2C_1C_2L_1L_2R}$$

$$b_5 = \frac{-4RD^3 + 12RD^2 - 12RD + 4R}{2C_1C_2L_1L_2R}$$

Table 4 Switched Inductor Zeta Converter Simulation Parameters

Circuit parameter	Values
V_{in}	100V
L1/L2	5uH/200uH
C1/C2	5uF
Co	220uF
R	10 ohm
Switching frequency	10kHz
V_m	1

Using the values shown in Table 1, the control to output voltage transfer function is found as

$$G_1(s) = \frac{-2894s^3 + 7.292 * 10^8 s^2 - 1.38 * 10^{12} s + 1.87 * 10^{17}}{s^4 + 312.5s^3 + 2.85 * 10^8 s^2 + 8.75 * 10^{10} s + 1.35 * 10^{15}}$$

Poles of the above transfer function $G_1(s)$ are (±)(10^4)* 1.6742i, (10^4)* (-0.0156 0.2189i).

The zeros are found 10^5(0.0044± 0.1606i), 10^5(2.5112).

DC gain is 138.8889 dB.

Gain margin is 0.6454 dB at 2.2820*10^4rad/s and phase margin is -2.9126^0 at 2.7747*10^4 rad/s

So, the uncompensated open loop system is marginally stable and the closed loop uncompensated system will be unstable. So, a compensator will be required to make the closed loop system stable. The bode plot of the transfer function is shown in Fig. 36.

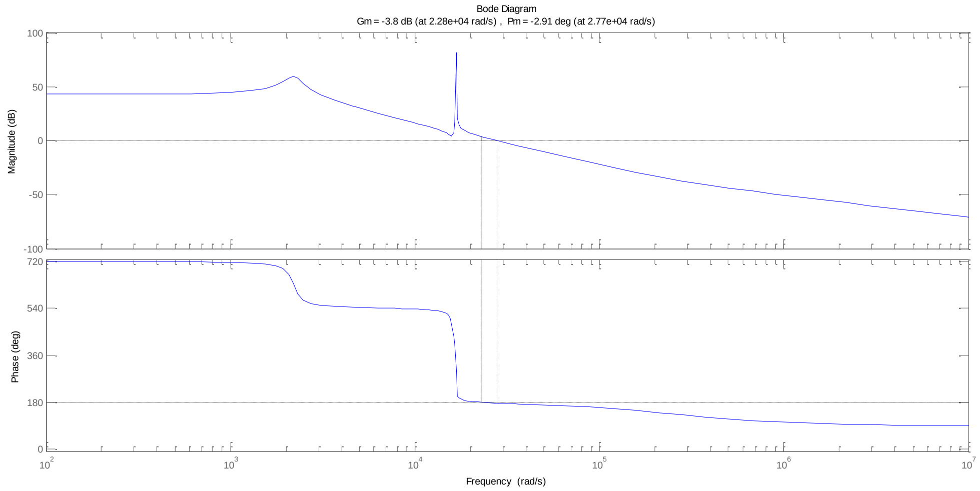


Fig. 36 Bode Plot for switched inductor zeta converter

3.3.4 Simulation

The simulation is performed in PSIM using the parameters shown in Table 3. The duty ratio is 0.5. The input current and voltage is shown in Fig. 37 with average input voltage of 100V and average input current of 10A.

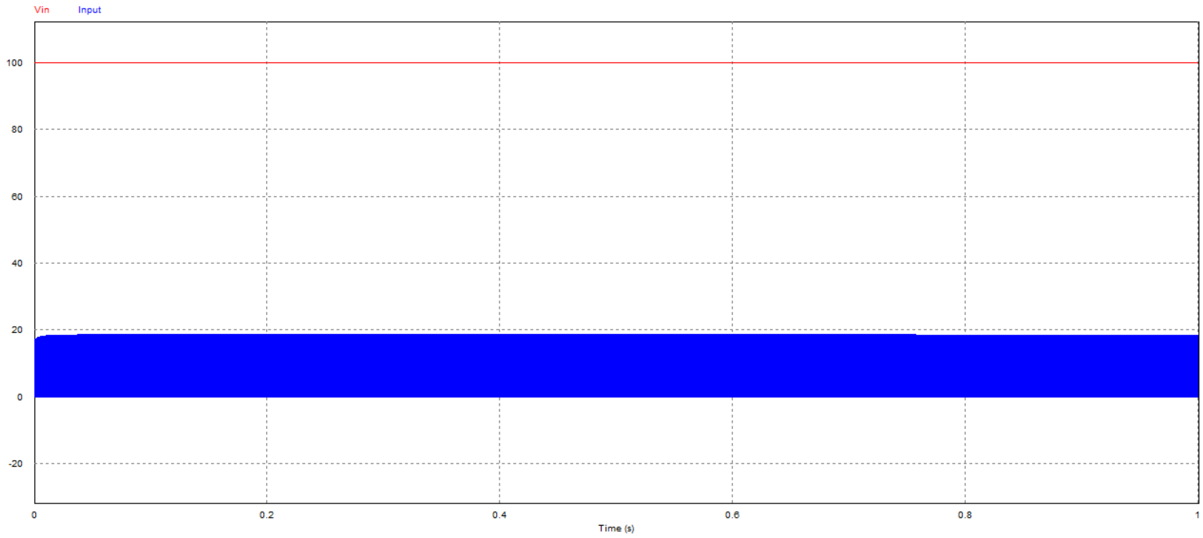


Fig. 37 Input signal for switched inductor zeta converter

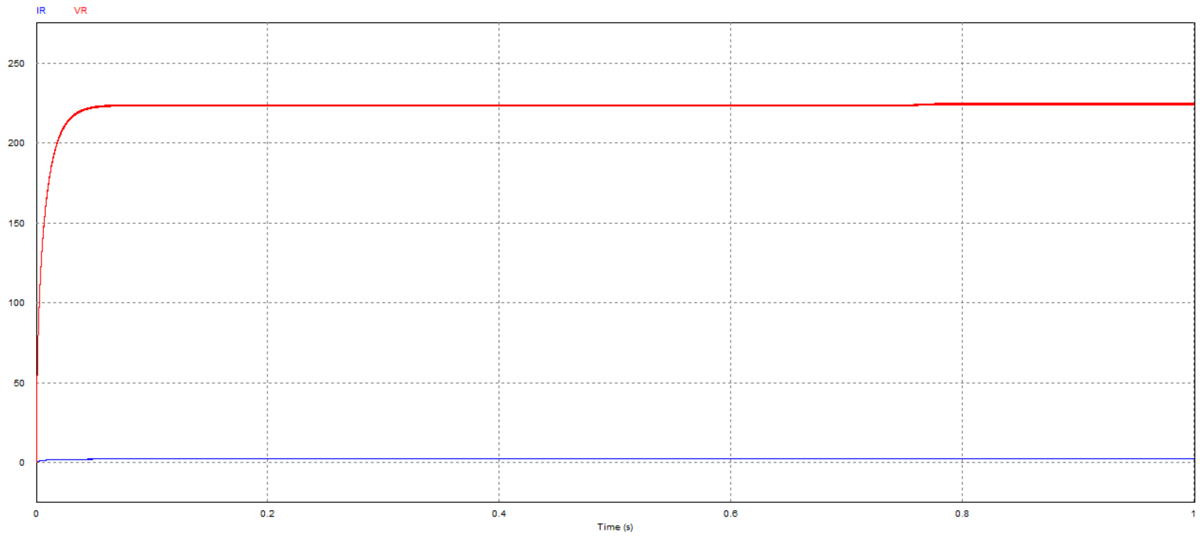


Fig. 38 Output signal for switched inductor zeta converter

The output current and voltage is shown in Fig. 38. The average output voltage is 215V and average input current of 5A.

Chapter 4

AC-DC Zeta Converter Design and Analysis

4.1 AC-DC Two Stage Switched-Inductor Zeta Converter

The AC-DC two stage switched inductor zeta converter is the bridgeless version of the conventional AC-DC switched inductor zeta converter. In this circuit, the diode bridge of the conventional circuit has been replaced in the way shown in Fig. 39. There are two separate current paths for each of the half cycle. Each of the half cycle circuit constitutes of a conventional switched inductor zeta circuit. The positive half cycle circuit is on during the positive half cycle. The negative half cycle circuit is on during the negative half cycle of the supply voltage. In this way, two separate paths for each of the half cycle are created. Thus, loss due to the diode bridge in the conventional circuit is minimized. So, the efficiency increases, the power factor (PF) improves and the total harmonic distortion (THD) is minimized. The load is simulated using a resistor. The proposed AC-DC two stage switched inductor zeta converter circuit is shown in Fig. 40. The proposed circuit has one switched inductor branch in each of half cycle circuit. Inductors L_3, L_5 and the diodes D_5 and D_7 constitutes the switched inductor branch in positive half cycle. The switched inductor branch of negative half cycle has the inductors L_4, L_5 and diodes D_6, D_8. The diodes D_1 and D_2 works to separate the positive half cycle circuit. On the other hand, diodes D_3 and D_4 works to separate the negative half cycle circuit. The capacitor Co is the output capacitor and resistor R is the load.

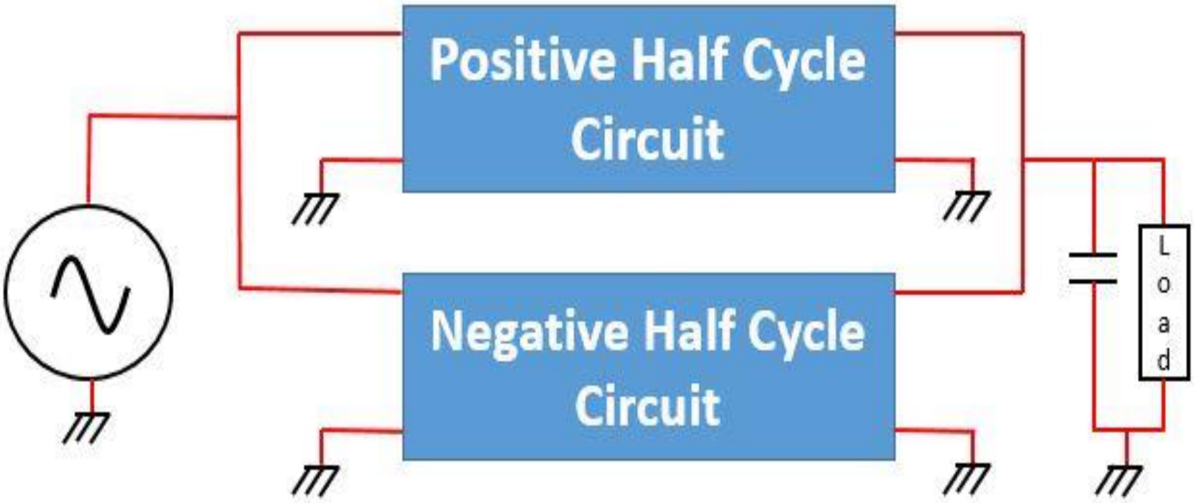


Fig. 39 Block diagram of the AC-DC zeta converter

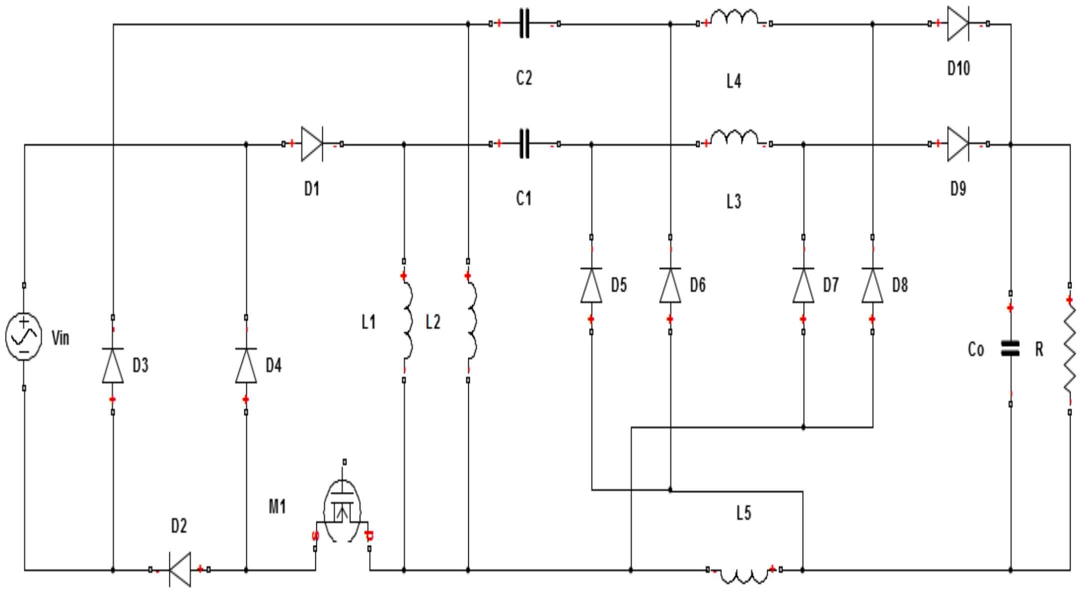


Fig. 40 Schematic Diagram of the AC-DC zeta converter

4.1.1 Operation Analysis

The circuit operation of the proposed AC-DC two stage switched inductor zeta converter can divided into two states. One is for positive half cycle and another is for negative half cycle.

Each of the half cycle operation can then be subdivided into two states based on the on time and off time of the MOSFET switch M1.

4.1.1.1 Positive Half Cycle Operation

The positive half cycle-on time operation of the circuit is shown in Fig. 41. The MOSFET M1 is on during this time. The diodes D_1 and D_2 conduct to connect the positive half cycle circuit to the AC source. During this time, the inductors L_3, L_5 charges in series as diodes D_5 and D_7 are not conducting.

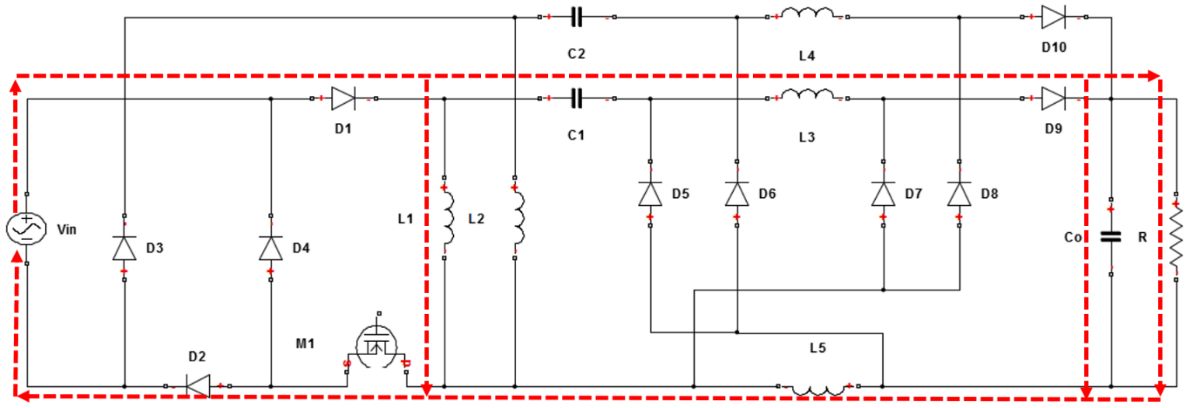


Fig. 41 On time operation for positive half cycle of the AC-DC zeta converter

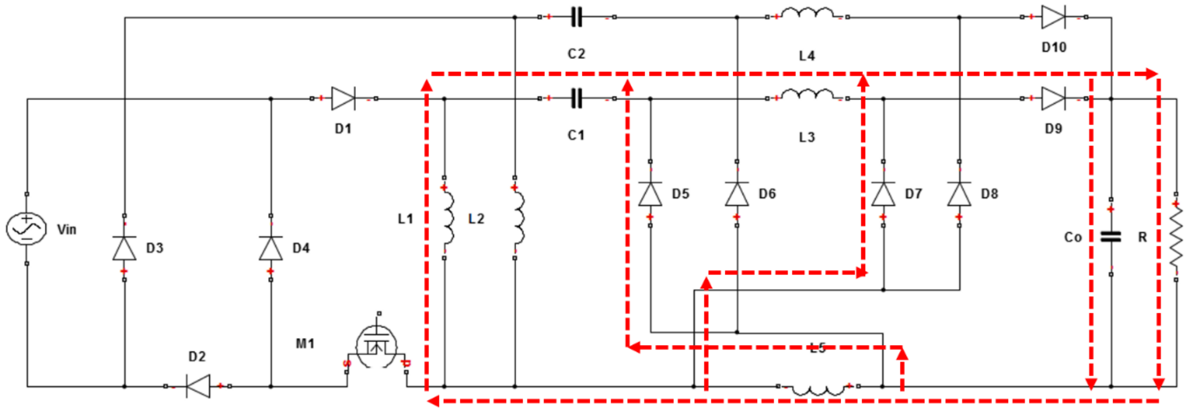


Fig. 42 Off time operation for positive half cycle of the AC-DC zeta converter

The positive half cycle-off time operation of the circuit is shown in Fig. 42. The MOSFET M1 is off during this time. So, the diodes D_1 and D_2 do not conduct to disconnect the positive half cycle circuit from the AC source. During this time, the inductors L_3, L_5 discharges parallelly as diodes D_5 and D_7 are conducting.

4.1.1.2 Negative Half Cycle Operation

The negative half cycle-on time operation of the circuit is shown in Fig. 43. The MOSFET M1 is on during this time. The diodes D_3 and D_4 conduct to connect the negative half cycle circuit to the AC source. During this time, the inductors L_4, L_5 charges in series as diodes D_6 and D_8 are not conducting.

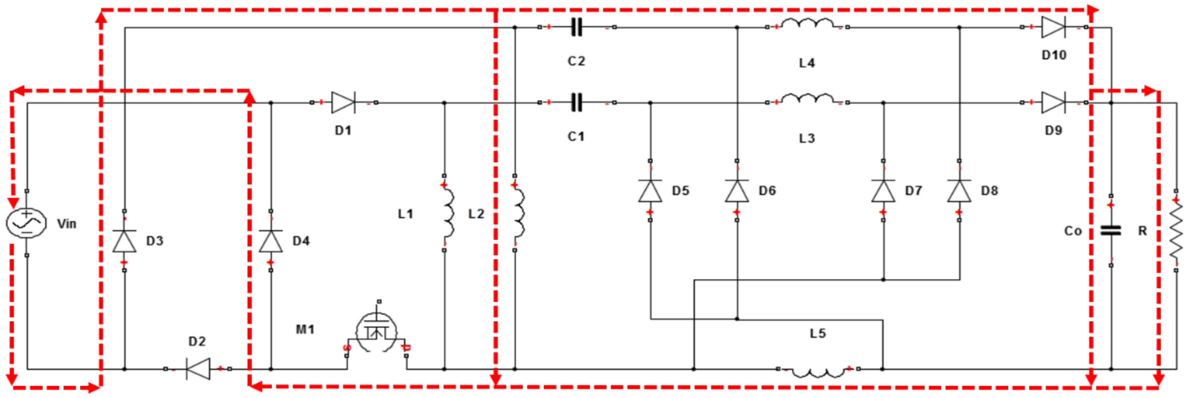


Fig. 43 On time operation for negative half cycle of the AC-DC zeta converter

The negative half cycle-off time operation of the circuit is shown in Fig. 44. The MOSFET M1 is off during this time. So, the diodes D_3 and D_4 do not conduct to disconnect the negative half cycle circuit from the AC source. During this time, the inductors L_4, L_5 discharges in parallel as diodes D_6 and D_8 are conducting.

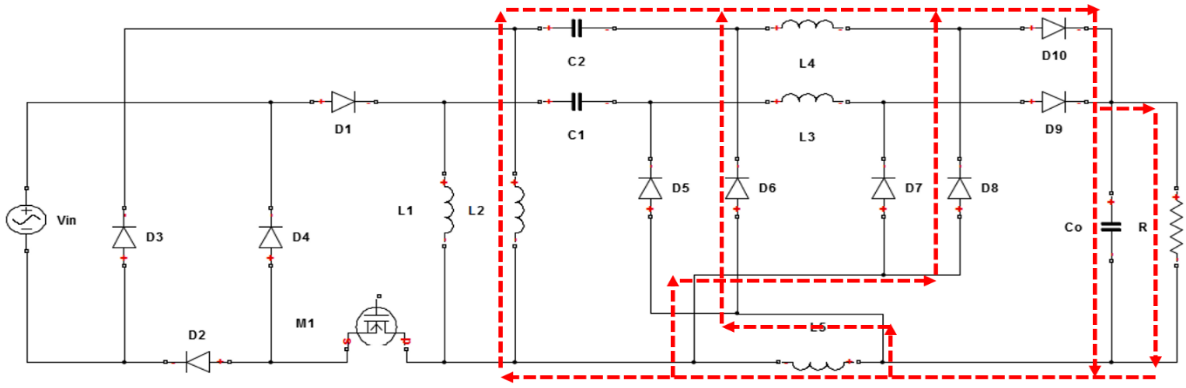


Fig. 44 Off time operation for negative half cycle of the AC-DC zeta converter

4.1.2 Simulation Result

The simulation is carried out in the PSIM software. The input voltage and the current are shown in Fig. 45. The input voltage is 220V (RMS) and the input current is 5A (RMS). The output voltage is shown in Fig.46. The average output voltage is 300V. Output current is shown in Fig. 47. The average output current is 3A. Fig. 48 shows the plot of efficiency with the varying output power. The output power varied from 250W to 2600W to compare the efficiency between the conventional and the proposed circuit. It shows that the efficiency for the proposed circuit is more than 96% for the mentioned output power range. The input power factor (PF) comparison is shown in Fig. 49 It shows that the PF improves for the proposed circuit and ranges from 0.5 to 0.8 for the output power range mentioned previously. The total harmonic distortion (THD) is compared in the Fig. 50 between the proposed and the conventional circuit. It also shows that the THD improves for the proposed circuit ranging from 0.65 to 2.10 % for the output power range mentioned above.

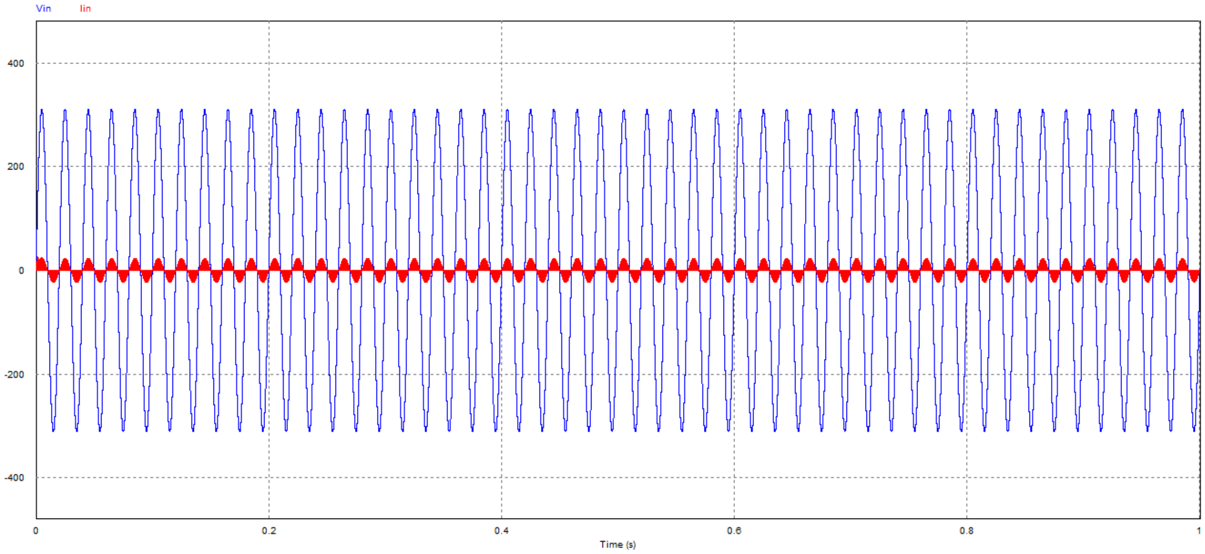


Fig. 45 Input voltage & current for AC-DC zeta converter

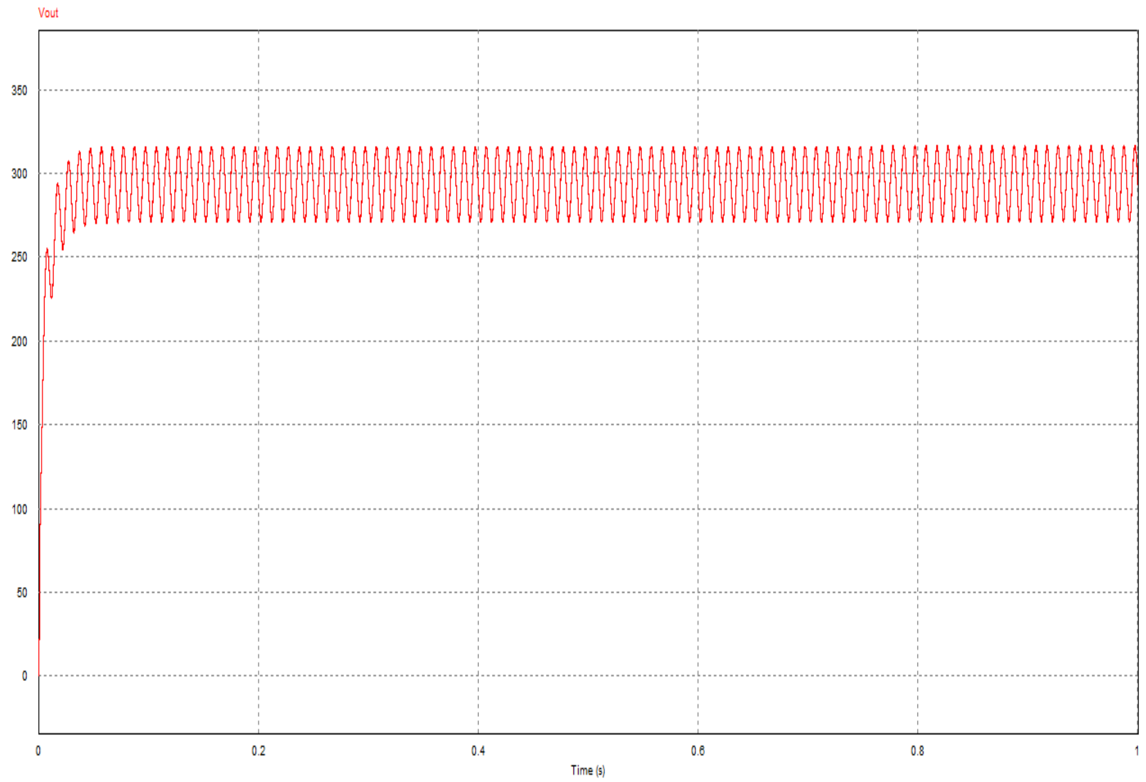


Fig. 46 Output voltage of the AC-DC zeta converter

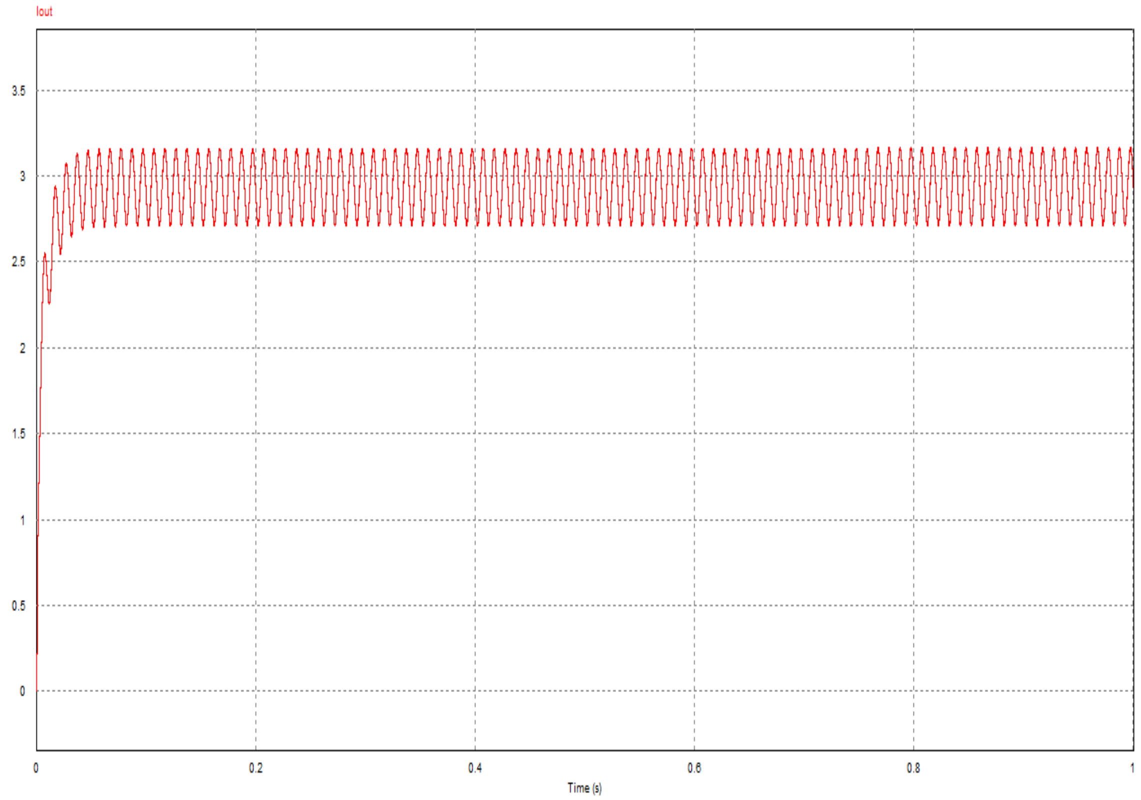


Fig. 47 Output current of the AC-DC zeta converter

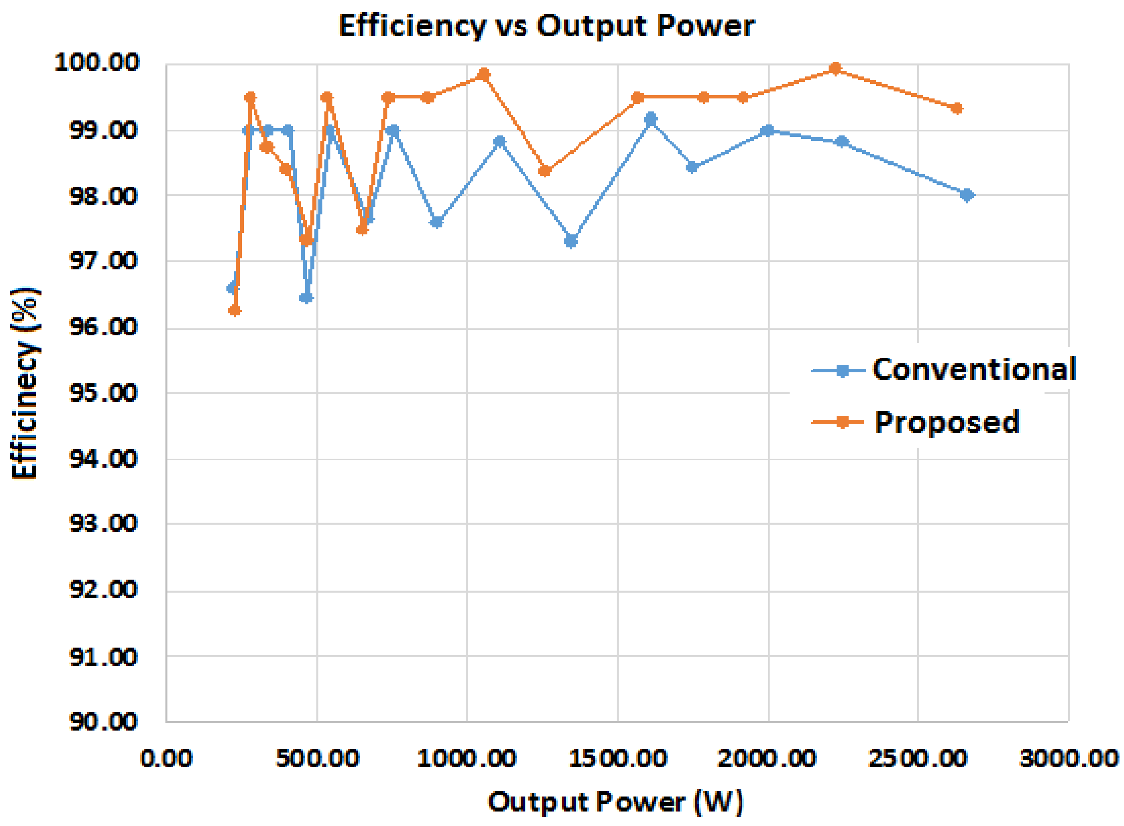


Fig. 48 Efficiency vs Output power of the proposed zeta converter

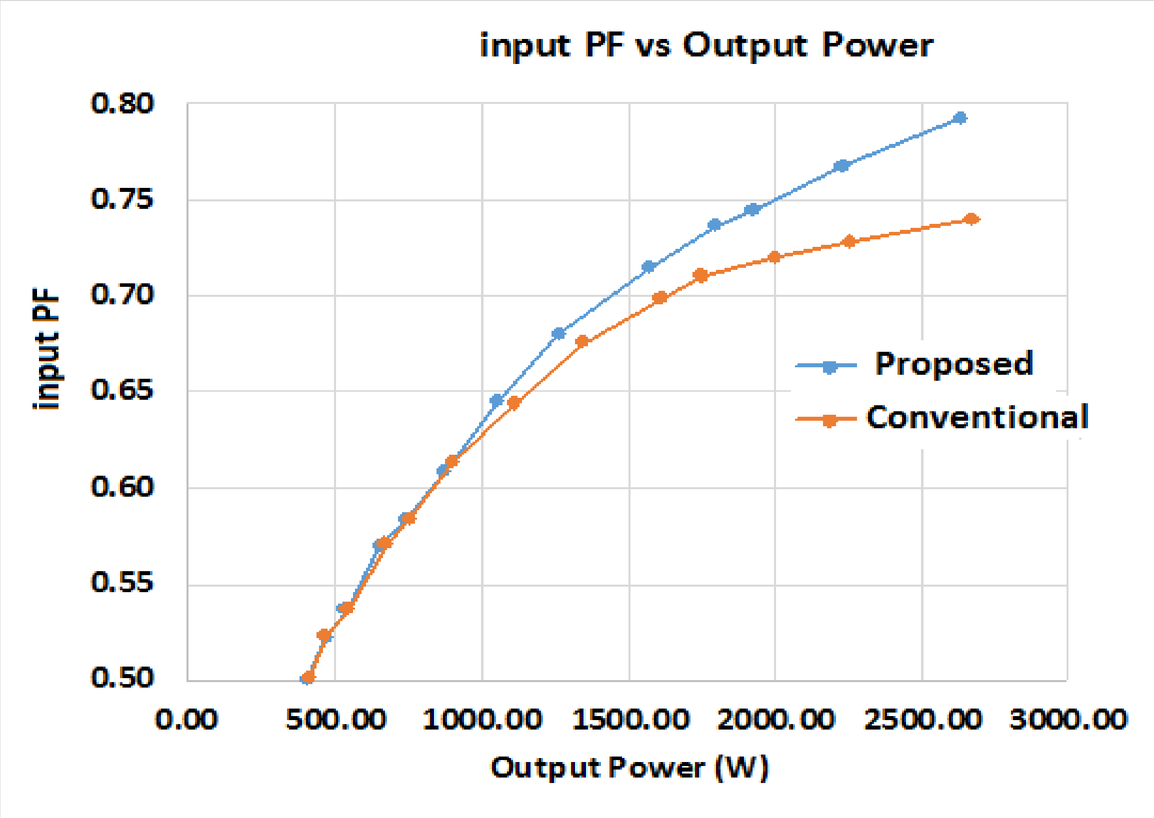


Fig. 49 Input PF vs output power of the proposed zeta converter

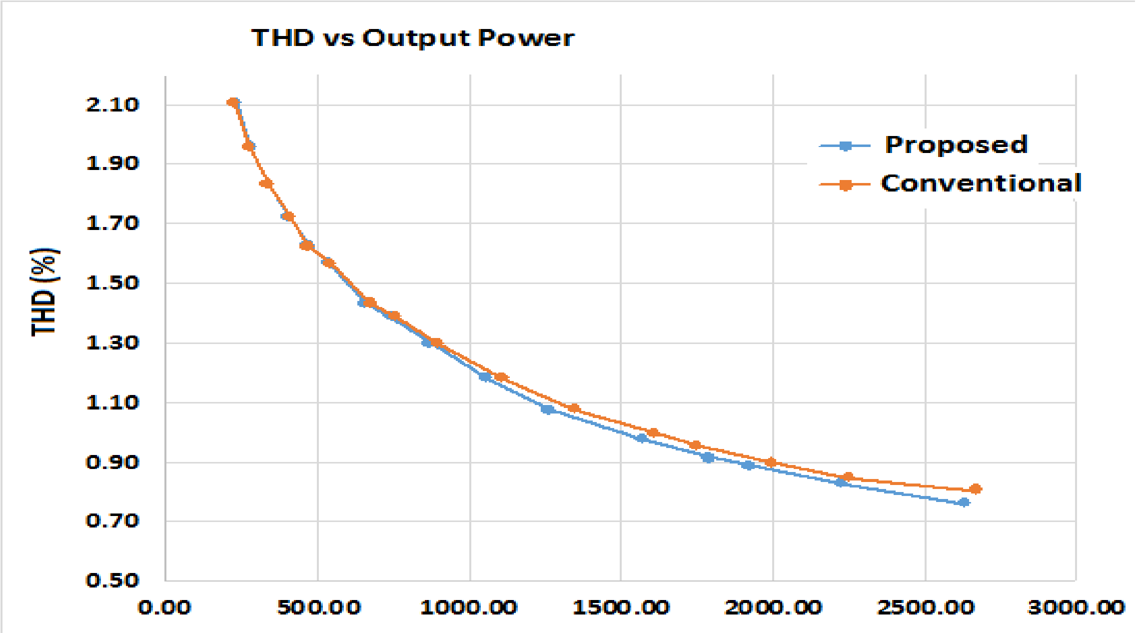


Fig. 50 THD vs Output power of the proposed zeta converter

Table 6. shows the comparison among the proposed topology and some recently developed topologies. It shows that the proposed circuit is better in terms of efficiency, THD and PF than the circuit proposed in 2016. But, it lags behind in terms of THD and PF from the circuit proposed in 2015 because the proposed circuit is an open loop system. Whereas the circuit proposed in 2015 is a closed loop system.

Table 5 Comparison with Recent Topologies

Parameters	Proposed AC-DC switched inductor zeta Converter	AC-DC Sepic Converter Proposed in [1] (2016)	AC-DC Zeta Converter with Feedback Controller Proposed in [2] (2015)
Efficiency	96-98%	87-97%	85-88%
Power Factor	0.5-0.8	0.3-0.35	1
Total Harmonic Distortion	0.75-2.0	.75-.85	.23-.35

Chapter 5

Published Thesis Work

A DC-DC buck converter having switched inductor-capacitor topology was accepted in IEEE 5th Region 10 Humanitarian Technology Conference (R10HTC) at BUET in 2017. The published work improves the bucking ability of the conventional circuit as well as increases the efficiency above 90%.

The authors of the published work are

1) Dr. Golam Sarowar, Assistant Professor, IUT
2) Md. Ashiqur Rahman, Student, IUT
3) Sadman Sakib, Student, IUT
4) Md. Fahim Hasan Khan, Student, IUT
5) Md. Zamilur Reza, Student, IUT

Chapter 6

Conclusion

The thesis work is carried out to contribute to the ever-progressing power electronics sector. Both the DC-DC and the AC-DC converters are focused in this thesis work to make output performance better. Two types of DC-DC buck converter, switched inductor and switched capacitor, are discussed in this book with dc steady state analysis, ac small signal analysis and simulation results. Another buck converter circuit has been developed using the switched inductor-capacitor and got accepted in a conference publication. Two types of DC-DC zeta converter, switched inductor and modified conventional, are also discussed with detailed analysis. The modified zeta circuit is a new developed circuit to increase the efficiency of the conventional zeta circuit above 95%. An AC-DC zeta converter is also developed to improve the power quality of the conventional AC-DC zeta converter. The developed AC-DC converter can raise the efficiency above 95%, increase the power factor (PF) by 6% compared to the conventional circuit and improve the total harmonic distortion (THD) 2-3% with respect to the conventional circuit. All the circuits developed in the thesis work are open loop system. The derived AC small signal analysis in chapter 2 and 3 can be used to make compensator and closed loop system. The closed loop system with a feedback from the output side will enable the circuits to perform better.

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