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Simulation and Performance Analysis of CCM Zeta Converter with PID Controller

P.Ramesh Babu,
Department of Electrical and Electronics Engineering,
Saranathan College of Engineering, Trichy, India
rameshbabu-eee@saranathan.ac.in

S.Ram Prasath
Department of Electrical and Electronics Engineering,
Saranathan College of Engineering, Trichy, India
ramprasath-eee@saranathan.ac.in

R.Kiruthika
Department of Electrical and Electronics Engineering,
Saranathan College of Engineering, Trichy, India
kirthikaramasamy@gmail.com

***Abstract*— DC-DC conversion is the chief stem of Power Electronics and is progressing rapidly. Many new topologies are still created every year. The Zeta converter is another converter topology to provide a regulated output voltage from an input voltage that varies above and below the output voltage. The benefits of the Zeta converter over the SEPIC converter include lower output-voltage ripple and easier compensation. The non-pulsating output current of the Zeta converter allows for the use of small output capacitors for satisfying the load voltage ripple requirement. The objective of this paper is to design and implement the CCM mode operation of non-isolated Zeta converter. The design formulas for the continuous conduction mode (CCM) are given. This paper deals with design and steady state analysis of closed loop non-isolated Zeta converter using PID control technique. The simulations have been performed by using MATLAB/Simulink. Through simulation it is confirmed that a PID compensation method improves the output response of the system.**

***Index Terms*—Zeta Converter, Continuous Conduction Mode (CCM), PID controller, DC-DC Converter**

I. INTRODUCTION

DC-to-DC converters are circuits which convert sources of direct current (DC) from one voltage level to another by changing the duty cycle of the main switches in the circuits. These converters are widely used in regulated switched mode dc power supplies and in dc motor drive applications. Operation of the switching devices causes the inherently nonlinear characteristic of the DC/DC converters. Due to this unwanted nonlinear characteristics, the converters requires a controller with a high degree of dynamic response. Pulse Width Modulation (PWM) is the most frequently consider method among the various switching control method. In DC/DC voltage regulators, it is important to supply a constant output voltage, regardless of disturbances on the input voltage. The input to these converters is often an unregulated dc voltage, which is obtained by rectifying the line voltage and it will therefore fluctuate due to variations of the line voltages [1], [2].

There are various types of DC-DC converters such as, Buck converter, Boost converter and Buck-Boost converter. The output of buck converter is less than the input voltage whereas the boost converter output is greater than the input voltage. The polarity of buck-boost converter is inversed of input signal. Fourth order converter had made applications of power possible where the demand for such requires less input voltage and high output voltage. Zeta, CUK and SEPIC converter are examples of these. These converters have the ability to either buck or boost the voltage applied to their inputs depending on their applications [3], [4].

Typical PWM DC/DC converters including the well-known buck, boost, buck-boost, CUK, Zeta, and SEPIC are categorized into buck and boost families. Using an alternative approach to modelling PWM DC/DC converters out of basic converter units (i.e., buck and boost converters), the small-signal model of the Zeta converter with CCM is derived in terms of h parameter (for buck family) [5].

At low charge level, the voltage may drop below the battery voltage for continuously supplying the load with constant voltage. Simplified steady-state analysis of the PWM Zeta converter for both continuous and discontinuous inductor current modes was described. Treating the converter with separate inductors as a particular case of the more general coupled-inductor case, the analysis results cover both the converter versions coupled and non coupled inductor [6].

Controller design for any system needs knowledge about system behaviour. This involves a mathematical relation between inputs to the system, state variables, and output called modelling of the system. The State variable approach is a power technique for analysis of switching converters. The state model of a system consists of the state equation and output equation [7], [8].

The input signal is given to the DC-DC converter, the output of the converter is send as feedback to a controller. A PID controller attempts to correct the error between a measured process variable and a desired set point by calculating and then outputting a corrective action that can

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adjust the process accordingly. By tuning the three constants in the PID controller algorithm the PID can provide control action designed for specific process requirements [9], [10]. Even though all the earlier converters made a great contribution to reduce ripple, the proposed converter with PID controller will be more effective for maintaining constant output voltage and to reduce ripple in the output voltage.

II. ZETA CONVERTER

The proposed converter is based on DC-DC converter to maintain the constant output voltage. The sixth DC-DC converter that we will study now was developed at the end of the 1980s, separately by Kazimierczuk, under the name of Dual SEPIC, and Barbi, under the name of Zeta converter (from the sixth letter of the Greek alphabet, to correspond to the "sixth" converter). Zeta is a fourth order DC-DC converter. Zeta converter will vary above or below the input voltage without change in output polarity. A Zeta is similar to a BUCK – BOOST converter but has advantages of having non-inverted output (the output voltage is of the same polarity as the input voltage). The inductors and the capacitors can also have large effects on the converter efficiency and ripple voltage. This converter transfers the energy between the inductance and the capacitance in order to change from the voltage to another. The transferred energy is controlled by switching device S (MOSFET).

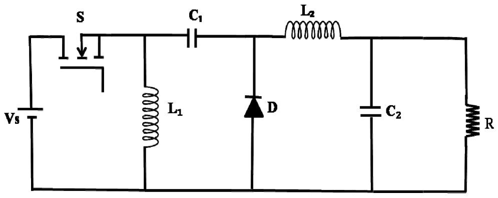


Fig.1.Schematic Diagram of Zeta Converter

III. OPERATING MODES OF ZETA CONVERTER

The converter circuit is divided into two parts as shown in fig.2 and fig.3. In mode 1 the switch will be closed as shown in fig.2. When S is turning on (ON-state), the diode is off. This is shown as an open circuit (for diode) and short circuit (for S). In this time interval diode D1 is OFF with a reverse voltage equal to - (V_S +V_O). During this state, inductor L_1 and L_2 are in charge phase. These mean that the inductor current i_{L1} and i_{L2} increase linearly.

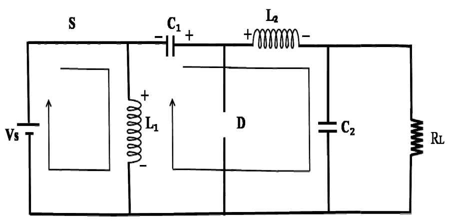


Fig.2.Zeta Converter when switch is ON

The capacitor C_1 will discharge and the energy will charged to V_O and it is connected in series with L_2. The sum of the charging inductor current flows through S.

Applying the Kirchhoff's voltage law to the circuit in Figure 2 and writing the voltage equations

$$\frac{di_{L1}}{dt} = \frac{V_S}{L_1} \tag{1}$$

$$\frac{di_{L2}}{dt} = \frac{V_s}{L_2} + \frac{V_{C1}}{L_2} - \frac{V_{C2}}{L_2} \tag{2}$$

By applying Kirchhoff's current law the rate of voltage through the capacitors will be,

$$\frac{dV_{C1}}{dt} = -\frac{i_{L2}}{LC_1} \tag{3}$$

$$\frac{dV_{C2}}{dt} = \frac{i_{L2}}{C_2} - \frac{V_{C2}}{R_L C_2} \tag{4}$$

In mode 2 the switch will be open as shown in fig.3. When S is turning off (OFF-state), the diode is on. Opposite to previous ON-state, the equivalent circuit shows that the diode is short circuit and S is open circuit. Inductor L_1, that was previously charged will now have to be in a discharging. At this state, inductor $L_1$and L_2 are in discharge phase. Since the voltage polarity of the inductor changes the diode will get forward biased and it will conduct.

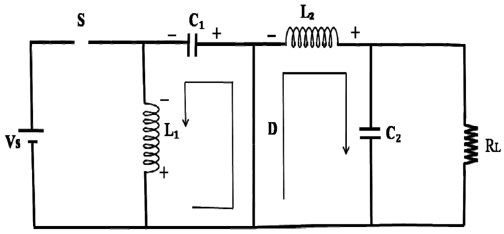


Fig.3.Zeta Converter when switch is OFF

Energy in L_1 and L_2 are discharged to capacitor C_1 and output part, respectively. As a result, inductor current I_{L1} and I_{L2} is decreasing linearly.

By applying Kirchhoff's voltage law, voltage across inductor L_1 is expressed as,

$$\frac{di_{L1}}{dt} = -\frac{V_{C1}}{L_1} \tag{5}$$

$$\frac{di_{L2}}{dt} = -\frac{V_{C2}}{L_2} \tag{6}$$

By applying Kirchhoff's current law, current flows through the capacitor C_1 is expressed as,

$$\frac{dV_{C1}}{dt} = \frac{i_{L1}}{C_1} \tag{7}$$

The relation between input and output voltages of the zeta converter is given by

The duty cycle D for zeta converter in CCM is given by,

$$D = \frac{V_O}{V_O + V_S} \tag{10}$$

$$\frac{D}{(1-D)} = \frac{V_O}{V_S} = \frac{I_{in}}{I_O} \tag{11}$$

IV. DESIGN EQUATION OF ZETA CONVERTER

Applying Kirchhoff's voltage law on Zeta converter circuit for the first and second mode the equations are derived below. The ripple of the current through the energy transferring (input) inductor can be expressed as,

$$\Delta I_{L1} = \frac{DV_S}{FL_1} \tag{12}$$

$$L_1 = \frac{DV_S}{F\Delta I_{L1}} \tag{13}$$

The output inductor current ripple can be expressed as,

$$\Delta I_{L2} = \frac{DV_S}{FL_2} \tag{14}$$

$$L_2 = \frac{DV_S}{F\Delta I_{L2}} \tag{15}$$

The capacitor ripple voltages ΔV_{C1}&ΔV_{C2} can be derived from the kirchoff's current law for first and second mode as

$$\Delta V_{C1} = \frac{1}{c_1}\int_0^{T_{ON}} i_{C1}\,dt \tag{16}$$

$$C_1 = \frac{DV_O}{FR_L\Delta V_{C1}} \tag{17}$$

$$\Delta V_{C2} = \frac{1}{c_2}\int_0^{T/2} \frac{\Delta I_{L2}}{4}\,dt \tag{18}$$

$$C_2 = \frac{DV_S}{8F^2L_2\Delta V_{C2}} \tag{19}$$

Where, F=switching frequency

From power loss equation,

$$\frac{dV_{C2}}{dt} = \frac{i_{L2}}{C_2} - \frac{V_{C1}}{R_L\,C_2} \tag{8}$$

$$V_O = V_S\frac{D}{1-D} \tag{9}$$

$$V_S I_{in} = V_O I_O$$

From that we can calculate for input current

$$I_{in} = \frac{V_O I_O}{V_S}$$

V. STATE SPACE MODEL

State-space averaging (SSA) is a well-known method used in modeling of switching converters. To develop the state space averaged model, the equations for the rate of inductor current change along with the equations for the rate of capacitor voltage change that are used.

A state variable description of a system is written as follow

$$\dot{X} = Ax + BU \tag{20}$$

$$V_O = Cx + DU \tag{21}$$

Where A is n x n matrix, B is n x m matrix, C is m x n matrix and D is reserved to represent duty cycle ratio.

For a system that has a two switch topologies, the state equations can be describe as

When switch is closed

$$\dot{X} = A_1x + B_1U \tag{22}$$

$$V_O = C_1x + D_1U \tag{23}$$

When switch is open

$$\dot{X} = A_2x + B_2U \tag{24}$$

$$V_O = C_2x + D_2U \tag{25}$$

For switch closed at time DT and open for (1-D)T, the weighted average of the equations are

$$\dot{X} = [A_1d + A_2(1-d)]x + [B_1d + B_2(1-d)]U \tag{26}$$

$$V_o = [C_1d + C_2(1-d)]x + [D_1d + D_2(1-d)]U \tag{27}$$

Let us assume the variables,

$$x_1 = i_{L1} \tag{28}$$

$$x_2 = i_{L2} \tag{29}$$

$$x_3 = V_{C1} \tag{30}$$

$$x_4 = V_{C2} \tag{31}$$

$$U = V_S \tag{32}$$

State space equation for on state is expressed from equation (1), (2), (3), (4) as

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \\ \dot{X}_4 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{L_2} & \frac{-1}{L_2} \\ 0 & \frac{-1}{C_1} & 0 & 0 \\ 0 & \frac{-1}{C_2} & 0 & \frac{-1}{C_2 R_L} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ \frac{1}{L_2} \\ 0 \\ 0 \end{bmatrix} [U]$$

State space equation for off state is expressed from equation (5), (6), (7), (8) as

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \\ \dot{X}_4 \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{-1}{L_1} & 0 \\ 0 & 0 & 0 & \frac{-1}{L_2} \\ \frac{1}{C_1} & 0 & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 & \frac{-1}{C_2 R_L} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}$$

Using on state and off state equation, the system state space equivalent equation became to be

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \\ \dot{X}_4 \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{(1-d)}{L_1} & 0 \\ 0 & 0 & \frac{d}{L_2} & \frac{-1}{L_2} \\ \frac{(1-d)}{C_1} & \frac{-d}{C_1} & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 & \frac{-1}{R_L C_2} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} \frac{d}{L_1} \\ \frac{d}{L_2} \\ 0 \\ 0 \end{bmatrix} [U]$$

$$C = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}$$

$$D = [0]$$

After finding the values of A, B, C and D, the transfer function can be found by using the MATLAB coding.

```
D=0.6;
L1=1.6e-3;
L2=1.6e-3;
C1=7.2e-4;
C2=1.5e-5;
R=10;
As= [0 0 (D-1)/L1 0;0 0 D/L2 -1/L2;(1 -D)/C1 -D/C1 0 0;0
1/C2 0 -1/(R*C2)];
Bs= [D/L1; D/L2; 0; 0];
Cs= [0 0 0 1];
Ds= [0];
Vs= 12;
[Num, den]= ss2tf(As,Bs,Cs,Ds)
sys= tf(num,den)
step (sys*Vs)
grid
```

Transfer function is

$$\frac{V_o(S)}{V_{in}(S)} = \frac{9.095S^3 + 2.5e^{007}S^2 - 6.67e^{-0.06}S + 8.681e^{012}}{S^4 + 6667S^3 + 4.212e^{007}S^2 + 3.009e^{009}S + 5.787e^{012}} \tag{33}$$

VI. PID CONTROLLER

A PID controller is feedback loop controlling mechanism. A PID controller corrects the error between a measured process value and a desired set point by calculating and then a corrective action adjust the process as per the requirement. The PID controller calculation involves three separate parameters, The Proportional value(P) determines the reaction to the current error, the Integral(I) determines the reaction based on the sum of recent errors and the Derivative (D) determines the reaction to the rate at which the error has been changing. The weighted sum of these three actions is used to adjust the process via a control element. By "tuning" the three constants in the PID controller the PID can provide control action designed for specific requirements. DC converters are modelled using state space analysis which directly determines state variables like inductor current and capacitor voltage. Requirement is to obtain a constant output voltage for input disturbance and this can be achieved by directly tuning I value.

Table I. Effect Of parameters

TYPE	RISE TIME	OVERSHOOT	SETTLING TIME	S-S ERROR
K_P	Decrease	Increase	Small change	Decrease
K_I	Decrease	Increase	Increase	Eliminate
K_d	Small change	Decrease	Decrease	Small change

The method of tuning PID parameters formally known as the Ziegler-Nichols method introduced by John Ziegler and Nathaniel Nichols. As in the method I and D gains are first set to zero. The P gain is increased until it reaches the critical gain K_{Cr} at which the output of the loop starts to oscillate. K_{Cr} and the oscillation period Pc are used to set the gains as shown in table II.

The transfer function model of the converter can be represented as

$$G(s) = \frac{9.095S^3+2.5e^{007}S^2-6.67e^{-0.06}S+8.681e^{012}}{S^4+6667S^3+4.212e^{007}S^2+3.009e^{009}S+5.787e^{012}}$$

By using transfer function derive for the quadratic equation by,
Where,
H(S)=feedback gain
H(s)=1

Table II. Gain Parameter Calculation

CONROLTYPE	K_P	T_i	T_d
P	$0.5*K_{cr}$	-	-
PI	$0.45*K_{cr}$	$P_{cr}/1.2$	-
PID	$0.6*K_{cr}$	$0.5*P_{cr}$	$0.125*P_{cr}$

Then,

$$1+\frac{9.095S^3+2.5e^{007}S^2-6.67e^{-0.06}S+8.681e^{012}}{S^4+6667S^3+4.212e^{007}S^2+3.009e^{009}S+5.787e^{012}} = 0$$

By solving the above equation, the characteristic equation if derived
Substitute s=jω,and equating real terms in the characteristic equation to find the value of ω

$$P_{cr} = \frac{2\pi}{\omega}$$
$$P_{cr} = (9.35 \times 10^{-3})$$

From the above equation solve for gain of the controller K_{cr} by using Routh-Hurwitz condition of stability

$$K_{cr} = 0.0153$$

Proportional gain constant

$$K_p = 0.6K_{cr}$$
$$K_p = 0.0092$$

Similarly for,

$$K_i = \frac{K_P}{T_i}$$
$$K_i = 166$$

Similarly for,

$$K_d = K_P T_d$$
$$K_d = 9.31 \times 10^{-5}$$

VII. Simulation & Results

For better transient and steady state response of the system a feedback path is given to the system. PID controller is used as a feedback. The importance of simulation is apparent for the preliminary design of any system. System behaviour and performance can be predicted with the help of the simulation. The diagram of the input regulated closed loop system designed in Matlab/Simulink is presented as shown in fig.4.

$$1+G(s)H(s)=0$$

Table III. Design Specification

PARAMETERS	VALUES
V_s	12V
V_o	18V
D	0.6
F	25KHz
R_L	10Ω
ΔI_{L1}	0.18A
ΔI_{L2}	0.18A
ΔV_{C1}	0.06V
ΔV_{C2}	0.06V
L_1	1.6 mH
L_2	1.6 mH
C_1	720 µF
C_2	15µF
K_P	0.0092
K_i	166
K_d	0.0000931

The simulation is carried out for different input (from 8V to 32V) and load (from 6Ω to 14Ω) conditions while the output voltage (V_O) was maintained at a constant level (18V). To maintain a constant output voltage even in presence of variation in input voltage form 8V to 32V, the duty cycle of gate pulse to the MOSFET is changed. And the dynamic response of the converter will get improved by the closed loop simulation.

There is the error in the output voltage of the open loop system it provides an unstable system. To make the system stable a feedback path is given as shown in fig.5. The error in the output voltage is compared with the reference voltage and it is given to the controller.

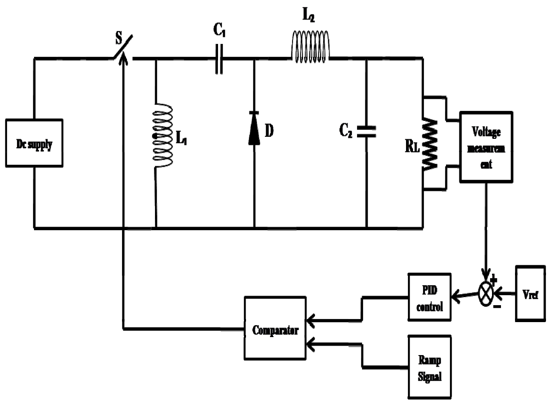


Fig.4.Block Diagram of Converter

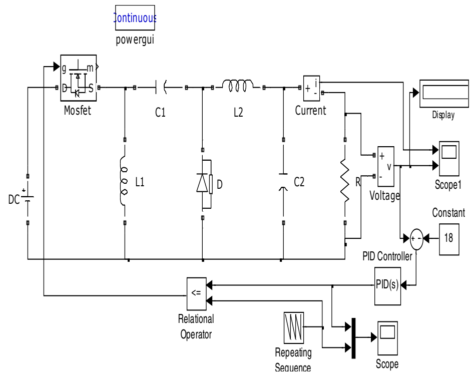
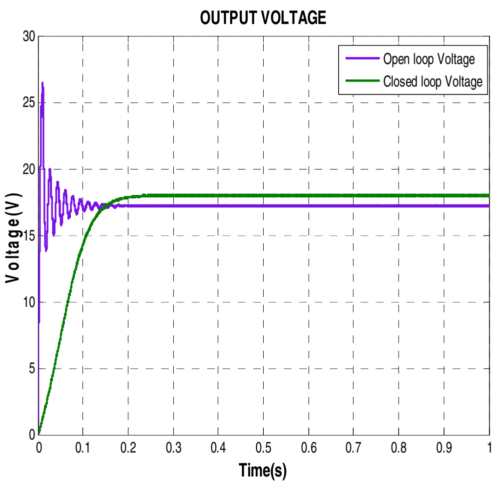


Fig. 5 Closed loop simulation of Zeta Converter

The signal from the controller is compared with the ramp signal and the output is given to the switch. The output is maintained constant and its dynamic response was improved as shown in the fig.6.and its output voltage ripple was reduced. Open loop simulation will have high peak over shoot as 26.7V. By providing the feedback to the converter by using PID controller the peak over shoot was reduced and hence its transient response was improved.



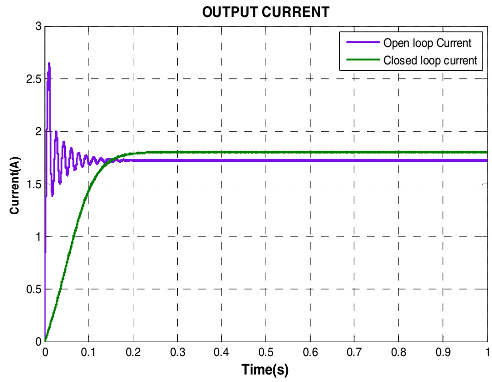


Fig.6.Output Voltage and Current for Simulation

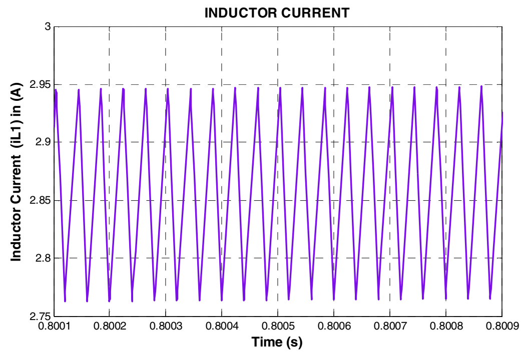


Fig.7.Inductor Current (I_{L1})
Ripple current (ΔI_{L1})=4.74%,

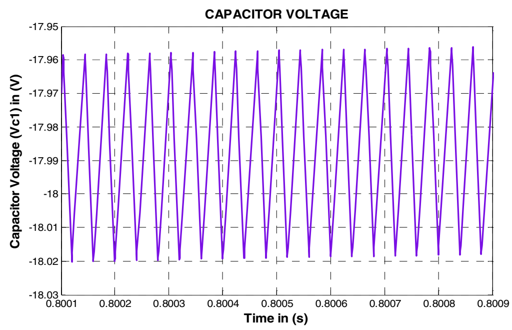


Fig.8.Capacitor voltage (V_{C1})
Ripple voltage (ΔV_{C1})=0.33%

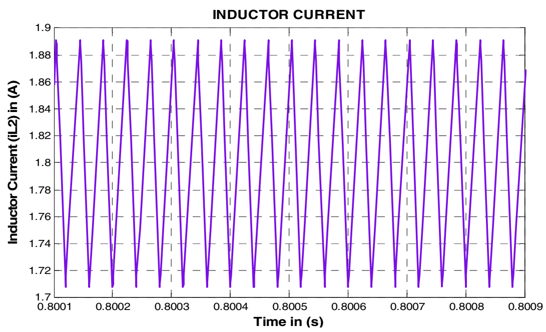


Fig.9.Inductor current (I_{L2})
Ripple current (ΔI_{L2})=8.5%

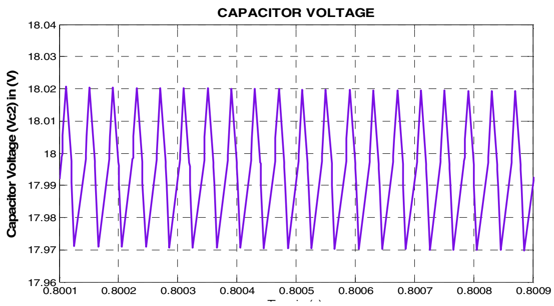


Fig.10.Capacitor voltage (V_{C2})
Ripple voltage(ΔV_{C2})=0.27%

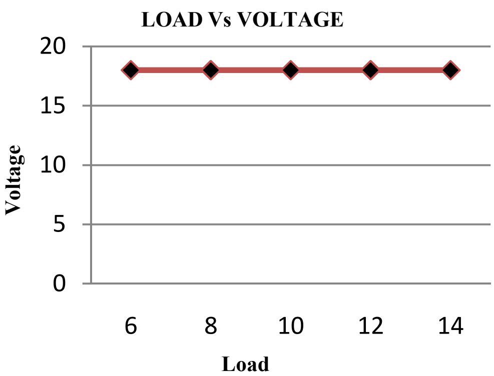


Fig. 11 Constant output Voltage with respect to Load

VIII. CONCLUSION

This paper has explained the principle of operation of the zeta converter with the design formulas for the continuous current mode (CCM) of operation. In this work, non-isolated Zeta converter circuit parameters have been obtained. PID control parameters have been obtained with the assist of state space form of the Zeta converter using MATLAB software. The circuit output voltage response and its ripple of an open-loop and closed loop system have been analyzed. From the results obtained in the simulation of proposed system, it is clear that both output voltage ripple and peak over shoot during transient condition are reduced even though load variations. Also, it maintains the constant output voltage for various load conditions.

REFERENCES

[1] Niculescu, Elena, Dorina Mioara-Purcaru, Marius-Cristian Niculescu, Ion Purcaru and Marian Maria, “A simplified steady-state analysis of the PWM Zeta converter”, In WSEAS International Conference. Proceedings. Mathematics and Computers in Science and Engineering, edited by N. E. Mastorakis, V. Mladenov, Z. Bojkovic, S. Kartalopoulos, A. Varonides, and M. Jha, no. 13.,World Scientific and Engineering Academy and Society, 2009.

[2] Niculescu, Elena, Dorina-Mioara Purcaru, and M. C. Niculescu, “A steady-state analysis of PWM SEPIC converter”, In Proceedings of the 10th WSEAS international conference on Circuits, pp. 217-222. World Scientific and Engineering Academy and Society (WSEAS), 2006.

[3] G.Mahendran and Kandaswamy,“Ant Colony Optimized Tuned DC-DC Converter”, International Journal of Computer Applications (0975 – 8887) International Conference on Innovations In Intelligent Instrumentation, Optimization And Signal Processing “ICIIIOSP-2013.

[4] Ioinovici, Adrian. Fundamentals and hard-switching converters. John Wiley & Sons, 2013.

[5] Wu, Tasi-Fu, and Yu-Kai Chen, “Modelling PWM DC/DC converters out of basic converter units”, Power Electronics, IEEE Transactions on 13, no. 5 (1998): 870-881.

[6] Vuthchhay,Eng and Chanin Bunlaksananusorn, “Dynamic modelling of a Zeta converter with State-Space averaging technique”, In Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology 2008,ECTI-CON 2008,5th International Conference on, vol. 2, pp. 969-972,IEEE 2008.

[7] Kochcha, Pijit and Sarawut Sujitjorn, “Isolated zeta converter: principle of operation and design in continuous conduction mode”, WSEAS Transactions on Circuits and Systems 9, no. 7 (2010): 483-492.

[8] Rashid, Muhammad Harunur. Power electronics: circuits, devices, and applications. Vol. 2. NJ: Prentice hall, 1988.

[9] Preeja, J. P. and S. V. Kayalvizhi, “Transient Response Improvement of Cuk Converter using SMC & FLC”.

[10] Verma, Sujata, S. K. Singh, and A. G. Rao, “Overview of control Techniques for DC-DC converters”, Research Journal of Engineering Sciences ISSN 2278 (2013): 9472