Comparison between Zeta Converter and Boost Converter using Sliding Mode Controller

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Abstract—This paper presents a dynamic modelling and control of a Zeta converter as well as boost converter evaluated in MATLAB/SIMULINK based simulation. A Zeta converter topology provides a positive output voltage from an input voltage and also provides option for regulating an unregulated power supply. The Zeta converter is configured from buck converter but unlike buck converter, it includes two inductors and two capacitors. A comparison between Zeta converter and Boost converter is done using sliding mode controller under the load voltage variation. The feedback loop provides voltage regulation against any disturbance in load voltage by keeping input side constant. The simulated output voltage, current and graph between voltage gain and duty ratio are shown in the paper.

Keywords—Zeta converter, Boost converter, Voltage mode control, Sliding mode controller etc.

I. INTRODUCTION

Switched DC-DC converters aid in increasing the voltage from a low battery voltage thereby facilitating in accomplishing a regulated DC output voltage which would rather require multiple battery sources.

Though zeta converter is similar to that of a buck-boost converter, it has an advantage of non-inverted output. It has a wider range of duty ratio than any other converter. The converter exhibits improved power factor, low input current distortion, low output current ripple and wide output-power range [1]. A boost converter is a DC-DC converter in which output voltage is greater than input voltage, while stepping down a current. As the control input appears in both voltage and current equation, the controlling of boost converter is difficult [7].

In an open loop system output cannot be compensated or controlled if there is an input voltage variation or disturbance. Therefore to regulate the DC-DC converters, different control techniques are applied and a robust output voltage is achieved.

Due to non-linearity of DC-DC converters, linear control techniques are not efficient; therefore to design a linear control system, small signal model is obtained by state space averaged model. The state space model is a time domain model where the system is described by differential equation.

The property of hysteresis control is extended in sliding mode control to multi variable environment, and is able to constrain the system status to follow trajectories which lie on a suitable surface in the state space. The motion of the system as it slides along the boundaries is called a sliding mode and the geometrical locus that contains these boundaries is called the sliding surface [6].

II. OPERATING PRINCIPLE OF ZETA CONVERTER AND DC-DC BOOST CONVERTER

A. Boost converter

The conventional boost converter topology is as shown in Fig.2. Also two modes of operation of boost converter are shown in Fig.3 and Fig.4 respectively.

a) Mode 1

In this mode, the switch S is ON, resulting in increasing inductor current. In this mode the equation becomes,

$$\Delta i_{ON} = \frac{d\text{P}}{L} V_s$$ ... (1)
**Fig. 3** Mode 1 operation of boost converter

In this mode, switch S is OFF, the inductor current flows through load and the equation becomes,

$$\Delta i_{OFF} = \frac{(V_s-V_o)(1-D)T}{L}$$  \hspace{1cm} (2)

**Fig. 4** Mode 2 operation of boost converter

**B. Zeta converter**

The equivalent circuit of Zeta converter is as shown in Fig. 5. It comprises of a switch, a diode, two capacitors $C_1$ and $C_2$, two inductors $L_1$ and $L_2$ and a standing resistive load.

**Fig. 5** Zeta converter topology

The operation of zeta converter is designed in Continuous Conduction Mode (CCM) and the circuit operation can be defined by two modes of operation are shown in Fig.6 and Fig.7 respectively.

**a) Mode 1**

In this mode, the switch $Q_1$ is ON and the diode $D_1$ is reverse biased. Inductors $L_1$ and $L_2$ is charged from the source and the inductor current $i_{L1}$ and $i_{L2}$ increases linearly. Also, discharging of $C_1$ and charging of $C_2$ take place.

**Fig. 6** Mode 1 operation of zeta converter

By Kirchhoff’s Voltage law,

$$L_1 \frac{di_{L1}}{dt} = V_s - V_1$$  \hspace{1cm} (3)

$$L_2 \frac{di_{L2}}{dt} = \frac{V_s}{L_2} + \frac{V_c_1}{L_2} - \frac{V_c_2}{L_2}$$  \hspace{1cm} (4)

By Kirchhoff’s current law,

$$C_2 \frac{dV_c_2}{dt} = i_{L1}$$  \hspace{1cm} (5)

**b) Mode 2**

In this mode, the switch $Q_1$ is OFF and the diode $D_1$ is forward biased. During this interval, previously charged inductor $L_1$ starts to discharge. So stored energy in $L_1$ and $L_2$ are discharged through capacitors $C_1$ and $C_2$. Therefore, the inductor currents $i_{L1}$ and $i_{L2}$ decrease gradually.

**Fig. 7** Mode 2 operation of zeta converter

By Kirchhoff’s voltage law, voltage across inductor ($L_1$) is given by,

$$L_1 \frac{di_{L1}}{dt} = -V_1$$  \hspace{1cm} (6)

Voltage across inductor ($L_2$) is given by,

$$L_2 \frac{di_{L2}}{dt} = -V_2$$  \hspace{1cm} (7)

By applying Kirchhoff’s current law, current through the capacitor $C_1$ is,

$$i_{L1} = C_1 \frac{dV_c_1}{dt}$$  \hspace{1cm} (8)

The relation between input voltage, output voltage and the duty cycle (D) of zeta converter in CCM is given by,

$$D = \frac{V_o}{V_s}$$

Therefore,

$$\frac{V_o}{V_s} = \frac{i_{L1}}{i_{L2}} = \frac{D}{D-1}$$

(9)

By voltm second balance,

$$V_s \times t_{ON} + (V_s-V_c_1) \times t_{OFF} = 0$$

Taking average over one cycle,

$$V_o = \frac{D}{D-1} \times V_s$$

\[ \text{(10)} \]
By applying volt-second balance, the relation between output voltage and input voltage is given by
\[ V_o = \frac{1}{D - 1} \cdot V_i \]

III. DESIGN OF PROPOSED SLIDING MODE CONTROLLER

To ensure stability in any operating condition, a suitable control technique should be employed for DC-DC boost converter that matches with their non-linearity in input voltage and load variations.

Sliding mode controller is a nonlinear control method that alters the dynamics of the system by applying a discontinuous control signal thereby forcing the system to slide along the cross section of system’s normal behavior. The sliding surface is selected in such a way so that the system trajectories near the surface are directed towards the surface itself by the proper controlling of the converter switch irrespective of the circuit parameters. The controller variable provides a fast transient response along with tracking a certain reference path to achieve desired dynamic response. If these conditions are satisfied, the system status moves from its initial value towards the sliding surface thereby maintaining the switching action [6].

IV. CONTROLLER FOR DC-DC CONVERTER

State space averaging is important for mathematical modeling of sliding mode controller. To develop state space model, the equations for the rate of change of inductor modeling of sliding mode controller. To develop state space model, the equations for the rate of change of capacitor model, the equations for the rate of change of inductor is given by
\[ \frac{dI_L}{dt} = \frac{1}{L} (V_i - V_o - R I_L) \]
\[ \frac{dV_C}{dt} = \frac{1}{C} (I_L - I_R) \]

Instead of state variables, consider new state variable that is the error vector of state space variable X to be considered. So, the sliding surface equation in state space is expressed by
\[ S = \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \alpha_4 x_4 = J^T x \quad \ldots (11) \]

Where
\[ J = [\alpha_1 \alpha_2 \alpha_3 \alpha_4] \]
\( \alpha_1, \alpha_2, \alpha_3, \alpha_4 \) are control parameters termed as sliding coefficients.

A sliding surface can be obtained by, \( S=0 \).

For this system, it is appropriate to have a general SM control law that adopts a switching function such as,
\[ u=1 \quad \text{when} \quad S>0 \]
\[ u=0 \quad \text{when} \quad S<0 \]

A sliding mode control system is designed for boost converter as shown in Fig.8 [8].

State-Space Model of Boost converter:
\[
\begin{bmatrix}
0 & -(1-D) \\
(1-D) & \frac{L}{C} \\
\frac{1}{C} & 0
\end{bmatrix}
\]
\[
\begin{bmatrix}
\frac{1}{L} & 0 \\
0 & \frac{1}{C}
\end{bmatrix}
\]
\[
\begin{bmatrix}
0 & 1 \\
1 & 0
\end{bmatrix}
\]
\[
0
\]

Where \( r_{c1} \) and \( r_{c2} \) are equivalent series resistors and \( r_{L1} \) and \( r_{L2} \) are DC resistors.

Fig.8 Control scheme of Zeta converter using sliding mode controller
The control scheme for boost converter is designed as shown in Fig.9 using sliding mode control technique [8].

![Control scheme of Boost converter using sliding mode controller](image)

**IV .DESIGN SPECIFICATIONS**

The Zeta converter is designed as follows;

The input inductor $L_1$ is given as,

$$L_1 = \frac{DV_s}{\Delta i_{L1}f_s} \quad \ldots (12)$$

Where, $\Delta i_{L1}$ is the permitted ripple current in inductor $L_1$ and considered to be 10% of output current $I_0$.

The value of input capacitor $C_1$ is given as,

$$C_1 = \frac{DL_0}{\Delta V_c f_s} \quad \ldots (13)$$

Where, $\Delta V_c$ is the permitted voltage ripple in capacitor $C_1$ and considered to be 2% of supply voltage $V_s$.

The output inductor $L_2$ is given as,

$$L_2 = \frac{DV_s}{\Delta i_{L2}f_s} \quad \ldots (14)$$

The value of output capacitor $C_2$ is given by,

$$C_2 = \frac{DV_s}{\omega \Delta V_c f_s L_2} \quad \ldots (15)$$

Simulink model of proposed converter is implemented with following design parameters:

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Zeta Converter</th>
<th>Boost Converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Voltage ($V_s$)</td>
<td>48 V</td>
<td>48 V</td>
</tr>
<tr>
<td>Output Power ($P_o$)</td>
<td>100 W</td>
<td>100 W</td>
</tr>
<tr>
<td>Switching frequency ($f_s$)</td>
<td>100 kHz</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Duty ratio ($D$)</td>
<td>69.71%</td>
<td>56.56%</td>
</tr>
<tr>
<td>Inductors, $L_1$=$L_2$</td>
<td>1.6 mH</td>
<td>1.5 mH</td>
</tr>
<tr>
<td>Input capacitor ($C_1$)</td>
<td>0.1591μF</td>
<td>273.34μF</td>
</tr>
<tr>
<td>Output capacitor ($C_2$)</td>
<td>23.3μF</td>
<td>121 Ω</td>
</tr>
<tr>
<td>Load resistor ($R_L$)</td>
<td>121Ω</td>
<td>121 Ω</td>
</tr>
<tr>
<td>Output Voltage ($V_o$)</td>
<td>110.5 V</td>
<td>109.4 V</td>
</tr>
</tbody>
</table>

**V. SIMULATION STUDIES AND RESULTS**

The performance of controller with reference load voltage variation is analyzed. Under the load voltage variation from 90 V to 120 V, the output voltage and output current can be regulated and controlled by controller.

**A). Simulink model of boost converter**

The closed loop simulink model of the proposed converter has been designed according to Table 1 parameters.

![Simulink model of closed loop control of Boost converter](image)

Output voltage of boost converter in closed loop configuration is shown in Fig.11.

![Output voltage of conventional Boost converter](image)
Output current of boost converter in closed loop configuration is shown in Fig. 12.

The output current under dynamic condition is as shown in Fig. 15.

A. Simulink model of Zeta converter

The closed loop simulink model of the proposed converter using sliding mode controller is shown in Fig. 13.

The output current under dynamic condition is as shown in Fig. 14.

From simulation results, the voltage and current stress across the inductor, capacitor and diode are tabulated as below:

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Boost Converter</th>
<th>Zeta Converter</th>
</tr>
</thead>
</table>
| Inductor current ($I_L$) | 2.11 A          | $I_{L1} = 2.22 A$  
|                  |                 | $I_{L2} = 0.9132 A$ |
| Capacitor voltage ($V_C$) | 109.4 V         | $V_{C1} = -110.5 V$  
|                  |                 | $V_{C2} = 110.5 V$ |
| Diode current ($I_D$) | 2.11 A          | 0.9134 A        |

A graph between voltage gain and duty cycle for both boost and Zeta converter is plotted as shown in Fig. 16.
VI. CONCLUSION

A performance comparison between Zeta converter and Boost converter is done and simulation results using sliding mode controller under the load voltage variation are discussed. Also dynamic modeling of Zeta as well as Boost converter is presented. It is understood that the Zeta converter is suitable for various applications because boost converter has reversed polarity of output voltage and high ripples in output voltage. The output voltage of Zeta converter is boosted more than the voltage obtained with the boost converter. The sliding mode controller is analyzed to regulate output voltage and output current under any disturbance either in supply side or in load side. The simulation results are shown with sliding mode control.

REFERENCES