

Performance Analysis of PI and SMC Controlled Zeta Converter



Mariammal Thirumeni, Deepa Thangavelusamy,

Abstract: This paper presents the design and analysis of DC-DC Zeta converter operating in the continuous conduction mode to regulate the output voltage of the converter for automotive battery recharge applications. The state space analysis of the converter is derived to obtain the transfer function of the converter. The presented DC-DC converter exhibits the non-linearity due to the presence of energy storage elements and degrades the performance of the converter. Therefore, this paper proposes a non-linear cascaded Proportional -Integral Sliding Mode Controller (PI-SMC) to improve the performance of the converter. PI-SMC Controller contains PI Controller in the outer loop for voltage regulation and an inner fast acting SMC Controller for current shaping. The PI controller is tuned by Root locus and Routh Hurwitz criterion and the steady state performance parameters are obtained for the PI-SMC Controlled Zeta converter. MATLAB/SIMULINK results are presented for Set point tracking of the controller. The results shows that the steady state performance indices such as Integral Absolute Error (IAE) and Integral Time Absolute Error (ITE) are significantly enhanced for the converter using the proposed cascaded control scheme compared to the conventional PI controller.

Keywords : DC-DC Converter, Zeta converter, PI Controller, PI-SMC Controller,

I. INTRODUCTION

Power electronic converters play a major role after the advent of renewable energy and smart grid applications for voltage regulation by proper switching action of the converters[1]. DC-DC converters play a major role in stepping down or stepping up the voltage level of the converters. Among the various DC-DC converter [2] topologies, zeta converter has the advantage such as continuous output current, lower output voltage ripple, and non inverted output. The converters provide the power electronics interface by converting voltages and currents from one form to another . The controller manages the power flow from the source to the load with high efficiency and high power density. The Various controller configurations are open loop and closed loop system. In both systems, PI[4] controllers can be utilized. The objective of the controller[3] is to maintain the voltage range of the converter within the specified operating point amidst disturbances and errors.

This is done by keeping the duty ratio, which is chosen as the control input within the maximum and minimum values. Basically any DC-DC converter has two switching logic as ON and OFF state.

By averaging the two dynamic states of the converter, the power converter can be expressed as a bilinear model with a continuous control input. Because of the simplicity, initially PI[5] control strategy was used. Since PI[6] controllers sometimes fail to satisfy the above mentioned specifications especially when disturbance rejection and transient response requirements were concerned due to the highly non linear characteristics of the converter, robust controllers such as sliding mode control, MPC were developed.

Since DC-DC converters are variable structured systems, SMC[7] approach , otherwise called as variable structure systems (VSS) was used whose structure changes intentionally during the time in accordance with a preset control law. Their structure changes due to the action of controlled switches and diodes. Direct and indirect control schemes for operating the DC-DC switching converters were available. In some converters such as boost and Cuk converter, the converters inherit the right half plane zero. This leads to instability in the converters making the controlled dynamic response of the system sluggish, when the control action is based on solely controlling the output voltage. So an inner current control loop in addition to the voltage control loop is included[8].A combination of PI controller in the outer loop and an SMC[9] controller in the inner loop for Zeta converter were carried out. The robustness of the SMC makes it convenient to be applied to electromechanical systems [10]. Some of the controls used to control the converters include Model Predictive[11] control(MPC),passivity based controls ,neural networks[12], state space averaging[13] and fuzzy logic. Direct control method and indirect control[14-17] methods were also used in which the converters were made to operate at infinite frequency and finite frequency respectively were studied. Literatures depicting the implementation of evolutionary algorithms to enhance the performance of the system such as GA [20], PSO [21,25] ,PSOGSA [22-24], to tune the PI controller and to stabilize the output voltage of the converter are also presented. In this proposed work, PI and SMC Controller for Zeta converter is designed and the steady state performance indices such as IAE and ITAE are compared with the conventional PI Controller.

Section 2 explains the model of Zeta converter and its design components, Section 3 explains the controller design, Conclusion part is explained in chapter 4.

Manuscript published on 30 September 2019

* Correspondence Author

Mariammal Thirumeni* , SELECT, VIT University , Chennai, India.
Email: t.mariammal2014@vit.ac.in

*Deepa Thangavelusamy, SELECT, VIT University, Chennai, India.
Email: deepa.t@vit.ac.in

© The Authors. Published by Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP). This is an [open access](https://creativecommons.org/licenses/by-nc-nd/4.0/) article under the CC-BY-NC-ND license <http://creativecommons.org/licenses/by-nc-nd/4.0/>

II. MODEL OF ZETA CONVERTER

The basic model of Zeta converter is a switched mode power supply with two inductors (L_1, L_2), two capacitors (C_1, C_2), a diode (D), and a switch (S). This converter transfers the energy between inductance and the capacitance in order to change from one voltage level to another voltage level. The transferred energy is controlled by commutation of switching device S (MOSFET) and diode D alternatively.

In this section, a brief note about Zeta converter is presented. A DC-DC converter can operate in continuous and discontinuous conduction modes. Here Zeta converter operates in continuous conduction mode and the Switching action based on PWM technique is implemented. Switch S turns ON for a period of DT and turns OFF for a period of $(1-D)T$, where T is the PWM period.

Fig 1 shows the schematic of the zeta converter and its PWM control signal.

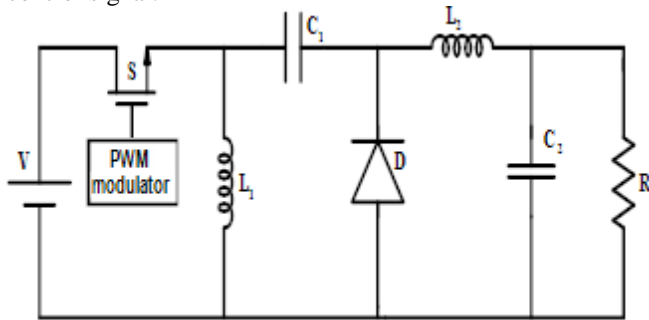


Fig.1 Zeta converter

2.1 Modes of operation

2.1.1 ON STATE

When the switch S is ON, it is closed for the period " αT ", the input voltage V is applied across L_1 and causes a linear increase of current to charge the inductor. The input voltage and the charged capacitor C_1 will increase the load current through the inductor L_2 . The diode has reverse voltage across it, so it will not conduct. The equivalent ON state mode is shown in fig 2.

2.1.2 OFF STATE

When the switch S is OFF, it is open for the period " $(1-\alpha)T$ ", the inductor L_1 polarity changes and charges the capacitor C_1 through the diode. The inductor L_2 polarity also changes and supplies the load. The inductor L_2 and capacitor C_2 in Zeta

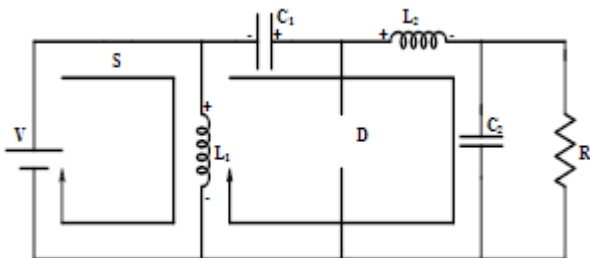


Fig 2 ON state model of Zeta converter

converter create a filter, which lowers the output ripple. The equivalent circuit for this mode is shown in fig 3.

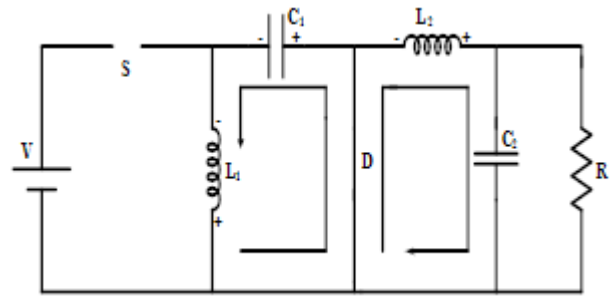


Fig 3.OFF state model of Zeta converter

2.1.3 Averaged Model of Zeta converter

ON state

By applying Kirchoff's current law,

$$\frac{di_1}{dt} = \frac{V_s}{L_1} \tag{1}$$

$$\frac{di_2}{dt} = \frac{V_s}{L_2} + \frac{V_{C1}}{L_2} - \frac{V_{C2}}{L_2} \tag{2}$$

By applying Kirchoff's voltage law,

$$\frac{dV_{C1}}{dt} = -\frac{i_{L2}}{C_1} \tag{3}$$

$$\frac{dV_{C2}}{dt} = \frac{i_{L2}}{C_2} - \frac{V_{C2}}{RC_2} \tag{4}$$

OFF state

By applying Kirchoff's current law

$$\frac{di_1}{dt} = -\frac{V_{C1}}{L_1} \tag{5}$$

$$\frac{di_2}{dt} = -\frac{V_{C2}}{L_2} \tag{6}$$

By applying Kirchoff's voltage law,

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

$$\frac{dV_{C2}}{dt} = \frac{i_{L2}}{C_2} - \frac{V_{C2}}{RC_2} \tag{8}$$

Output voltage at both modes,

$$V_0 = V_{C2} \tag{9}$$

Using ON state and OFF state matrix, the system state space equivalent matrices A, B, C and D are

$$A = \begin{bmatrix} 0 & 0 & \frac{-(1-\alpha)}{L_1} & 0 \\ 0 & 0 & \frac{\alpha}{L_2} & -\frac{1}{L_2} \\ \frac{1-\alpha}{C_1} & -\frac{\alpha}{C_1} & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 & -\frac{1}{RC_2} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{\alpha}{L_1} \\ \frac{\alpha}{L_2} \\ 0 \\ 0 \end{bmatrix}$$

$$C = [0 \ 0 \ 0 \ 1]$$

D = 0

2.1 Design of Zeta converter components

The Converter operating in continuous conduction mode is designed as follows. The specifications are Supply voltage $V_s = 120V$, Switching frequency $f_s = 100KHz$, Load resistance $R = 25\Omega$ Output voltage $V_o = 60V$, Load current $I_o = 5A$, Duty cycle $\alpha = 0.5$ taking into consideration the ripple current is 10% of the source current and the ripple voltage is 1.3 to 1.6% of the output voltage. The values are

$$\Delta i_{L_2} = \frac{\alpha V_s}{fL_2} = 0.4A \tag{10}$$

$$\Delta i_{L_1} = \frac{\alpha V_s}{fL_1} = 1A \tag{11}$$

$$\Delta i_{L_2} = \frac{\alpha V_s}{fL_2} = 0.4A \tag{12}$$

$$\Delta V_{C_1} = \frac{\alpha V_s}{8f^2 C_1 L_1} = 0.033A \tag{13}$$

$$\Delta V_{C_2} = \frac{\alpha V_s}{8f^2 C_1 L_2} = 0.048A \tag{14}$$

$$L_1 \geq \frac{(1-\alpha)^2 R}{2\alpha f} = 600\mu H \tag{15}$$

$$L_2 = \frac{(1-\alpha)R}{2f} = 1.3mH \tag{16}$$

$$C_1 \geq \frac{\alpha}{8f(1-\alpha)R} = 15\mu F \tag{17}$$

$$C_2 \geq \frac{1}{8fR} = 12\mu F \tag{18}$$

Table 1. Parameter values of Zeta converter

Components	values
Inductor L_1	600 μ H
Inductor L_2	1.3 mH
Capacitor C_1	15 μ F
Capacitor C_2	12 μ F
Resistive load	25 Ω
Input Voltage V_s	120 V
Frequency	100 KHz

The open loop transfer function is

$$\frac{V_o}{\alpha} = \frac{1.282e^7 S^2 - 7.288e^7 S^1 + 2.849e^{14} S}{S^4 + 3333S^3 + 1.014e^8 + 1.242e^{11} + 2.849e^{14}}$$

Poles are

$$\begin{aligned} & -1051.1 + 9733.2i \\ & -1051.1 - 9733.2i \\ & -615.4 + 1610.6i \\ & -615.4 - 1610.6i \end{aligned} \tag{19}$$

Zeros are

$$\begin{aligned} & 0.0000 + 4714.1i \\ & 0.0000 - 4714.1i \end{aligned}$$

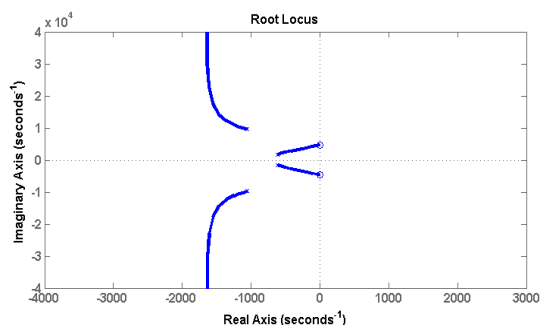


Fig 4. Root locus plot showing the location of poles

As all the poles are located in the left half of S-plane, the system is stable. The root locus is a plot of location of closed loop poles in the complex S-plane. The root locus branches starts from the poles of the transfer function and ends at zeros. Here, among the four root locus branches, two of the branches ends at zeros and two branches ends at infinity. The gain K is varied to obtain the plot. Since for all the values of K, the plot lies in the left half, the system is stable.

3. Control Schemes

3.1 PID Controller

The structure of the PID control system is

$$u(t) = K_p [e(t) + \frac{1}{T_i} \int e(t) dt + T_d \frac{de(t)}{dt}] \quad (20)$$

where $u(t)$ is the input signal, the error signal $e(t) = r(t) - c(t)$, $r(t)$ is the reference input signal, and $c(t)$ is the output signal.

The three functionalities of PID controller are

- i) Proportional term provides the control action proportional to the error signal through the gain factor.
- ii) Integral term is meant to reduce the steady state error to zero through low frequency compensator.
- iii) Derivative term provides an improvement in transient response by means of high frequency compensation

So a combination of PID controller is a lead-lag compensator having one pole at the origin and one zero at infinity. Since derivative term degrades stability, only PI controller is used in this work. For optimal performance, K_p and K_i terms must be properly tuned. Fig.5 shows the block diagram representation of Zeta converter with the PI Controller.

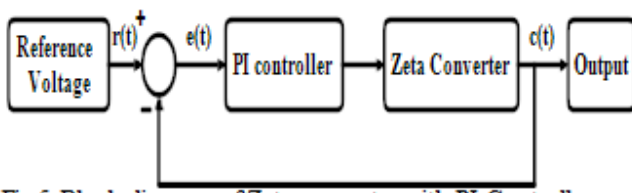


Fig.5 Block diagram of Zeta converter with PI Controller

3.2 Tuning of PI Controller

The controller parameters were obtained by Zeigler-Nichols method of tuning. In this method, the proportional gain was varied keeping Integral value as zero till sustained oscillations were obtained. Based on the critical time period (T_{cr}) and critical gain (K_{cr}), the values of proportional gain and integral gains are calculated. Hence the values of K_p and K_i obtained by Ziegler-Nichol's method was $K_p=1$ and $K_i =200$.

3.3 Sliding Mode Controller

Switched Mode Power Supplies exhibit non-linear nature which is represented as SMC, obtained from Variable Structure Systems. It provides various advantages such as stability even for large line and load variations, robustness, good dynamic response and easy to implement. VSS systems are system whose structure changes intentionally with time based on the control law. The control variables are directed in such a way which forces the system trajectory to approach a surface called as the sliding surface. The instance at which the changes occur in the system is determined by the current state of the system. The direction of the trajectory is independent of the system parameters. The trajectory is forced to follow the sliding surface.

3.3.1

Design of Sliding Mode controller

In this section, the controller employs a switching function to determine the input states. The switching function u can be determined from the control parameters x_1 and x_2 using the state trajectory computation.

$$S = \alpha x_1 + x_2 = Jx + 0$$

α - control parameter termed as sliding mode co-efficients

$$J = [\alpha, 1] \text{ and}$$

$$X = [x_1, x_2]$$

By enforcing $S = 0$, a sliding line with gradient α can be obtained. The purpose of this sliding line with gradient is to serve as a boundary to split the phase plane into two regions.

Each of this region is specified with a switching state to direct the phase trajectory towards the sliding line. (21)

When the phase trajectory reaches and tracks the sliding line towards the origin, the system is considered to be stable, i.e., $x_1=0$ and $x_2=0$. If the phase trajectory is at any arbitrary position above the sliding line ($S=0$), $u=1$ must be employed so that the trajectory is directed towards the sliding line. Conversely, when the phase trajectory is at any position below the sliding line, $u=0$ must be employed for the trajectory to be directed towards the sliding line. However there is no assurance that the trajectory can be maintained on this line.

3.4 Closed loop control

3.4.1 Proportional Integral and Sliding mode controller

Fig.6 shows the closed loop control of DC-DC Zeta converter with a cascaded controller which consists of both PI controller for voltage control and an SM controller for current control. The output voltage is compared with the reference voltage and the voltage error is eliminated by the PI controller by regulating the output voltage. The Inductor current is compared with the reference current and the current error is eliminated by the SMC control. The presence of right half plane zero [19] called as non minimum phase behavior of the converter makes its control with the single loop too difficult. To improve the performance and to make the converter to well track the reference voltage, a two loop control is used.

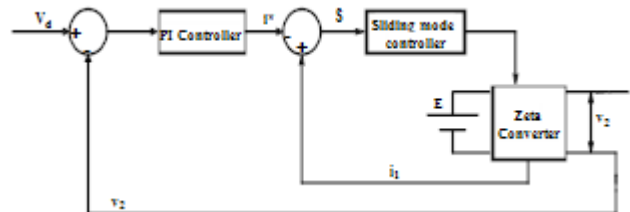


Fig.6. Block diagram of Zeta PI-SMC Controller

The current error is computed by means of a high pass filter and the voltage error is obtained by comparison with the reference voltage. A PI controller is used to eliminate the dc value which is present in the sliding function of the converter. The integral action is activated only when the system is on the sliding surface. In this way, the dynamic response of the converter is not affected thus maintaining a fast response during sliding.

In the voltage control mode, the voltage error is produced and it is eliminated by the use of PI controller. Sliding mode controller controls the current in the inner loop. It produces the current control signal which is given as a pulse to the MOSFET switch.

i_1 is the feedback current i^* is the reference current for the inner loop. V_d is the reference voltage. v_2 is the output voltage. S is the control signal. E is the voltage input to the Zeta converter.

Hence the control law is stated as

$$u = \begin{cases} 1 & \text{'ON' when } S > 0 \\ 0 & \text{'OFF' when } S < 0 \end{cases} \quad (21)$$

The switching signal is given by

$$S = i_1 - i^* \quad (22)$$

The control signal is

$$U = 0.5(1 - \text{sign}(S)) = 1 \text{ if } S < 0 \text{ or } 0 \text{ if } S > 0 \quad (23)$$

The switching function S and its derivative are equal to zero when the sliding mode occurs.

Before the sliding mode, it is in the reaching mode.

The existence condition of sliding mode can be checked by Lyapunov function. The function is chosen as

$$H = \frac{1}{2} S^2 > 0 \text{ if } S \neq 0. \quad (24)$$

$$H' = \frac{1}{2} * 2S * S' = SS' \quad (25)$$

Differentiating the switching signal S

$$S' = i_1' - i^* \quad (26)$$

$$i_1' = \frac{1}{L_1} [Eu - (1-\alpha)v_1] \quad (27)$$

$$S' = -(1-\alpha) \frac{1}{L_1} v_1 + \frac{E\alpha}{L_1} - i^* \quad (28)$$

$$SS' = S[-(1+\alpha) \frac{1}{L_1} v_1 + \frac{E\alpha}{L_1} - i^*] \quad (29)$$

$$| = \frac{S}{L_1} [(-1+\alpha)v_1 + E\alpha - L_1 i^*]$$

Substitute $\alpha = \frac{1}{2} \text{sign}(s)$ in the above equation

$$SS' = \frac{S}{L_1} [(-1 + \frac{1}{2}(1 - \text{sign}(s)))v_1 + E(\frac{1}{2}(1 - \text{sign}(s))) - L_1 i^*]$$

$$= \frac{S}{L_1} [-v_1 + \frac{1}{2} v_1(1 - \text{sign}(s)) + \frac{E}{2} - E \text{sign}(s) - L_1 i^*] \quad (30)$$

$$= \frac{S}{L_1} [-\frac{1}{2} v_1 - \frac{1}{2} v_1(1 - \text{sign}(s)) + \frac{E}{2} - E \text{sign}(s) - L_1 i^*] \quad (31)$$

$$= \frac{S}{2L_1} [2E - 2L_1 i^* - v_1 - v_1 |S| - E |S|]$$

$$(|2E - 2L_1 i^* - v_1| - v_1 - E) < 0$$

$$H' = SS' < \frac{1}{2L_1} |S| (|2E - 2L_1 i^* - v_1| - v_1 - E) \quad (32)$$

denotes the attraction domain for the sliding manifold.

Equivalent control

Sliding mode control requires that all the states be continuous and controllable. In order to achieve performance specification for the converter, the discontinuous control is replaced by a continuous equivalent control. The term α in discontinuous control is replaced by α_{eq} in continuous system. Solving $S' = 0$ for α_{eq} renders

$$S' = \frac{-(1-\alpha)v_1}{L_1} + \frac{E\alpha}{L_1} - i^* = 0 \quad (33)$$

$$\frac{-v_1}{L_1} + \frac{\alpha_{eq} v_1}{L_1} + \frac{E\alpha_{eq}}{L_1} - i^* \quad (34)$$

$$\alpha_{eq} \left\{ \frac{v_1}{L_1} + \frac{E}{L_1} \right\} - \frac{v_1}{L_1} - i^* \quad (35)$$

$$\alpha_{eq} = \frac{L_1 i^* + v_1}{v_1 + E}$$

3.4.2 To determine the parameters of k_p and k_i

The Routh array is

S^4	D_4	D_2	D_0
S^3	D_3	D_1	0
S^2	p_1	p_2	0
S^1	p_3	0	0
S^0	p_4	0	0

$$\text{Where } p_1 = (D_3 D_2 - D_4 D_1) / D_3,$$

$$p_2 = (D_3 D_0 - D_4 * 0) / D_3, p_3 = (p_1 D_1 - D_3 p_2) / p_1,$$

$$p_4 = p_3 p_2 / p_3$$

Routh Hurwitz criterion states that the necessary and sufficient condition for stability is that, all the elements in the first column of the Routh array be positive. Hence to satisfy stability, $D_4 > 0, D_3 > 0, p_1 > 0, p_3 > 0, p_4 > 0$ must be met. Using the above method, the values of K_p and K_i obtained are $K_p = 0.5, K_i = 53.1982$

4 Results and discussion

4.1. Case A: Set point tracking of PI Controller

A set point tracking method is used to track the output voltage in the converter. The reference voltages are set as 60V, 180 V, and 60 V at an interval of 0.1s. The transfer function is

$$\frac{V_o}{\alpha} = \frac{1.282e^{-7} S^2 - 7.288e^{-7} S^1 + 2.849e^{-14} S}{S^4 + 3333S^3 + 1.014e^8 + 1.242e^{11} + 2.849e^{14}}$$

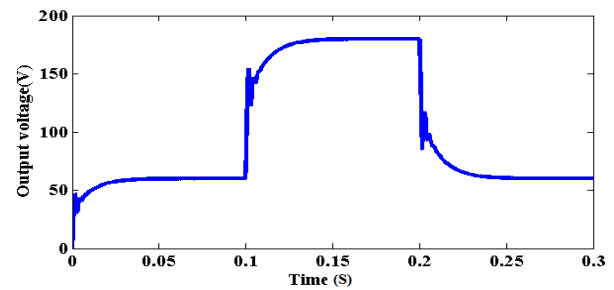


Fig.7. Output voltage of Zeta converter with PI Controller

4.2 Case B: Set point tracking of PI & SMC controller

The objective of control is to track a constant reference voltage amidst load and input voltage variations. Set point tracking of the output voltage is a condition in which the controller tracks the reference voltage asymptotically.

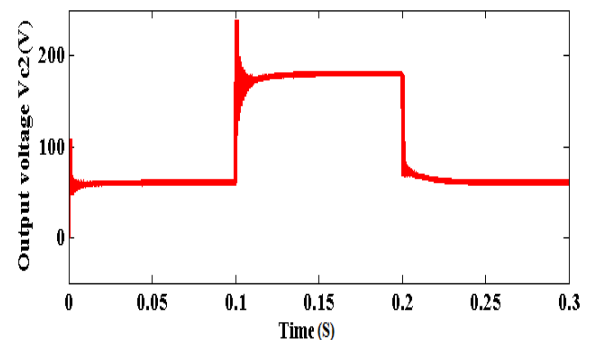


Fig.8. Output voltage of Zeta converter with PI and SMC Controller

The reference voltages are set as 60V, 180V, 60 V for a period

of 0.1s interval. Fig shows the response waveform for $V_d = 60V$ for 0 to 0.1sec, $V_d = 180V$ for 0.1 to 0.2sec, $V_d = 60V$ for 0.2 to 0.3s. The converter tracks the output voltage smoothly with a slight overshoot and little undershoot and the current converges to equilibrium the points. Due to the

Performance Analysis of PI and SMC Controlled Zeta Converter

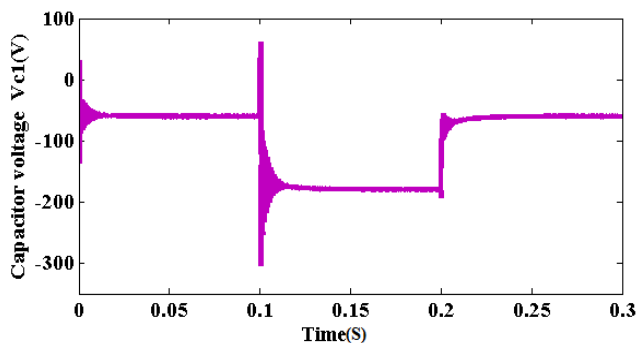


Fig.9. Capacitor voltage of Zeta converter with PI & SMC Controller

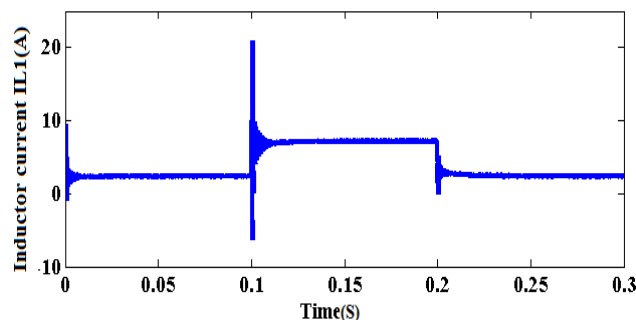


Fig.10. Inductor current 2 of Zeta converter with PI & SMC Controller

Non minimum phase behavior of the converter, a spike is Observed at the start of each interval after which the spike subsides.

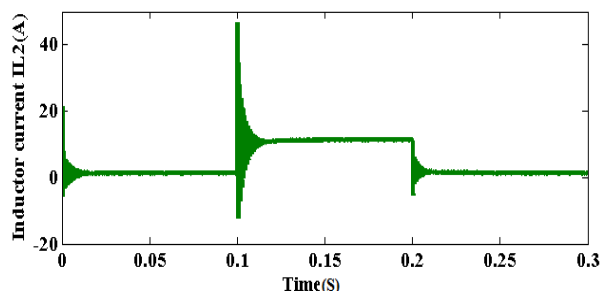


Fig.10. Inductor current 1 of Zeta converter with PI & SMC Controller

Table 4 Proportional and Integral gains of PI and PI-SMC Controller

Controllers	K_p	K_i
PI controller	1	200
PI- SMC controller	0.5	53.1982

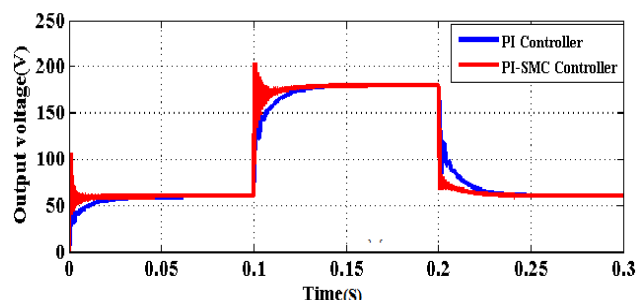


Fig.11 Output voltages of PI and PI-SMC Controller of Zeta converter

Table 4 shows the Proportional and Integral gains for PI tuned PI controller and PI & SMC controller. The values of K_p and K_i obtained for PI controller using Zeigler's-Nicholas method are 1 and 200 respectively whereas the values of K_p and K_i for PI & SMC controller tuned by root locus and Routh Hurwitz criterion are 0.5 and 53.1982 respectively.

Table 5 Performance indices comparison of PI and PI-SMC controller

Controllers	IAE	ITAE	ISE	ITSE
PI controller	1.579	0.2054	49.23	6.781
PI- SMC controller	0.5811	0.08015	11.31	1.545

Table 5 shows the steady state performance indices comparison of PI and PI-SMC Controller of Zeta converter. It can be inferred from the table that the IAE is reduced from 1.579 to 0.5811 and ITAE is also reduced from 0.2054 to 0.08015 which shows there is an improvement in the performance of PI-SMC Controller than the PI controller. Reduction in IAE and ITAE of PI- SMC controller results in the better steady state performance making the response of the PI-SMC Controller outperforming than the PI Controller.

III. CONCLUSION

PI-SMC controller with PI controller in the outer loop for voltage regulation and SMC controller in the inner loop for processing the current signal is done. To tune the PI parameter of PI-SMC controller, Root locus and Routh Hurwitz method is used and based on the locus of poles in the S-plane, the controller is tuned perfectly. Tabulated results shows that the parameters tuned by the proposed method yields reduction in IAE and ITAE proving the superiority of the controller over the conventional PI controller. MATLAB /Simulink results are also presented to validate the proposed approach.

REFERENCES

1. Power Electronics. Converters, Applications and Design (Ned Mohan, Tore M. Undeland, William P. Robbins), John Wiley and Sons, Inc, 2003.
2. S. Cuk and R. D. Middlebrook, 'Advances in Switched-Mode Power Conversion, vol II. Tesla Co., Pasadena, 1981.
3. H.Sira-Ramirez and R. Silva-Ortigoza, Control design techniques in power electronics devices. Springer science & Business Media, 2006.
4. K.J.Åström and T. Hägglund, *PID Controllers: Theory, Design, and Tuning*. Research Triangle Park, NC: Instrument Soc. Amer., 1995
5. K.J Åström, T.Hägglund, C. C. Hang, and W. K. Ho, "Automatic tuning and adaptation for PID controllers—a survey," *Control Eng. Pract.*, vol.1, no. 4, pp. 699–714, 1993
6. H. Si-Ramirez, 'Nonlinear P-I Controller Design for Switch Mode DC-DC Power Converters.' *IEEE Tmns. Circuits and Systems*, Volume: 38, Number: 4, pp. 410 -417, April 1991.
7. Utkin. "Sliding Modes and Their Application in Variable Structure Systems," MR FZl publishers, Moscow, Russia, 1978.
8. R.Venkatramanan, k Sabanovic and S. Cuk, "Sliding Mode Control of DC-TO-DC Converters," *in proceedings of IECON' 1985*. pp. 25 1 -258,1985
9. Vadim Utkin, "Variable Structure Systems with Sliding Modes" *IEEE Transactions On Automatic Control* vol AC.22, N°2 , April 1977
10. Utkin. V, Guldner.J, Jingxin, S. Sliding Mode Control in Electro-Mechanical Systems; CRC Press: Boca Raton, FL, USA, 2009; pp. 325–355.

11. J.Neely, R. DeCarlo, and S. Pekarek, "Real-time model predictive control of the C' uk converter," in *Proc. IEEE 12th Workshop Ctrl. Modeling Power Electron.*, Jun. 2010, pp. 1–8.
12. L.Flores, J. L. B. Avalos, and C. A. B. Espinoza, "Passivity-based controller and online algebraic estimation of the load parameter of the DC-to-DC power converter Cuk type," *IEEE Latin Amer. Trans.*, vol. 9, no. 1, pp. 50–57, Mar. 2011.
13. Mahdavi, M.R. Nasiri, A. Agah, and A. Emadi, "Application of neural networks and state-space averaging to DC/DC PWM converters in sliding mode operation," *IEEE/ASME Trans. Mechatronics*, vol. 10, no. 1, pp. 60–67, Feb. 2005.
14. L.G.Shiau and J.L.Lin, "Direct and indirect SMC control schemes for DC-DC switching converters", Proceedings of the 36th SICE Annual Conference. International Session Papers, Tokushima, 1997, pp. 1289-1294
15. Siew-Chong Tan, Y. M. Lai, C.K. Tse and M. K. H. Cheung, "A fixed-frequency Pulse width modulation based quasi sliding-mode controller for buck converters", in *IEEE Transactions on Power Electronics*, vol. 20, no. 6, pp. 1379-1392, Nov. 2005.
16. M. Zeinali and L. Notash, "Continuous sliding mode control design for a class of MIMO nonlinear uncertain systems: Theory and experiment," *2009 IEEE Control Applications, (CCA) & Intelligent Control, (ISIC)*, Saint Petersburg, 2009, pp. 1134-1139.
17. E. Kayacan, O. Cigdem and O. Kaynak, "Sliding Mode Control Approach for Online Learning as Applied to Type-2 Fuzzy Neural Networks and Its Experimental Evaluation," in *IEEE Transactions on Industrial Electronics*, vol. 59, no. 9, pp. 3510-3520, Sept. 2012.
18. L. Schmitz; D. C. Martins; R. F. Coelho, "Generalized High Step-Up DC-DC Boost-Based Converter With Gain Cell," in *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. PP, no. 99, pp. 1-14.
19. Y. Zhang; J. Liu; Z. Dong; H. Wang; Y. Liu, "Dynamic Performance Improvement of Diode-capacitor Based High Step-up DC-DC Converter Through Right-half-plane Zero Elimination," in *IEEE Transactions on Power Electronics*, vol. PP, no. 99, pp. 1-1
20. S.Durgadevi and M. G. Uma maheswari, "Analysis and design of single phase power factor correction with DC– DC SEPIC Converter for fast dynamic response using genetic algorithm optimised PI controller," in *IET Circuits, Devices & Systems*, vol. 12, no. 2, pp. 164-174, 3 2018.
21. G.Mühürçü, E. Kose, A. Muhurcu and A. Kuyumcu, "Parameter optimization of PI controller by PSO for optimal controlling of a Buck converter's output," 2017 International Artificial Intelligence and Data Processing Symposium IDAP, Malatya, 2017, pp. 1-6.
22. S. Mirjalili and S. Z. M. Hashim, "A new hybrid PSO-GSA algorithm for function optimization," 2010 International Conference on Computer and Information Application, Tianjin, 2010, pp. 374-377.
23. E. Z. Zhang, Y. F. Wu and Q. W. Chen, "A hybrid multi-objective PSO-GSA approach for environmental/economic dispatch," 2015 IEEE 10th Conference on Industrial Electronics and Applications (ICIEA), Auckland, 2015, pp. 455-460.
24. S. Sun and Q. Peng, "A hybrid PSO-GSA strategy for high-dimensional optimization and microarray data clustering," 2014 IEEE International Conference on Information and Automation (ICIA), Hailar, 2014, pp. 41-46.
25. M. R. Yousefi, S. A. Emami, S. Eshtehardiha and M. Bayati Poudeh, "Particle swarm optimization and genetic algorithm to optimizing the pole placement controller on Cuk converter," 2008 IEEE 2nd International Power and Energy Conference, Johor Bahru, 2008, pp. 1461-1465.



Deepa Thangavelusamy is currently working as an Associate Professor in the School of Electrical Engineering from Vellore Institute of Technology, Chennai Campus. She completed her Ph.D. from the College of Engineering, Guindy, Anna University in process control. She completed her B.Tech. in Electrical and Electronics Engineering from Manonmaniam Sundaranar University, Tirunelveli and M.Tech. from the College of Engineering, Guindy, Anna University in power system. Her research interest includes process control, control systems, power electronics and intelligent controllers.

AUTHORS PROFILE



Mariammal Thirumeni is a Research scholar at SELECT, VIT University, Chennai. She Completed her B.E in Electrical and Electronics from Manonmaniam Sundaranar University and M.E from College of Engineering, Guindy in Power electronics. Her research areas include Power electronics, Control systems.