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Performance Indices of Cuk Converter Implementing PI and PI-SMC Control

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ABSTRACT

Cuk converter operating in continuous conduction mode is designed. The transfer function model of the converter is obtained from the state space averaged model. Its of fourth order due to the presence of inductors and capacitors. Two controllers are implemented. They are Proportional-Integral(PI)and Proportional-Integral Sliding mode controller(PI-SMC). In PI controller, the values of PI gains are obtained by trial and error method whereas in PI-SMC, the gains are obtained by root locus method. The system stability is analyzed by Routh stability criterion. The performance indices such as ISE and IAE with their controllers are compared. The results obtained from simulation shows that the PI-SMC control gives better voltage regulation and less error than PI controller.

Keywords: Cuk Converter(DC-DC),PI controller, Sliding mode controller.

I. INTRODUCTION

DC-DC switching converters have become a keystone in power processing systems in contrast to signal processing systems.In Power processing systems, the dc-dc converters are used to control the power flow from the input to the output with maximum efficiency. The important features of power processing systems include voltage regulation, maximum power transfer, capability of association with other processes [1]. Nowadays Pulse Width Modulated (PWM) converters which gives optimal operation at specific operating points is discussed in [2]. A modified Zero Voltage Transition PW modulated Cuk converter is presented. Here Cuk converter provides better performance with minimum duty cycle and reduction in losses [3]. Paralleled DC-DC power converters sliding mode control with dual stage design is explained in[4],[5] discussed the implementation of various Non linear control in DC-DC converters.

Cuk Converters are converters which gives an output voltage, either greater or less than the input voltage. Designing a stable Cuk converter using classical control loop design methods is not an easy task .In order to ensure an adequate phase margin for stable operation, the value of reservoir capacitor C_2 needs to support full load current which seems to cause reliability problem for cuk converter topology. A converter for bipolar DC link based on SEPIC-Cuk combination is designed. The switching mode is shared by both converters and they operate at same duty cycle which does not require the synchronization of various switches [6]. A Zero Voltage Switching PWM active clamping Cuk operating at high frequency is presented [7]. Surface for ideal line regulation, surface for ideal load regulation and surfaces for hysteric current control are analyzed [8].

Power Factor Correction (PFC) Cuk Converter fed BLDC motor drive for low switching losses is done [9]. A Single stage three phase inverter based on Cuk Converter for PV applications is designed. With this inverter,the energy storage elements can be reduced in order to improve the reliability, size and total cost[10]. Inorder to extract Power Factor Correction (PFC) Cuk Converter fed BLDC motor drive for low switching losses is derived[9]. A Single stage three phase inverter based on Cuk Converter for PV applications is

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designed. With this inverter,the energy storage elements can be reduced in order to improve the reliability, size and total cost[10]. Inorder to extract the maximum power output from the Converters for solar panels, a novel maximum power point tracking technique is discussed[11]. Paralleled DC-DC converters under closed loop operation results in regulated output voltage is provided[12]. By implementing sliding mode control[13], the need to use expensive, large and high ESR electrolytic capacitor in the Cuk design can be eliminated and improvements in reliability are done[13].A Cuk converter implementing the clamping action is done in [14]. It overcomes the limitations of conventional cuk converter.

PI controller is used, as the derivative term is sensitive to noise[15].Various other control methods were explained such as current mode controller, Passivity based controller, Model Predictive control, neural network and Fuzzy logic controller[16]-[20] Sliding mode design is a time domain design through which the system can be characterized under small signal and large signal conditions. It is also a Non-linear control technique. The important feature of this approach is that, it is low sensitive to parameter variations. Based on the operating point, it exhibits variable structure .Hence called as Variable Structure Systems (VSS). A VSS is a system whose structure changes according to the current state of the system. Depending on the switching condition and the surface, the Cuk converter structure varies. Control law decides the performance of cuk converter using different control techniques. In Cuk converter ,the switching surface is represented as the combination of four state variable errors.A system using both PID control and SMC embraces better performances. [21]

This paper is organized as follows. Section I gives the introduction. Section II explains the Cuk converter model and their operation in ON and OFF modes. Section III explains the controllers used for Cuk Converter. Section IV explains the conclusion of the paper.

II. CUK CONVERTER MODEL

Cuk converter model is shown in Fig. 1. It consists of a source voltage V, a switch M, and freewheeling diode D. Two capacitors C_t and C_o are used.C_t transfers energy and C_o stores energy. Two inductors L_i and L_0 and a load resistor R are used. The Voltage across the capacitors are denoted as v_1 and v_2.The current through the inductors are denoted as i_1 and i_2 respectively. u denotes the control signal applied to the gate of MOSFET switch.

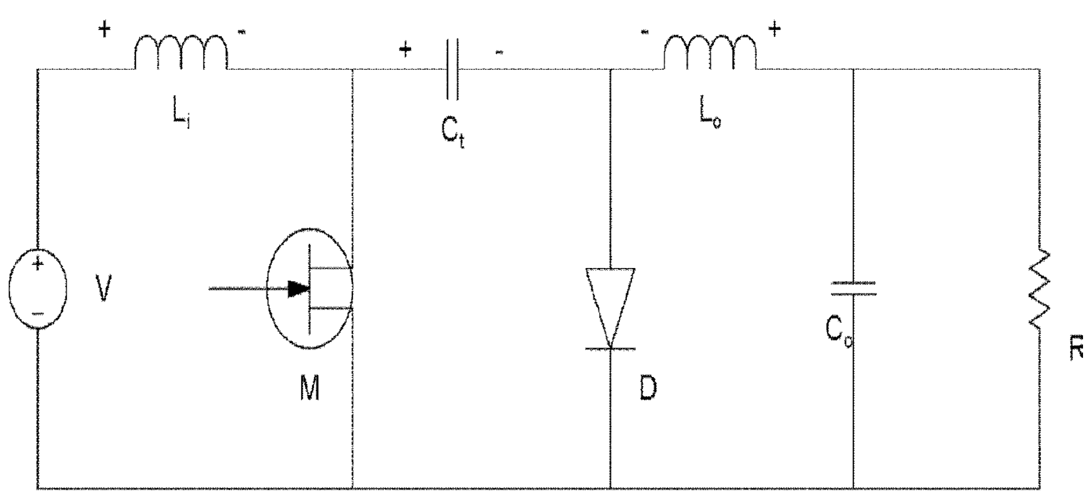


Figure 1: Cuk converter model

The charging and discharging modes are denoted as u=1 & u=0 are shown in Fig. 2 and Fig. 3 respectively.

Mode 1 (Switch ON)

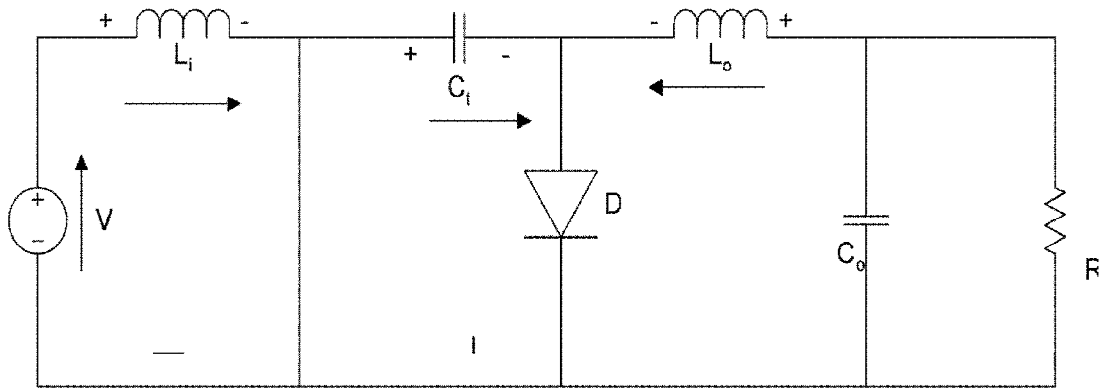


Figure 2: ON state mode of Cuk converter

Mode 2 (Switch OFF)

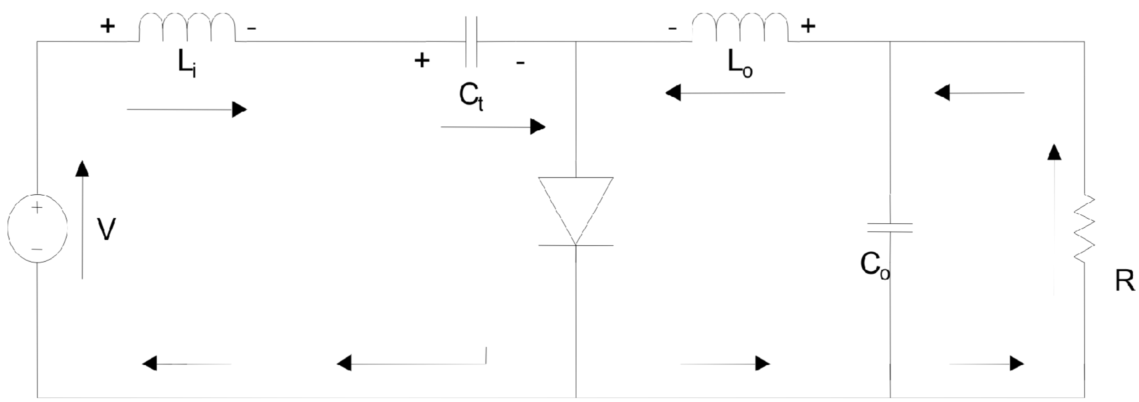


Figure 3: OFF state mode of Cuk converter

The state space equations of the Cuk converter are

$$\frac{di_1}{dt} = \frac{1}{L_i}\left[E-(1-u)v_1\right] \tag{1}$$

$$\frac{di_2}{dt} = -\frac{1}{L_o}\left[uv_1 + v_2\right] \tag{2}$$

$$\frac{dv_1}{dt} = \frac{1}{C_t}\left[ui_2 + (1-u)i_1\right] \tag{3}$$

$$\frac{dv_2}{dt} = \frac{1}{C_o}[i_2 - \frac{v_2}{R}] \tag{4}$$

Where i_1, $i_{2,}$ v_1 and v_2 are the state variables ,V is the source variable and u is the control variable.

The open loop transfer function is

$$\frac{0.000375s^3 - 0.16125s^2 + 160s + 130000}{8.4375e^{-7}s^4 + 0.0044625s^3 + 5.58875s^2 + 3320s + 130000}$$

III. CONTROLLERS USED IN CUK CONVERTER

Two control techniques used are PI , PI-SMC.

A.PI Controller

The most commonly used controller is PID controller. This controller calculates the error as the difference between the measured variable and the desired set point. Three parameters are involved called the three term control. The proportional, the integral and the derivative term .The proportional value determines the reaction to the current error ,the integral value determines the reaction to the accumulation of the past error and the derivative term predicts future error based on the current rate of change of error. Here a controller with Proportional Integral control is used, as the derivative action is sensitive to noise whereas the absence of integral value may prevent the system from reaching the steady state value. PI controller is basically a low pass filter and systems with such controller will have a slower rise time and longer settling time.

Input signal is the step signal. The output is the measured variable. The error signal is the difference between the input and the measured variable. Proportional term leads to an overshoot, integral term reduces the steady state error and the derivative term is used for damping the response. During steady state, the system is very steady because of the absence of derivative term. Here the response is slower compared to PID controller. The values of $K_{p,}$, K_i are obtained by trial and error method.

Proportional gain=9.8,Integral gain=180.

The block diagram of Cuk converter with PI controller is shown in Fig. 4.

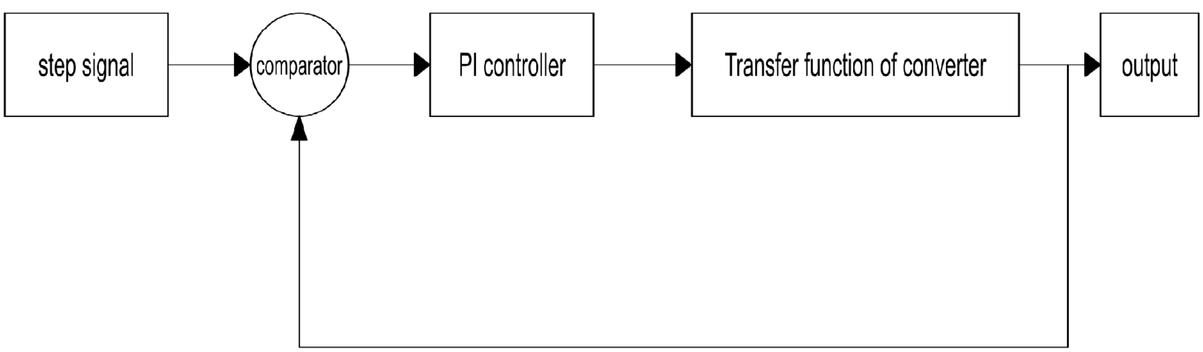


Figure 4: Block diagram of Cuk converter with PI controller

Fig. 5 Shows the response of Cuk converter with PI controller.The output voltage is -200 V upto 0.1 sec. At 0.1 sec, the output voltage is increased to -50V upto 0.2 sec. After that it decreases from 0.2 to 0.3 sec to -200 V.

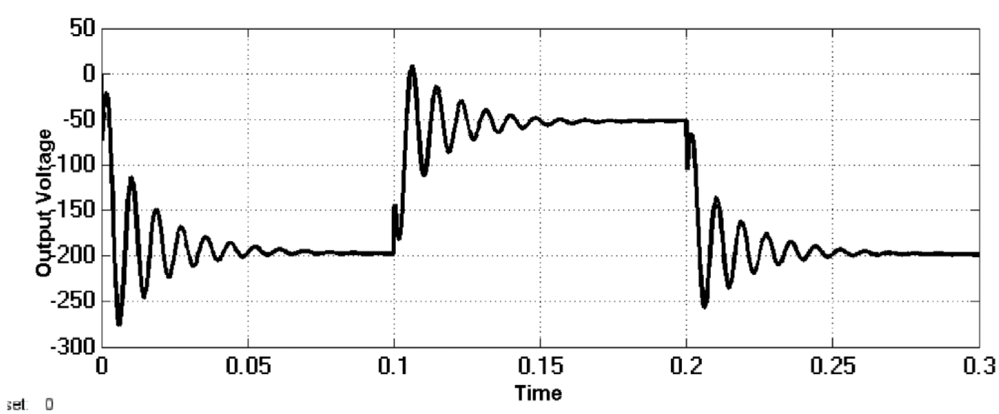


Figure 5: Response of Cuk converter with PI controller

(B) Sliding mode control

Filippov's method is used to investigate the existence of sliding mode motions in a converter. Its immediate corollary proposed by Utkin *et al.* [22] is called as equivalent control method.The substitution of the control variable in the switched model of the converter leads to the sliding ideal dynamics.

The motion of the system on the switching line or a surface is called as sliding. A sliding mode is said to exists if in the location of switching surface the state velocity vectors are directed towards the surface. The switching surface attracts trajectories whenever they are nearby and once the trajectory intersects the switching surface ,it will stay on it. A surface is attractive if

i) The trajectory starts on the surface remains there and

ii) The trajectory starts outside the surface tends to it at least asymptotically.

The equation for sliding mode control can be written as

$$s\dot{s} < 0 \tag{5}$$

This condition is an attractive domain of sliding mode control.For any system ,this criteria should be satisfied both in the transient and in the steady state.

Here PI-SMC controller is used.

(C) PI-SMC controller

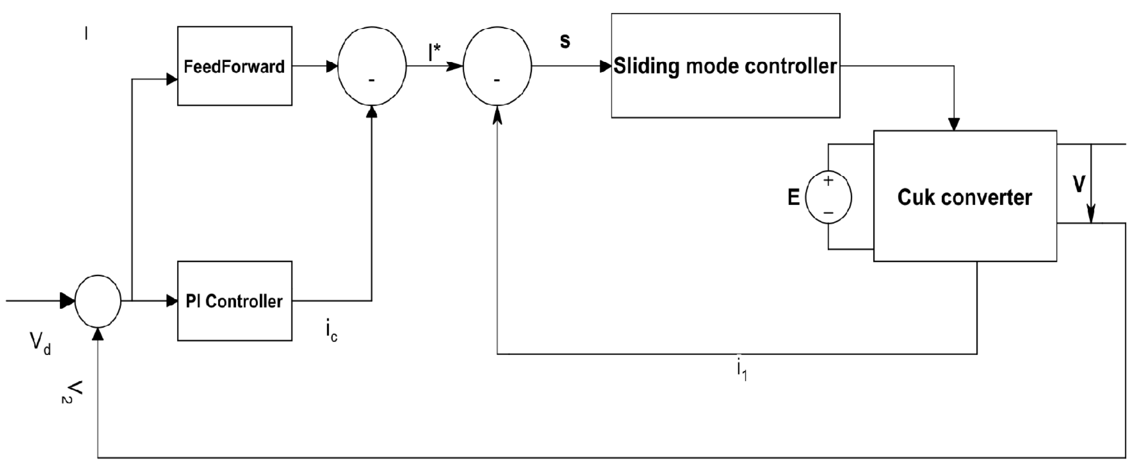


Figure 6: Block diagram of PI-SMC control

Fig. 6. Shows the block diagram of PI-SMC control. It is a combination of outer voltage loop and an inner current loop. The Cuk converter when operated in the open loop mode,a voltage error is produced and it is is eliminated by the use of PI controller .To control the inductor current ,sliding mode controller is used. In the current loop, the sliding mode current control signal is obtained which is given as the gate signal to the MOSFET switch.The overall current reference for the current loop is $i^*=i_{1d} + i_c$

The switching signal is given by

$$s = i_1 - I^*. \tag{6}$$

The control signal is

$$U=0.5(1-\text{sign}(s)) = 1 \text{ if } s< 0 \text{ or } 0 \text{ if } s>0. \tag{7}$$

The existence condition of the sliding mode can be derived with a Lyapunov function. Let this function be

$$P = 0{,}5\ s^2 > 0 \text{ is } S \neq 0. \quad (8)$$

Differentiating yields

$$s' = -(1-u)\frac{1}{L}v + \frac{E}{L} - i^{*\prime} \quad (9)$$

The derivative of P is

$$P' = ss' \leq \frac{1}{2L}|s|(|2E - 2L_i i^{*\prime} - v_1| - v_1) \quad (10)$$

The sufficient condition for P'< 0 is

$$|2E - 2L_i i^{*\prime} - v_1| - v_1 < 0 \quad (11)$$

In the steady state, $v_2$is negativeand can be greater or lesser than E. The cuk converter produces lesser inverted output voltage with opposite polarity. Here the values of Kp ,Ki are obtained by Routh stability theorem.

(i) Routh Hurwitz criterion

This is a time domain approach to determine the location of roots of the characteristic polynomial. It involves two steps. First the Routh table is prepared from the co-efficients of the characteristic polynomial and then from the table, the location of the roots either in the LH, RH or in the imaginary axis is determined.It gives an idea about how much the gain of the system can be increased before the closed loop system becomes stable. From the location of the poles and zeros, the stability can be determined.

Consider the characteristic equation

$$a_0 s^n + a_1 s^{n-1} + \ldots\ldots.. + a_{n-1} s^{n-1} + a_n = 0. \quad (12)$$

The Routh mode second order approximation of the loop transfer function is

$$\frac{31.56s + 2.565e^4}{s^2 + 686.5s + 5.129e^4} \quad (13)$$

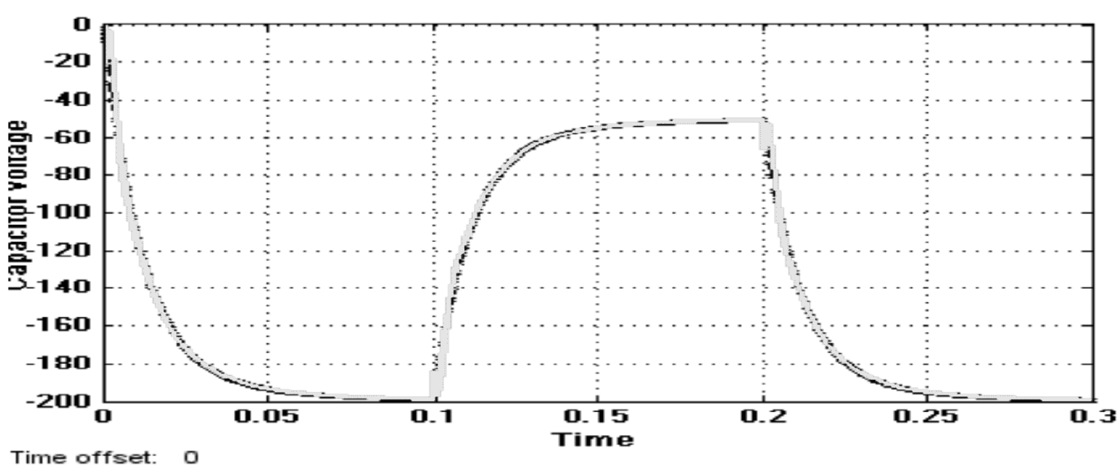


Figure 7: Shows the output voltage waveform for Routh mode second order approximation which resembles the same as fourth order waveform.

With PI controller

$$s^3 + 2\delta w_n s^2 + K_p w_n{}^2 s + K_i w_n{}^2 = 0 \tag{14}$$

To find the absolute stability with RH criterion,

i) The co-efficients in the first column of the Routh array must be positive.

ii) All the co-efficients in the characteristic polynomial must be present .If any of the co-efficient is zero, then the roots will be in the RHP or on the imaginary axis ,hence the system is unstable.

(ii) Routh Array

The Routh array is formed as

$$\begin{array}{|l l l l} s^3 & a_o & a_2 & a_4 \\ s^2 & a_1 & a_3 & a_5 \\ s^1 & h_o & h_1 & \\ s^0 & h_2 & a_5 & \end{array}$$

$$h_o = \frac{a_1 a_2 - a_0 a_3}{a_1}$$

$$h_1 = \frac{a_1 a_4 - a_o a_5}{a_1}$$

$$h_2 = \frac{h_o a_3 - a_1 h_1}{h_o}$$

The values of Kp ,ki are obtained by keeping one value fixed and by varying the other parameter.A real pole gets closer to the imaginary axis if the value of K increases .The pair of complex conjugate poles also moves closer to the imaginary axis. Hence the marginal value of K for stability of the system can be predicted by root locus method.

(iii) Minimum and Non minimum phase system

Minimum phase system is one which has all the poles lying in the left half plane and non-minimum system has atleast one zero or pole in the right half plane. With this converter, four poles and three zeros makes the converter stable.

Table 1
Design Parameters

Inductor L_i	30 mH
Inductor L_0	30 mH
Capacitor C_t	150 µF
Capacitor C_0	50 µF
Resistive load	10 &!
Input Voltage E	100 V
Reference Voltage V_d	-200
Proportional Gain K_p	-0.01
Integral Gain K_i	-13

(iv) Set point tracking

The switching frequency is chosen as 100KHz.and the minimum sliding mode pulse width is 10 microseconds. If low value of switching frequency is chosen, current ripples are produced more. Hence higher switching frequency is chosen. Here the PI gains are k_p=-0.01 and k_i=-13.This is obtained by Routh –Hurwitz criterion and root locus method.

The open loop transfer function is

$$\frac{0.000375s^3 - 0.16125s^2 + 160s + 130000}{8.4375e^{-7}s^4 + 0.0044625s^3 + 5.58875s^2 + 3320s + 130000} \tag{13}$$

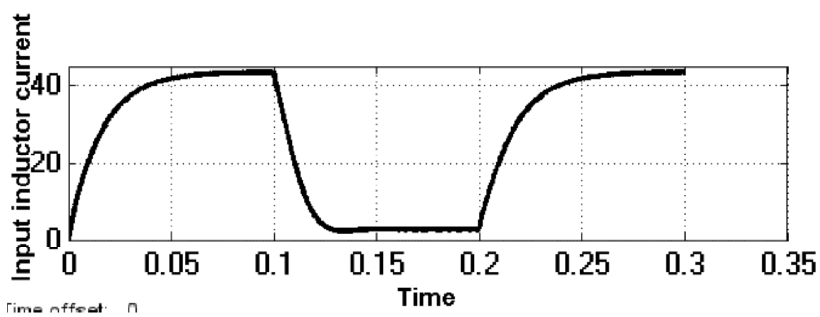
The poles of open loop transfer function are

-3.8227 + 0.0000i, -0.7121 + 0.6722i, -0.7121 - 0.6722i, -0.0420 + 0.0000i.

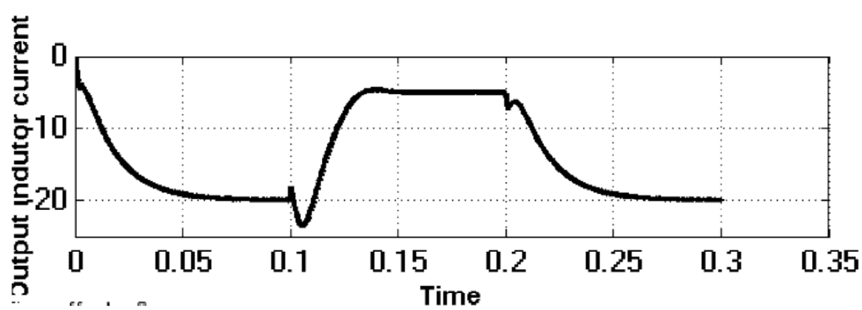
The zeros are

4.5852 + 8.1649i, 4.5852 - 8.1649i, -4.3926 + 0.0000i.

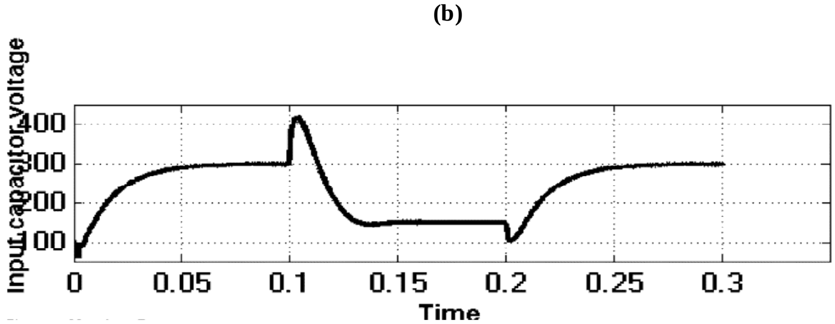
The dominant pole is -42 which decides the transient behaviour of the system. Two zeros in the right half phase plane. The results shows the system response for variation in the reference voltage .The voltage waveform is expected to have a non-mimimum phase behaviour. The diagram shows the response waveform for Vref=-200V from 0 to 0.1s,Vref=-50V from 0.1 to 0.2s and Vref=-200V from 0.2 to 0.3s.It is observed that the voltage and current converges to the equilibrium points. The waveforms for capacitor voltages and inductor currents are shown.



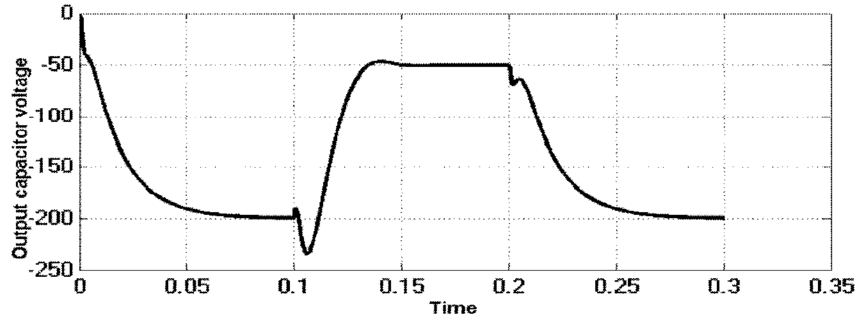
(a)



(b)



(c)



(d)

Figure 8: Capacitor voltages and Inductor currents for variation in reference voltage

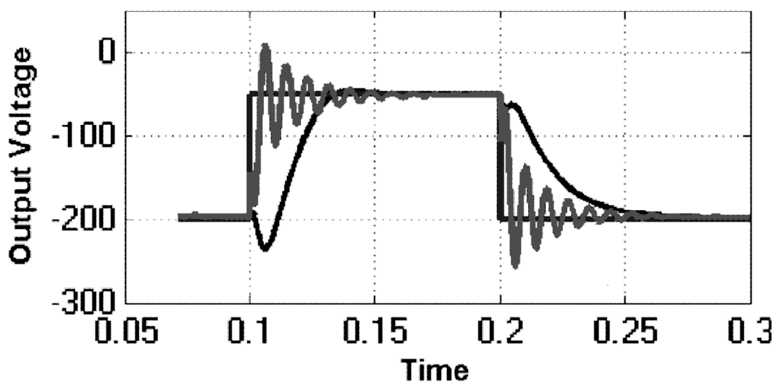


Figure 9: Errors in PI and PI-SMC controller

Table 2
Performance indices comparision of PI and PI-SMC controller

Controller	*ISE*	*IAE*
PI	9.554	2.151
PI-SMC	4.244	1.29

IV. CONCLUSION

Cuk converter is designed and simulated in the continuous conduction mode. Simulation shows that the Cuk converter was simulated with PI and PI-SM controllers. The error was obtained with both the controllers and their results were compared.It shows that the PI-SM control shows less error compared to PI controller and provides a better voltage regulation**.**

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