

Comparative Analysis of Performance of the SEPIC Converter Using PID and Fuzzy Logic Controllers for LED Lighting Applications

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Abstract— This paper presents an analysis of the dynamic performance on DC-DC SEPIC (Single Ended Primary Inductor Converter) converter which is operating in continuous conduction mode (CCM) with PID and fuzzy logic controller implementation. The operational analysis and design is done for 20W load. SEPIC converter is a suitable converter when the input voltage has got wide variations around the rated voltage. One of the applications in which source side variations are wide is LED lighting fed by battery which is charged from PV systems present in street lighting in rural areas. Similarly, the other application is LED lamps fed by AC source considering universal input range. Therefore, importance is given to source side disturbance of SEPIC converter. Hence in this paper, a PID controller and fuzzy logic controller have been implemented to improve the dynamic and steady state performance of the SEPIC converter when source voltage is subjected to wide variations keeping the output voltage at a constant value at steady state. Simulation results have been obtained using MATLAB/SIMULINK. The percentage overshoot, rise time and settling time have been compared and analyzed.

Index Terms—DC-DC power conversion, Fuzzy Logic controller, Proportional Integral Derivative (PID) control, SEPIC converter.

I. INTRODUCTION

Due to the recent advancement in the Light Emitting Diode (LED) technology, it is regarded as the next generation green light source because of its environment friendliness, longer life time, high efficacy, flicker free and compact size over the conventional lighting devices such as incandescent bulbs, halogen bulbs and even the compact fluorescent light bulbs. As these LED lamps require low voltage DC source, they may be supplied through battery or AC supply from the grid is rectified and then filtered to obtain the required DC voltage. But the variations normally considered in the AC supply side is 90 – 270V, DC output voltage of the rectifier will also have corresponding wide variations. SEPIC converter is a suitable converter when the input voltage has got wide variations around the rated voltage. This is because

SEPIC is a DC to DC converter which is capable of operating in either step up or step down mode.

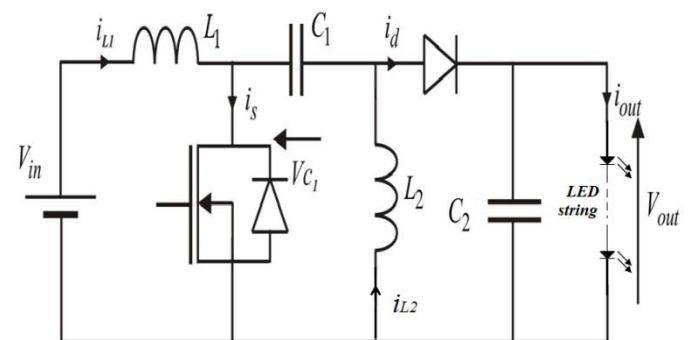


Fig.1 Circuit diagram of the SEPIC converter

For duty cycle above 0.5, it will step up and below 0.5; it will step down the voltage to the required value. But conventional power converter such as buck, boost and buck-boost converters cannot maintain a wide operation range with high efficiency, especially if up-and-down voltage conversion has to be achieved. These characteristics can be obtained in a Single Ended Primary Inductor Converter (SEPIC). Also, the SEPIC converter provides positive regulated output voltage for the given input voltage unlike the buck-boost converter which provides negative regulated output voltage. Isolation is provided by series coupling capacitor which protects the converter when short circuit occurs. Non- inverted output, low equivalent series resistance (ESR) of coupling capacitor minimizes ripple and prevent heat built up which make it reliable for wide range of operation. Some of the drawbacks in conventional buck-boost converter like inverted output, pulsating input current, high voltage stress and floating switch make it unreliable for the wide range of operation. So in order to overcome this, SEPIC converter is used. Simple topologies like the Buck, Boost and Buck-Boost being insufficient for such demands, more complex converters, like the SEPIC (Simple Ended Primary Inductor Converter), shown in Figure1, are of great interest to fulfill these requirements, which could lead to the design of a “universal DC-DC converter”. Therefore, this

converter is suitable for applications whose input voltage has got wide variations around the nominal voltage such as battery based applications, Maximum Power point Tracking in PV applications, regulating the voltage in renewable applications such as Wind, Solar and Hydel power generation. Converter modeling has been a huge field of research. The implementation of control laws and algorithms requires very accurate models that represent, to a great extent, the behavior of an electronic circuit. This has been the most challenging task to power electronics and control engineers and researchers.

II. MODES OF OPERATION

This type of converter gives the output voltage whose magnitude is greater or lesser than the input voltage. It provides non-inverting output and positive voltage gain. The output of the SEPIC converter is controlled by the duty cycle of the MOSFET switch. It is a Buck-Boost derived topology, but has a non-inverted output i.e., the output voltage polarity is same as the input voltage. Here it consists of a series (coupling) capacitor C1 which is mainly used to couple the energy from the input to the output (and thus can respond more gracefully to a short circuit output) and being capable of true shutdown, when the switch is turned off i.e., its output drops to zero volt. The SEPIC converter exchanges the energy between the capacitors and inductors in order to convert from one voltage to another. The amount of energy that is exchanged is controlled by switch S1, which is typically a transistor such as a MOSFET; MOSFET switch offers much higher input impedance and lower voltage drop than bipolar junction transistors (BJTs), and do not require biasing resistors as MOSFET switching is controlled by differences in voltage rather than a current, as with BJT switches.

A. Continuous conduction mode

A SEPIC converter is said to be operating in continuous-conduction mode if the current through the inductor L1 never falls to zero. During the steady-state operation of the SEPIC converter, the average voltage across capacitor C1 (V_{C1}) is equal to the input voltage (V_{in}). Because capacitor C1 blocks direct current (DC), the average current across it (I_{C1}) is zero, making inductor L2 the only source of load current. Therefore, the average current through inductor L2 (I_{L2}) is the same as the average load current and hence independent of the input voltage.

Looking at average voltages, the following can be written:

$$V_{in} = V_{L1} + V_{C1} + V_{L2} \quad (1)$$

Because the average voltage of V_{C1} is equal to V_{IN} ,

$$V_{L1} = -V_{L2} \quad (2)$$

For this reason, the two inductors should be wound on the same core material. Since the voltages are the same in magnitude, their effects of the mutual inductance will be zero, assuming the polarity of the windings is correct. Also, since the voltages are the same in magnitude, the ripple currents from the two inductors will be equal in magnitude. The average currents can be summed as follows:

$$I_{D1} = I_{L1} - I_{L2} \quad (3)$$

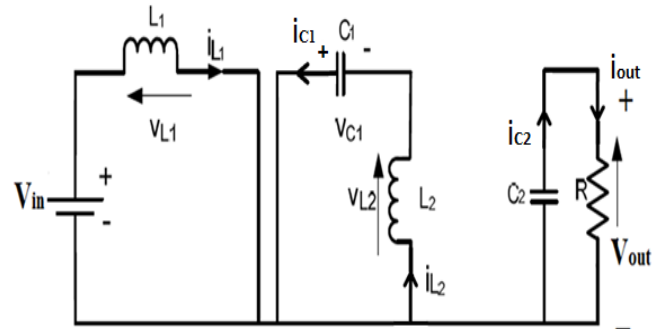


Fig.2 Circuit operation when Switch (S1) is closed

When switch S1 is turned on, current I_{L1} increases and the current I_{L2} increases in the negative direction. (Mathematically, it decreases due to arrow direction.) The energy to increase the current I_{L1} comes from the input source. Since S1 is a short while closed, and the instantaneous voltage V_{C1} is approximately V_{IN} , the voltage V_{L2} is approximately $-V_{IN}$. Therefore, the capacitor C1 supplies the energy to increase the magnitude of the current in I_{L2} and thus increase the energy stored in L2. The simplest way to visualize this is to consider the bias voltages of the circuit in a d.c. state, then close S1.

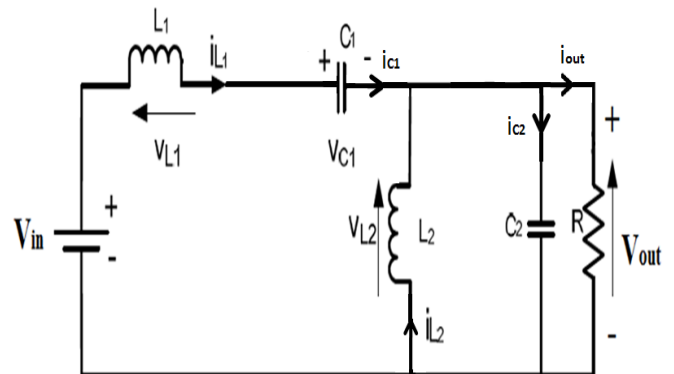


Fig.3 Circuit operation when Switch (S1) is open

When switch S1 is turned off, the current I_{C1} becomes the same as the current I_{L1} , since inductors do not allow instantaneous changes in current. The current I_{L2} will continue in the negative direction, in fact it never reverses direction. It can be seen from the diagram that a negative I_{L2}

will add to the current I_{L1} to increase the current delivered to the load.

Using Kirchoff's Current Law, it can be shown that

$$I_{D1} = I_{C1} + I_{L2} \quad (4)$$

It can then be concluded, that while S1 is off, power is delivered to the load from both L2 and L1. C1, however is being charged by L1 during this off cycle, and will in turn recharge L2 during the on cycle. Because the voltage (potential) across capacitor C1 may reverse direction every cycle, a non-polarized capacitor should be used. However, an electrolytic capacitor may be used in some cases, because the voltage across the capacitor C1 will not change unless the switch is closed long enough for a half cycle of resonance with inductor L2, and thus the current in inductor L1 could be quite large. The capacitor C_{IN} is required to reduce the effects of the parasitic inductance and internal resistance of the power supply. The boost/buck capabilities of the SEPIC are possible because of capacitor C1 and inductor L2. Inductor L1 and switch S1 create a standard boost converter, which generates a voltage (V_{S1}) that is higher than V_{IN} , whose magnitude is determined by the duty cycle of the switch S1. Since the average voltage across C1 is V_{IN} , the output voltage (V_O) is $V_{S1} - V_{IN}$. If V_{S1} is less than double V_{IN} , then the output voltage will be less than the input voltage. If V_{S1} is greater than double V_{IN} , then the output voltage will be greater than the input voltage.

B. Design of SEPIC Converter

The design of the SEPIC converter is based upon the following formulae.

The maximum duty cycle is given as,

$$D_{max} = \frac{V_{out} + V_D}{V_{in(min)} + V_{out} + V_D} \quad (5)$$

The minimum duty cycle is given as,

$$D_{min} = \frac{V_{out} + V_D}{V_{in(max)} + V_{out} + V_D} \quad (6)$$

The ripple current flowing is equal for both the inductors L1 and L2 is given as,

$$\Delta I_L = I_{out} \times \frac{V_{out}}{V_{in(min)}} \times 40\% \quad (7)$$

The inductor value is calculated as,

$$L_1 = L_2 = L = \frac{V_{in(min)}}{\Delta I_L \times f_{sw}} \times D_{max} \quad (8)$$

As per the thumb rule, the coupling capacitor C1 is taken as $10\mu F$.

The output capacitor is given as,

$$C_2 \geq \frac{I_{out} \times D_{max}}{V_{ripple} \times 0.5 \times f_{sw}} \quad (9)$$

Therefore, the values of the duty cycle range, inductors L1, L2 and capacitors C1, C2 are calculated by using the above equations and it is shown in table-I.

TABLE – I: Design parameters of SEPIC converter

Model parameters	Values
Input voltage	12 volts
Power	20 Watts
Output voltage	15 volts
Switching frequency	20 KHz
Duty cycle range	0.34 to 0.66
Resistance	11.25 ohms
Output current	1.33 amps
Inductor L1	2.646×10^{-4} H
Inductor L2	2.646×10^{-4} H
Coupling capacitor C1	$10\mu F$
Output capacitor C2	4.389 mF

III. MODELLING OF CONVERTER

Modelling of a particular converter is done by either Circuit Averaging method or State Space Averaging method. Analytical and circuit based models that become complicated for fourth order, and some second order systems [3]. The simplest approach is to use the state space analytical method. Mathematical model determines the voltage, current and signal transfer function of the switching converter.

A. State Space Analysis

State Space Analysis of SEPIC converter for continuous conduction mode can be done in two modes of operation. For a given network has two states in CCM, S1 on, S2 off

and S1 off, S2 on, the response of the network in each state may be time weighted and averaged.

The state equations can be expressed in matrix form as,

$$\begin{aligned} \dot{X} &= A_1x + B_1u & (10) \\ Y &= C_1x + D & (11) \end{aligned}$$

Where \dot{X} is the time derivative of the state variable vector, A_1 is the state matrix, x is the state variable vector, B_1 is the input matrix, u is the input, and Y is the output.

The state variables are taken as,

$$x_1 = i_{L1}, \quad x_2 = i_{L2}, \quad x_3 = V_{C1}, \quad x_4 = V_{C2}$$

Mode 1: Switch S- ON ($0 < t < DT$)

$$A_1 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{L_2} & 0 \\ 0 & -\frac{1}{C_1} & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{RC_2} \end{bmatrix} \quad B_1 = \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Mode 2: Switch- OFF ($DT < t < (1-D)T$)

$$A_2 = \begin{bmatrix} 0 & 0 & -\frac{1}{L_1} & -\frac{1}{L_1} \\ 0 & 0 & 0 & -\frac{1}{L_2} \\ \frac{1}{C_1} & 0 & 0 & 0 \\ \frac{1}{C_2} & \frac{1}{C_2} & 0 & -\frac{1}{RC_2} \end{bmatrix} \quad B_2 = \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

The state space averaged equation is given as,

$$\dot{X} = [A_1d + A_2(1-d)]x + [B_1d + B_2(1-d)]u \quad (12)$$

Therefore, the large signal model is expressed as,

$$\begin{bmatrix} \dot{i}_{L1} \\ \dot{i}_{L2} \\ \dot{v}_{C1} \\ \dot{v}_{C2} \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{d-1}{L_1} & \frac{d-1}{L_1} \\ 0 & 0 & \frac{d}{L_2} & \frac{d-1}{L_2} \\ \frac{1-d}{C_1} & -\frac{d}{C_1} & 0 & 0 \\ \frac{1-d}{C_2} & \frac{1-d}{C_2} & 0 & -\frac{1}{RC_2} \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{C1} \\ v_{C2} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \end{bmatrix} [u]$$

Determining the small signal control-to-output transfer function is analogous to the large signal case. It should become apparent that the state space method of deriving equations for any given variable in terms of another variable, large signal or small signal becomes controllable using elementary matrix operations. Overall this process allows one to easily derive the transfer functions and determine the response of a given network.

The transfer function of audio susceptibility is expressed as,

$$\frac{V_{out}}{V_{in}} = \frac{3.811 \times 10^5 s^2 - 1.733 \times 10^{-6} s + 8.013 \times 10^{13}}{s^4 + 20.175s^3 + 1.918 \times 10^8 s^2 + 3.862 \times 10^8 s + 6.399 \times 10^{13}} \quad (13)$$

The transfer function of the control voltage gain is expressed as,

$$\frac{V_{out}}{\hat{d}} = \frac{-682.75^3 + 2.06 \times 10^7 s^2 - 1.43 \times 10^{11} s + 3.895 \times 10^{15}}{s^4 + 20.175s^3 + 1.918 \times 10^8 s^2 + 3.862 \times 10^8 s + 6.399 \times 10^{13}} \quad (14)$$

The above obtained transfer function is used to calculate the Kp, Ki and Kd values of the PID controller which is briefly explained in section IV(A). For better transient and steady state response of the system, PID controller is incorporated in the feedback path.

IV. CONTROLLERS

A. PID Controller

A Proportional-Integral- Derivative controller (PID controller) is a control loop feedback mechanism which is widely employed in controllers being used in industries. A PID controller computes an error value as the difference between a measured process variable and a desired setpoint. The controller attempts to minimize the error by adjusting the process through the use of a manipulated variable. With the help of the obtained transfer functions in equation 13 and 14, by using Ziegler- Nicholas method, the Kp, Ki and Kd values are calculated for the PID controller.

The steps to determine the values of the PID controller are:

From the obtained transfer function in equation 13 the characteristic equation is calculated and equated to zero,

$$1+G(S) H(S) = 0 \tag{15}$$

The characteristic equation which is calculated for the designed SEPIC converter is given as,

$$S^4 + 20.17S^3 + 1.9218 \times 10^8 S^2 + 3.862 \times 10^9 S + 14.412 \times 10^3 = 0$$

By using the Routh-Hurwitz method, the critical gain K_c is determined. The K_p , K_i and K_d values are found using the formulae in table II.

TABLE –II: Formulae for the PID controller using Ziegler-Nicholas method

Type	K_p	T_i	T_d
PID	$0.6 K_c$	$0.5 T$	$0.125 T$

From this, the K_p , K_i and K_d are obtained as,

$$K_p = 0.6 K_c \tag{16}$$

$$K_i = K_p / T_i \tag{17}$$

$$K_d = K_p \times T_d \tag{18}$$

The proportional and derivative controller will reduce the rise time and over shoot, hence the dynamic response is better. Integral controller reduces the steady state error and hence the steady state response is better. The comparator compares the output voltage with reference output voltage which is 15V to calculate the error and this error is given as input to the PID controller. The output of PID controller is used to control the duty cycle of the gate pulse given to the MOSFET. The DC output voltage V_{out} is stabilized at the reference value even during the changes in input voltage and the load.

B. Fuzzy Logic Controller

FUZZY Logic Control (FLC) has been successfully applied to a wide variety of engineering problems, including dc-dc converter. It has been shown that fuzzy control can reduce development costs and provide better performance than the linear controllers. Fuzzy control is an attractive control method because of its structure, which consists of fuzzy sets that allow partial membership and “if . . . then . . .” rules, resembles the way human intuitively approaches a control problem [8]. Fuzzy control is of great value for problems where the system is difficult to model due to complexity, nonlinearity, and or imprecision. In this proposed Fuzzy Logic Controller, triangular membership functions have been used both for input and output variables [9]. The implication is done by mamdani type and the method of defuzzification is centroid. General block diagram of fuzzy logic controller is shown in figure 4.

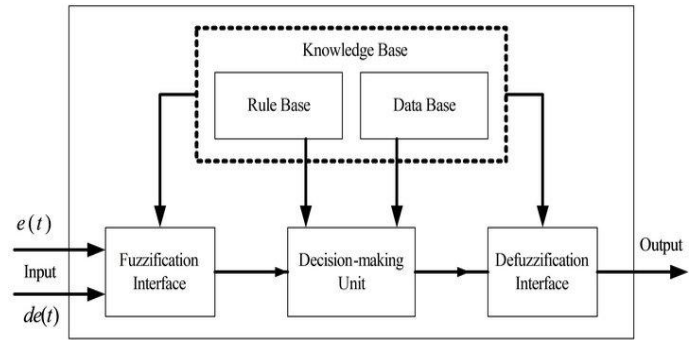


Fig.4 Block diagram of Fuzzy Logic Controller

The triangular membership function used for the input and output variables are shown if figures 5, 6, and 7 respectively.

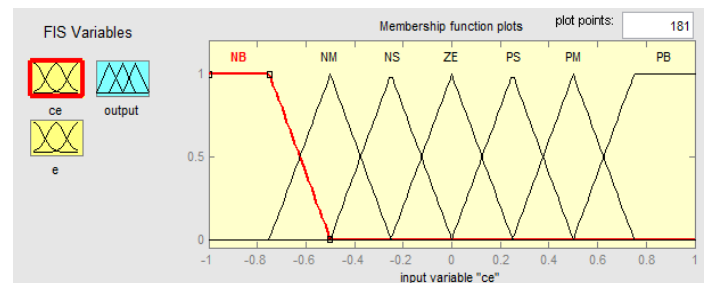


Fig.5 Triangular membership function of the input variable ‘ce’

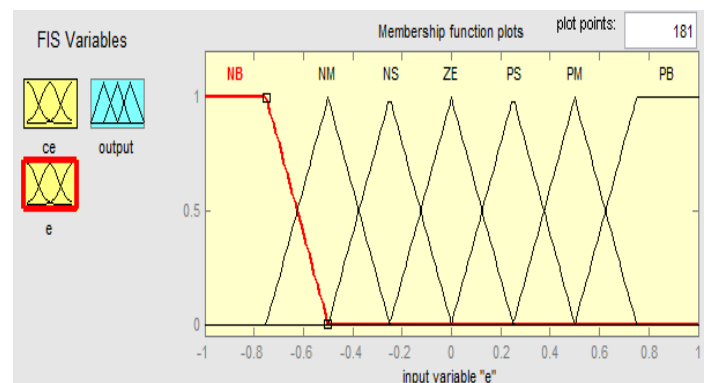


Fig.6 Triangular membership function of the input variable ‘e’

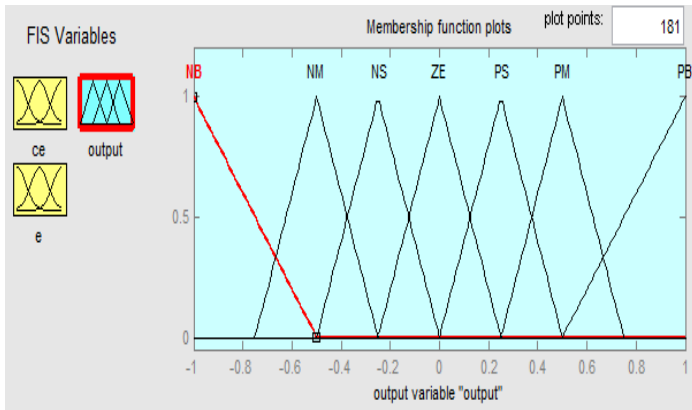


Fig.7 Triangular membership function of the output variable

The Fuzzy rule table and the control surface for our system are shown in table III and in figure 8.

TABLE -III: Fuzzy Rule Table

Error (e)		Error (e)						
		ce	NB	NM	NS	ZO	PS	PM
Change in error (ce)	NB	PB	PB	PB	PB	PM	PS	ZO
	NM	PB	PB	PB	PM	PS	ZO	NS
	NS	PB	PB	PM	PS	ZO	NS	NM
	ZO	PB	PM	PS	ZO	NS	NM	NB
	PS	PM	PS	ZO	NS	NM	NB	NB
	PM	PS	ZO	NS	NM	NB	NB	NB
	PB	ZO	NS	NM	NB	NB	NB	NB

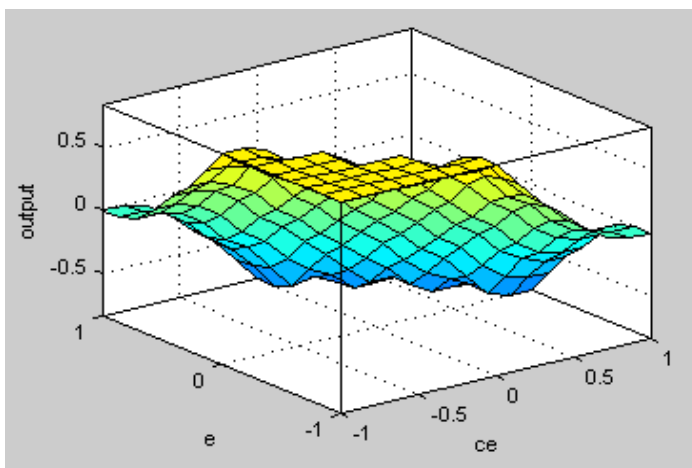


Fig. 8 Control surface of Fuzzy Logic Controller

V. SIMULATION RESULTS

The simulation results presented in this section are developed using MATLAB SIMULINK. The SEPIC converter is simulated according to switching function, which is valid in CCM (Continues Conduction Mode) operations. Here the LED load is designed with the equivalent resistance. The design parameters of the SEPIC converter [5] and [6] is given in table-I.

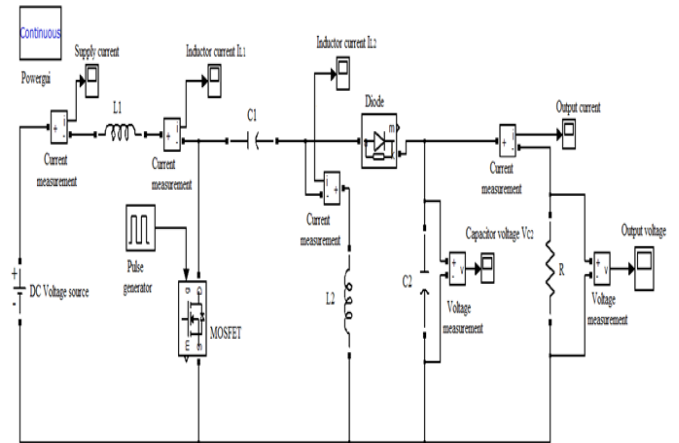


Fig.9 Open loop simulation of SEPIC converter

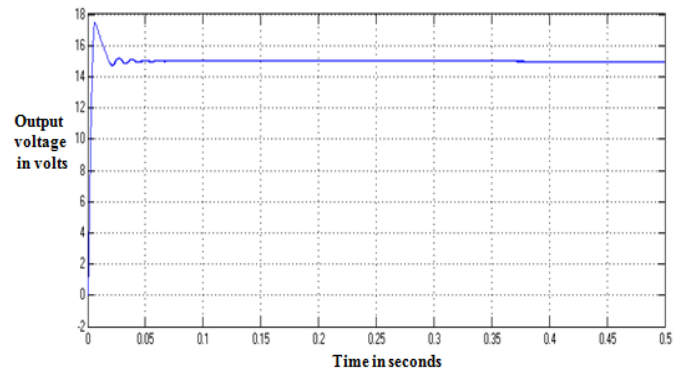


Fig.10 Simulated output voltage of open loop SEPIC converter

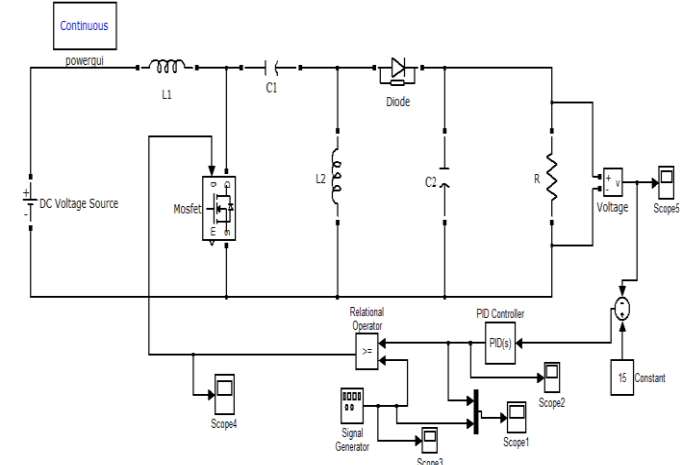


Fig.11 Closed loop simulation of SEPIC converter using PID Controller

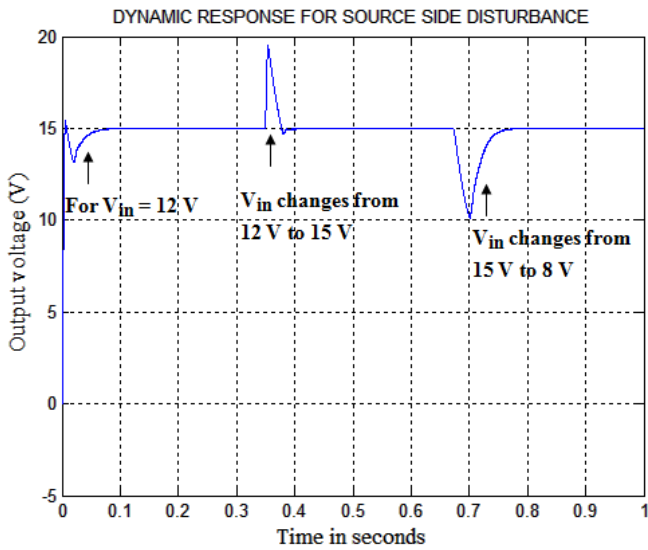


Fig.12 Simulated output voltage with source side disturbance of closed loop SEPIC converter

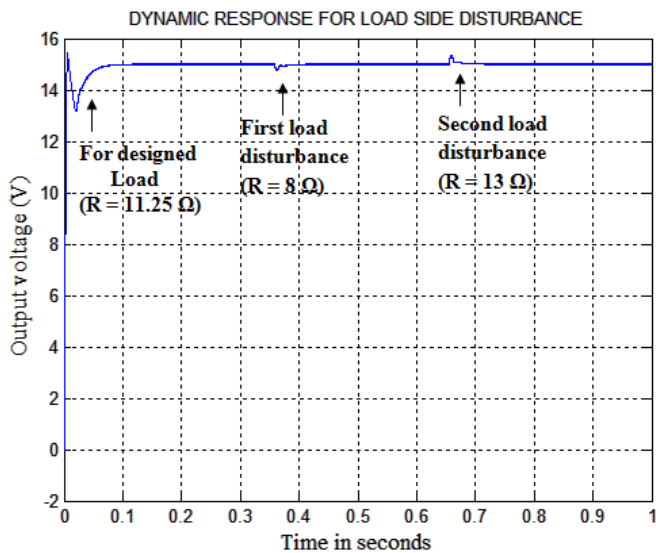


Fig.13 Simulated output voltage with load side disturbance of closed loop SEPIC converter

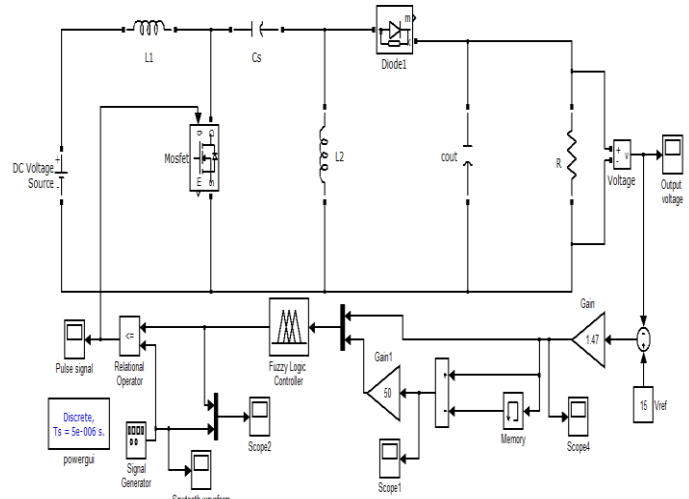


Fig.14 Closed loop simulation of SEPIC converter using Fuzzy Logic Controller

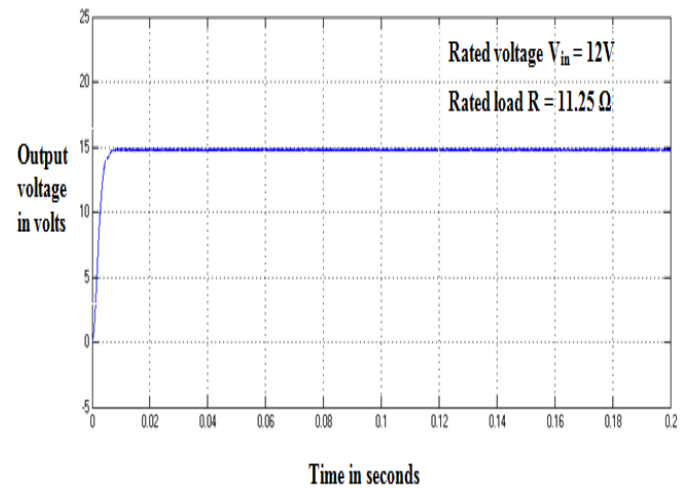


Fig.15 Simulated output voltage of closed loop SEPIC converter using Fuzzy logic controller

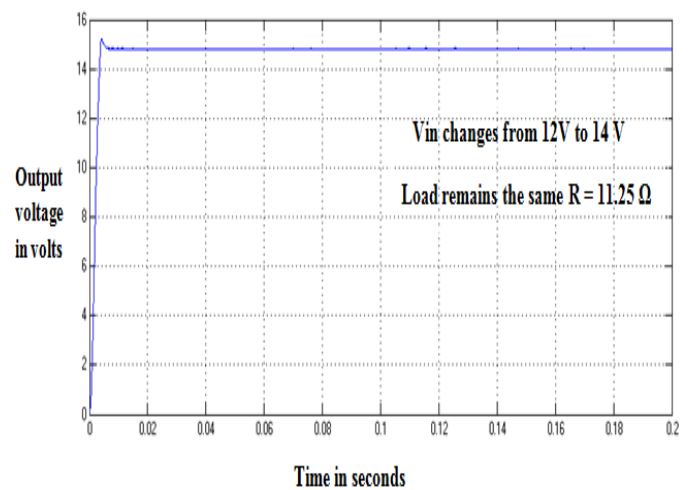


Fig.16 Simulated output voltage with source side disturbance of closed loop SEPIC converter using FLC

TABLE- IV: Analysis of Dynamic Performance

Description	Percentage of Overshoot	Settling Time	Rise time	Observation
Open loop SEPIC converter	17%	80 milli seconds	3.6 milli seconds	Poor
Closed loop SEPIC converter using PID Controller	2%	100 milli seconds	3.8 milli seconds	Fair
Closed loop SEPIC converter using Fuzzy Logic Controller	0%	9 milli seconds	4.2 milli seconds	Good

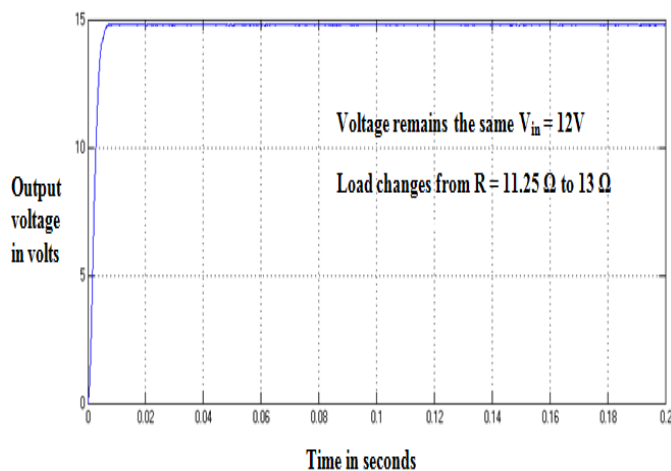


Fig.17 Simulated output voltage with load side disturbance of closed loop SEPIC converter using FLC

IV. CONCLUSION

PID and Fuzzy logic controllers were implemented for SEPIC converter. Open loop and closed loop simulations were done in MATLAB/SIMULINK environment. From the observation of open loop simulation results, the output of open loop system has an overshoot of 17 % which is unacceptable and a settling time of 80 milli seconds. Therefore, it was concluded to implement PID Controller to improve the dynamic performance. By incorporating the PID controller, the overshoot is minimized to around 2% and the settling time is observed to be 100 milli seconds. Though overshoot has been reduced to an acceptable level,

settling time has slightly increased compared to open loop system. Hence, Fuzzy Logic Controller was implemented to the same SEPIC converter.

The simulation results show that settling time is around 9 milli seconds which is a significant reduction compared to open loop as well as PID controller response and there is no overshoot at all. Both PID controller and Fuzzy logic controller tracks the reference output voltage perfectly when the source and load side disturbances are given. Thus, closed loop response of the SEPIC converter using the Fuzzy Logic Controller is observed to be superior to the PID Controller.

REFERENCES

- [1] K. M. Tsang and W. L. Chan, "Fast Acting Regenerative DC Electronic Load based on a SEPIC Converter," *IEEE Transactions on Power Electronics*, Vol. 27, no. 1, January 2012
- [2] Hadi Y. Kanaan, Kamal Al-Haddad, "A Novel Averaged-Model-Based Control of a SEPIC Power Factor Corrector Using the Input/Output Feedback Linearization Technique," *IEEE Transactions on Power Electronics*, 2005
- [3] V. Eng, U. Pinsopon, and C. Bunlaksananusorn, "Modeling of a SEPIC converter operating in Continuous Conduction Mode," *ECTI-CON 2009.6th International Conference on*, 2009, pp. 136-139
- [4] V. Vorpérian, "Analyzing the Sepic Converter," 2006 Ridley Engineering Inc., [On line], www.switchoverpower.com
- [5] Dongbing Zhang, "AN-1484 Designing a SEPIC converter," *Texas Instruments*, SNVA168E- May 2006-Revised April 2013
- [6] Wei Gu, "Designing A SEPIC Converter," *National Semiconductor Application Note 1484* June 2007
- [7] Hyunsoo Koh, "Modeling and Control of Single Switch Bridgeless SEPIC PFC Converter," *Virginia Polytechnic Institute and State University*, July 2012
- [8] Fazel Taeed, Zainal Salam, Member, IEEE, and Shahrin M. Ayob, Member, IEEE, FPGA Implementation of a Single- Input Fuzzy Logic Controller for Boost Converter with the Absence of an External Analog to Digital Converter, *IEEE Transactions on Industrial Electronics*, Vol.59, No. 2, February 2012
- [9] Alexander G. Perry, Guang Feng, Member, IEEE, Yan-Fei Liu, Senior Member, IEEE, and Paresh C. Sen, A Design Method for PI-like Fuzzy Logic Controllers for DC-DC Converter, *IEEE Transactions On Industrial Electronics*, Vol. 54, No. 5, October 2007
- [10] Zhongming Ye, Fred Greenfield, and Zhixiang Liang, Design Considerations of a High Power Factor SEPIC Converter for High Brightness White LED Lighting Applications *IEEE Intersil Corporation* 1001 Murphy Ranch Road, Milpitas, CA 95035 USA, 2008



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