Hardware Implementation of Fuzzy Logic Controller for DC-DC Buck Boost Converter using FPGA

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Abstract—*This paper presents the application of mamdami based Fuzzy Logic Controllers (FLC) for DC-DC buck boost converter. The Fuzzy Logic Controllers plays an inevitable role in the field of power electronics. This work gives the overall model of DC-DC converter in a closed loop behavior with FLC. The simulation studies show that the performance of the FLC for buck boost converter attains a steady state response of 4 milliseconds operated at switching frequency 10 KHz. The Simulink model of DC-DC buck boost converter with mamdami based FLC is verified on Matlab. In order to validate the DC-DC buck boost converter circuit, the FLC is implemented on FPGA platform. The results of simulation and experimental have been comparatively analyzed. It is found that the experimental implementation results show that the ripples in the output steady state response of the buck boost converter is about 5% less than that of simulation study.*

Keywords*: Fuzzy Logic Controllers (FLC), Field Programmable Gate Array (FPGA).*

1. INTRODUCTION

Fuzzy logic controller (FLC) is one of the most widely used applications of fuzzy set theory. DC-DC converters are basically used for generating an output voltage at desired level and when a control technique is used in a dc-dc converter, it produces the output more efficiently as compared to the converter when used in open loop. Control systems are designed and implemented to accomplish the requirements by providing specified voltage level irrespective of uncertainties and disturbances occurred in power semiconductors [1] and therefore more efficient technique is necessary to design control system. When nonlinear phenomenon characteristics occur in DC-DC converters, they make their control and analysis very difficult [2]. There are many control techniques used to control these DC-DC converters for example PI, PID controller and Fuzzy Logic based Controller. Here PI, PD, PID controllers are linear controllers and Fuzzy Logic Controller is a nonlinear controller. It is difficult to control the nonlinear phenomena occurring in converters with the help of linear controllers due to limited operating points [3]. Fuzzy logic does not need exact information about the system and works with approximate mathematical model. New rules can be added into it and it is very robust in nature. And hence it provides better output with lower rise time, peak time and settling time.

The FLC has faster transient responses and is more robust than several control method and which are presented [4-6]. In this paper, firstly a general FLC and PID controller which is compared on Matlab/Simulink is presented. In the model system, five membership functions and a rule table are described. Mathematical model of the buck- boost converter is also given [6-9].

The paper is organized as follows Section II this deals with the buck boost converter overall structure. Section III the DC-DC converter with Fuzzy Logic Controller algorithm is revisited. Section IV Simulation and experimental results are compared. Section V Hardware results of FPGA is presented. At the last section, the conclusion is presented.

2. BUCK BOOST CONVERTER

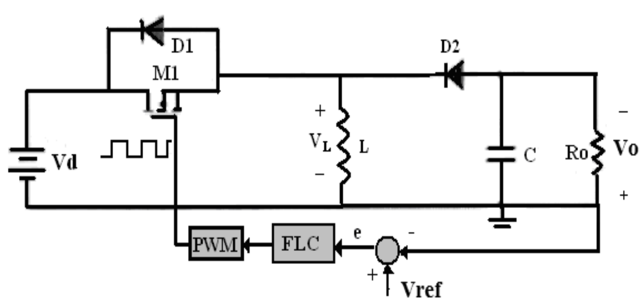


Fig. 1: Fuzzy logic control with buck-boost converter system

The converter consists of a dc input voltage source V_1, controlled switch S_1, inductor L_1, Diode D_1, a filter capacitor C_1 and a load resistance R_1. When switch S becomes on, the input voltage source V_1 gets connected to the inductor L_1 and therefore inductor current increased and diode reversed biased. And therefore capacitor produces output V_o at the load. When the switch is turned off, the diode gets forward biased and the diode provides a path for the inductor current. Inductor L_1 is connected to the load R_1 and the capacitor C_1. Therefore energy transferred from inductor to the capacitor and then to the load. Fig. 1 shows the buck-boost converter system with the FLC controller. The actual output voltage V_0 *is* compared to the reference voltage V_{ref} to produce an error signal that is used to determine the switching signal duty cycle. The switching signal is applied on the MOSFET used to reduce and enlarge output voltage on the circuit. The buck converter system is analyzed for switch on time and off time which is called duty cycle ratio *D*. The circuit equations are written as below.

1. The input power *Pin* is

$$P_{in} = V_{in} \cdot I_{in} = 50 Watt \quad (1)$$

2. Assuming the efficiency *n* to be 90 %

$$n = Po \div Pin \Rightarrow Po = 45 Watt \quad (2)$$

3. The output current is

$$Io = Po \div Vo = \frac{45}{12} = 3.75A \quad (3)$$

4. The output resistance is

$$R = Vout \div Iout = \frac{12}{3.75} = 3.2\Omega \quad (4)$$

5. The inductor minimum value (D=0.5) is

$$L = \frac{R(1-D)^2}{2f} = \frac{3.2x0.25}{2x10x10^3} = 40\mu H \quad (5)$$

6. The minimum capacitor value is

$$\frac{\Delta Vo}{Vo} = \frac{DT_s}{RC} = \frac{0.5x10^3}{10x3.2xC} = C = 156\mu F \quad (6)$$

3. FUZZY LOGIC CONTROLLER ALGORITHM

The system variables and a rule table which depend on the variables are described for the control algorithm. The buck converter output voltage is controlled by changing the switching duty cycle. The system error is defined as a difference between the reference voltage and measured output voltage value [2]. For the system; r (k) is the reference voltage and y (k) is the measured output voltage values then the error voltage is calculated using Equation (7).

$$e(k) = r(k) - y(k) \quad (7)$$

The change in the error voltage is also calculated as;

$$e(k) = e(k) - e(k-1) \quad (8)$$

The membership functions for each of the fuzzy variables are shown in Fig. 2(a) and (b)

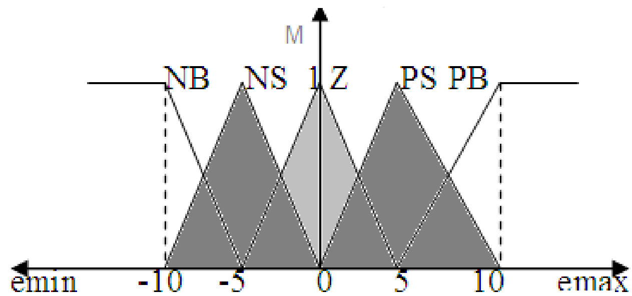
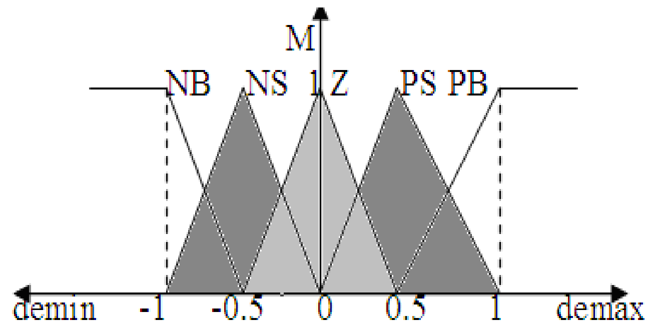


Fig. 2: a) Triangle membership function for error



b) Triangle membership function for change in error

Table I: Fuzzy Rule

		Δe				
		NB	NS	ZZ	PS	PB
e	PB	ZZ 1	PS 2	PS 3	PB 4	PB 5
	PS	NS 6	ZZ 7	PS 8	PS 9	PB 10
	ZZ	NS 11	NS 12	ZZ 13	PS 14	PS 15
	NS	NB 16	NS 17	NS 18	ZZ 19	PS 20
	NB	NB 21	NB 22	NS 23	NS 24	ZZ 25

Finally, If the output space, *du*, is partitioned into more than three regions as it has been done for e and de axes, then the positive and negative regions should be divided into sub-regions such as NB, NS, PS and PB. At the same time some of the fuzzy rules can be presented as follows:

1- ***If*** e is PB **and** de is NB ***then*** du is ZZ.

2- ***If*** e is PS **and** de is NB ***then*** du is NS.

3- ***If*** e is ZZ **and** de is NB ***then*** du is NS.

4- ***If*** e is NS **and** de is NB ***then*** du is NB.

5- ***If*** e is NB **and** de is NB ***then*** du is NB.

These rules can be presented as in Table 1 for three fuzzy regions. This rule table can be used in the FLC rule-based controller with Simulink design. A fuzzy logic based controller consists of three sections namely fuzzifier, rule base and defuzzifier as shown in Fig. 3[10-12].

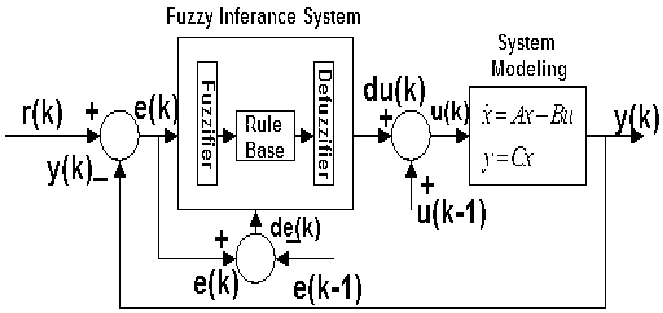


Fig. 3: The basic structure of fuzzy logic controller with the feedback.

The input signals error and change in error, for each sampling, to the FLC are converted to generate fuzzy sets in fuzzifier. The signals are used in a rule table to determine the fuzzy number of the compensated output signal. Finally, the resultant united fuzzy subsets representing the controller output are converted into the crisp values. The crisp values of the fuzzy subsets used in this multiplication process are the values that have maximum membership degree of 1.0 in the corresponding fuzzy subsets. The block diagram of rule base function fuzzifier and defuzzification is shown in Fig. 4. The main steps for developing the FLC are outlined in this part. The main block of converter with Matlab/Simulink is shown in Fig. 8. There is only a feedback and FLC added for control. The output voltage is compared with the reference voltage and generated and error signal. This error signal is driven by FLC. The output signal of FLC is compared with a saw toot signal to generate a PWM signal which drives the switching MOSFET. The FLC converter is simulated and experimentally verified using FPGA board to compare with PID controller. DC-DC converter with FLC shown in Fig. 5.

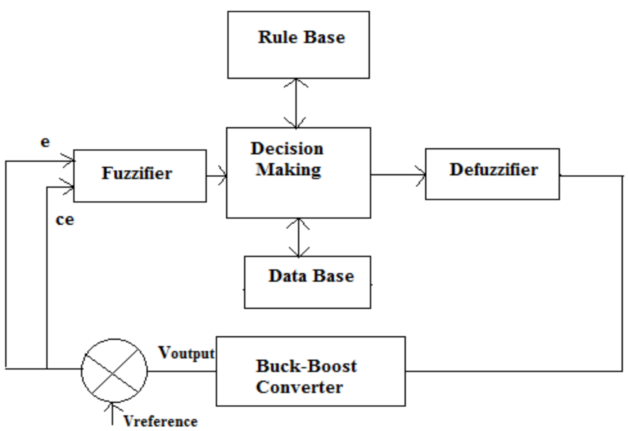


Fig. 4: The Process from fuzzification to Defuzzification.

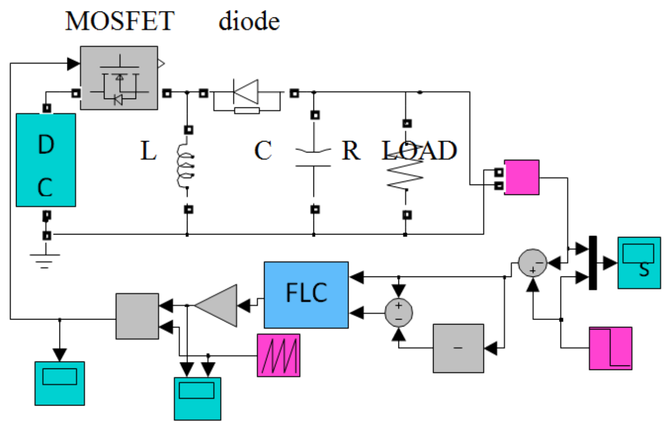


Fig. 5: FLC with DC-DC Buck-Boost converter

Table II: Simulation Parameters

DC Input Voltage	12 Volts
Reference output Voltage	2V(Buck) 30V(Boost)
Switching Frequency	10KHz
Filter inductor	40µ H
Filter Capacitance	156 µ F
Output Resistance	3.2Ω

4. SIMULATION RESULTS AND DISCUSSION

In this section results are derived and discussed. A Fuzzy logic controller and Proportional-Integral- Derivative controller [12-14] are studied for the Buck-Boost converter and its simulink model was designed. The two models using fuzzy logic and PID controller are tested for both buck mode and boost mode.

(A) Buck mode: Output voltage is calculated for $V_{reference}$ = 10 volt and V_{input} = 12 volt. Rise time, peak time and settling time are analyzed for reference voltage that has been varying from 2 volt to 10 volt.

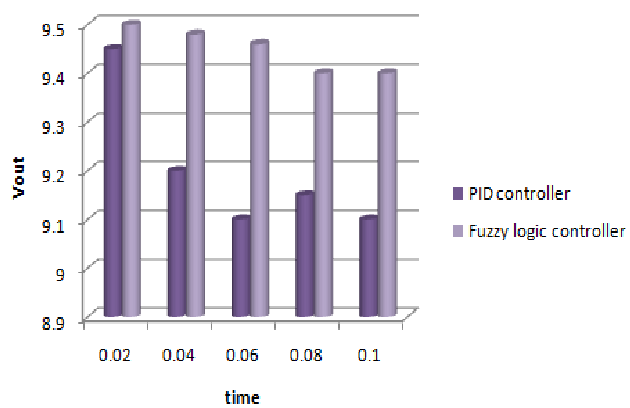


Fig. 6: Output voltage for reference voltage = 10 volt

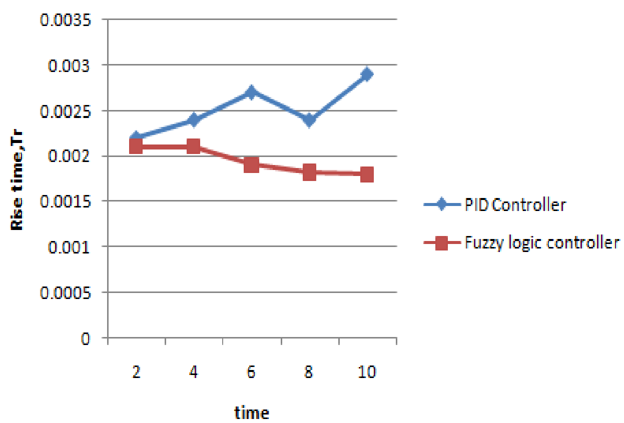


Fig. 7: Rise time in Buck mode

PID controller has rise time below 0.0029sec and Fuzzy logic controller has rise time below 0.0021sec are shown in Fig. 7.

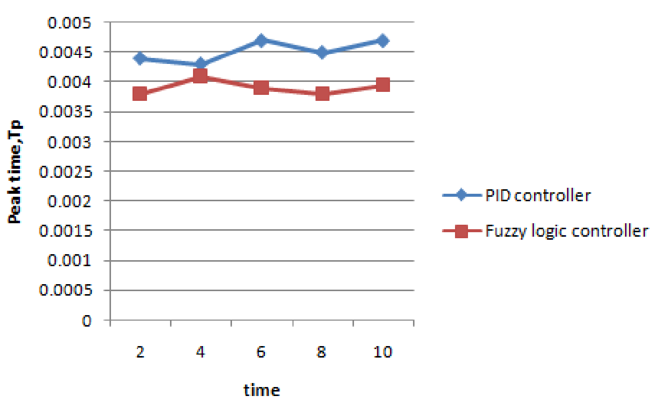


Fig. 8: Peak time in Buck mode

PID controller has peak time below 0.0047sec and Fuzzy logic controller has peak time below 0.0041sec are shown in Fig. 8.

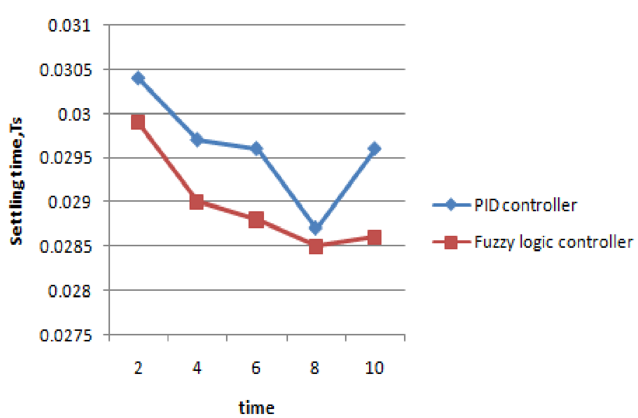


Fig. 9: Settling time in Buck mode

PID controller has settling time below 0.304sec and Fuzzy logic controller has peak time below 0.298sec are shown in Fig. 9.

(B) Boost mode: Output voltage is calculated for $V_{reference}$ = 30 volt and V_{input} = 12 volt. Rise time, peak time and settling time are analyzed for reference voltage varying from 14 volt to 30 volt is shown in Fig. 10.

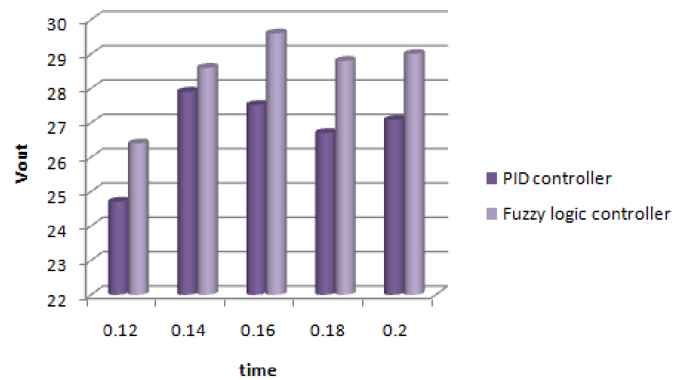


Fig. 10: Output voltage for reference voltage = 30 Volt

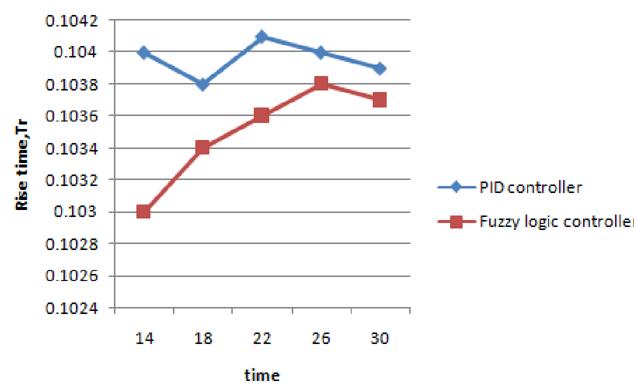


Fig. 11: Rise time in Boost mode

PID controller has rise time below 0.1041sec and Fuzzy logic controller has rise time below 0.1038sec are shown in Fig. 11.

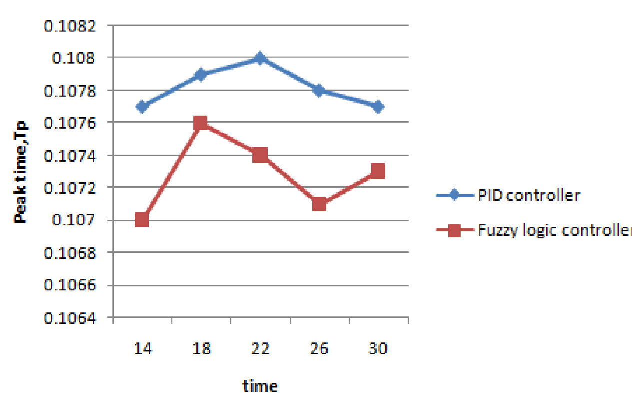


Fig. 12: Peak time in Boost mode

PID controller has peak time below 0.108sec and Fuzzy logic controller has peak time below 0.1076sec are shown in Fig. 12. The results attained for DC-DC converter with FLC are better compared to that of linear controllers. The design is experimental verified using Xilinx FPGA board and the obtained results are compared with that of the simulation.

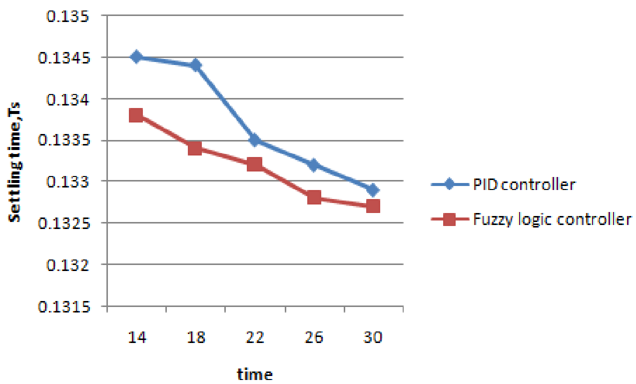


Fig. 13: Settling time in Boost mode

PID controller has settling time below 0.1345sec and Fuzzy Logic Controller has settling time below 0.1336sec are shown in Fig. 13.

5. HARDWARE RESULTS OF FPGA

The FLC is designed using VHDL and implemented on SPARTAN-3AN (XCS1400AN) with Xilinx 13.2. The device utilization SPARTAN-3AN (XCS1400AN) is shown in Table III. The output timing PWM signal is generated and given as input signal to the MOSFET for switching activity.

Table III: Spartan-3AN(XCS1400AN)

Logic utilization	Used	Available
No of Slice Flip Flops	985	22,582
No of occupied slices	7,986	11,264
Total No of Slice LUTS	14,574	22,528

6. CONCLUSION

In this paper, a Fuzzy Logic Controlled (FLC) buck-boost DC-DC converter for load battery systems has been presented. The buck-boost converter circuit has been designed with Matlab/Simulink and simulation results have been obtained. We have successfully designed and implemented the Mamdami based PI fuzzy logic controller for buck-boost converter on Xilinx FPGA board using VHDL. Simulation and experimental based tests are considered for the design implementation. The simulation results of Matlab/Simulink approach also. For the controller FLC, PI, and FLC+PI controllers are used and the simulation results are compared. It can be seen from the results that there is no big overshoot in output voltage and no need for any change in parameters to stable the system. It can be noted that it is possible to use a fuzzy logic controller for power electronics applications. The duty cycle is varied for the buck-boost operation of DC-DC converter.The output load resistance is 3.2Ω . The settling time of DC-DC converter is 4 milliseconds. The peak overshoot at the output voltage is between 4% to 5%.

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