A Comparative Study of Fuzzy Logic Controller and Proportional Integral Controller on Buck- Boost Converter

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Abstract - This paper is presents a comparative study of Fuzzy Logic Controller (FLC) and Proportional Integral Controller (PIC) on Buck-Boost Converter (BBC). The objective is to find comparative advantages of both controllers on BBC. The model circuit of BBC with FLC and PIC has been derived to analyse the effectiveness of the controls methodology. The controls methodology is then verified by numbers of simulations and the advantages good response time in term of shortest rise time, settling time, smaller overshoot, less voltage deviations and robustness are indicated in comparison FLC with a conventional PIC. Simulation is held in MATLAB- SIMULINK environment.

Keywords- Fuzzy Logic Controller, Buck- Boost Converter, Proportional- Integral- Derivative Controller, Pulse Width Modulation Generator.

1. INTRODUCTION

Recently, the control systems for many power electronics appliance have been increasing widely. Crucial with these demands many researcher or designer have been struggle to find most economic and reliable controller. The idea to have control system in dc- dc converter is to ensure desire voltage output can be produce efficiently to meet the demand need. Basically, feedback controller compares the output of the power processor unit with a reference value, and the error between the two is minimized by the controller.

Continuous development of advanced high-speed digital circuits, digital control will slowly replace the currently used analogue controller in high frequency switching converters. Intelligent power supplies are expected to play important roles in aerospace, communication and automobile industries in the near future [1].

Conventionally, PI, PD and PID controller are most popular controllers and widely used in most power electronic appliances but disadvantage of PID that is requires complex mathematical model of the control process or may be expensive in terms of computer processing power and memory, and a system based on rules based likes FLC may be more effective. DC-to-DC converters have been dominating controlled by analogue integrated circuit technology and linear system control design techniques [2].

L. A. Zadeh presented the first paper on fuzzy set theory in 1965. Since then, a new language was developed to describe the fuzzy properties of reality, which are very difficult and impossible to be described using conventional methods. Fuzzy set theory has been widely used in the control area with some application to dc-to-dc converter system [3].

The fuzzy control systems are based on expert knowledge that converts the human linguistic concepts into an automatic control strategy without any complicated mathematical model [4].

2. METHODOLOGY

2.1 BUCK- BOOST TOPOLOGY

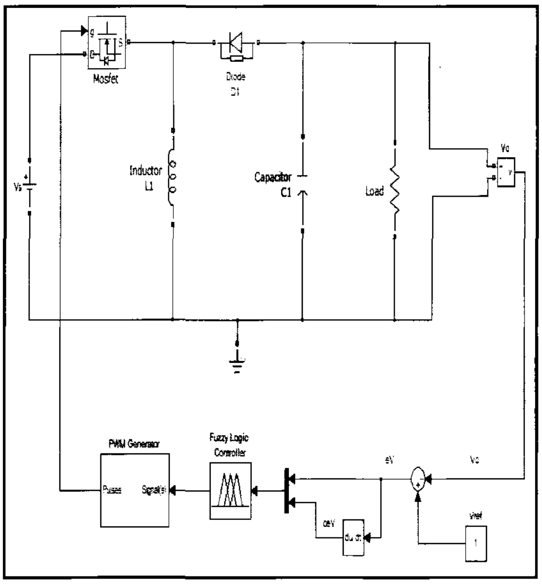

Figure 1: Buck- Boost circuit diagram of closed loop fuzzy logic controller.

2.1.1 CIRCUIT DESCRIPTION

The circuit diagram as illustrated at Figure 1 basically used a pair of switches, usually one controlled (e.g. MOSFET) and one uncontrolled (e.g. diode), to achieve unidirectional power flow from input to output and also use one capacitor and one inductor to store and transfer energy from input to output. They also filter or smooth voltage and current.

The dc-dc converters can be operated in two distinct modes either in Continuous Conduction mode (CCM) or Discontinuous Conduction mode (DCM). In practice, a converter may operate in both modes. Therefore, a converter and its control should be designed based on both modes of operation [5].

However, for this purposed only consider the BBC operated in CCM.

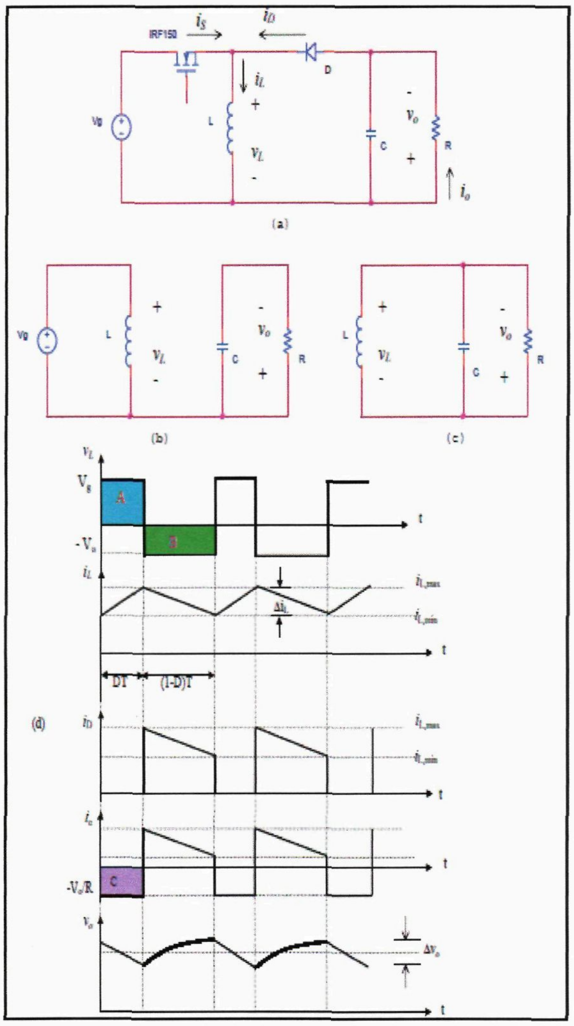

Figure 2: (a) Buck- Boost Converter (b) Switch on for time DT (c) Switch off for time (1- DT) T (d) Key wave forms [5]

2.1.2 CIRCUIT OPERATION

Referring to Figure 2, when the switch is on for a time duration DT, the switch conducts the inductor current and the diode becomes reverse biased. This results in a positive voltage $V_L = V_g$ across the inductor. This voltage causes a linear increase in the inductor current i_L. When the switch is turned off, because of the inductive energy storage, i_L continues to flow. This current now flows through the diode, and $V_L = -V_o$ for a time duration (1-D) T until the switch is turned on again [5].

2.1.3 ANALATICAL EXPRESSIONS OF V_o, ΔiL AND ΔV_o.

Assuming that no power loss in the converter whereas power absorbed by the load must equal power supplied by the source;

$$P_o = Ps \tag{1}$$

$$\frac{Vo^2}{R} = V_g i_s \tag{2}$$

But average source current related with average inductor current as:

$$i_s = i_L D \tag{3}$$

Therefore,

$$\frac{Vo^2}{R} = V_g i_L D \tag{4}$$

Substituting for average inductor current, i_L,

$$i_L = \frac{Vo^2}{VgRD} = \frac{Po}{VgD} = \frac{VgD}{R(1-D)^2} \tag{5}$$

For a buck-boost converter, it is obvious that

$$i_L = i_s + i_o$$

$$\Delta i_L = \frac{1}{L}\int_0^{DT} VL\, dt$$

$$= \frac{1}{L}[\text{shaded area under waveform } V_L]$$

$$= \frac{1}{L} V_g \, X \, DT \tag{6}$$

Substitution equation (4) and (5) to get V_o

Therefore,

$$V_o = -V_g\left[\frac{D}{(1-D)}\right] \tag{7}$$

where, V_o is output voltage, V_g is voltage supply and D is duty ratio.

Note that the output voltage V_o is always negative and by varying the Duty cycle, D the output voltage can be increased and decreased. If D > 0.5 the output voltage is higher than input voltage and if D< 0.5 the output voltage is lower than input voltage [5].

From the information of the capacitor current, i_c, the peak-peak output voltage ripple, Δv_o can obtain.

$$\Delta V_o = \Delta V_c = \frac{1}{C}\int i_c \, dt$$

$$= \frac{1}{L}[\text{shaded area}, i_c\,]$$

Therefore

$$\Delta V_o = \frac{1}{C} X \frac{Vo}{R} X\, DT \qquad (8)$$

The proposed Buck- Boost circuit is operated in CCM condition. Therefore,

$$L_{min} = \frac{(1-D)^2\, X\, R}{2\, X\, fs}$$

where D is duty ratio and fs is switching frequency and R is load resistor.

2.2 FUZZY CONTROLLER FOR BUCK- BOOST CONVERTER

Fuzzy rules are expressed in MATLAB-SIMULINK environment in terms of implications of if . . . then . . . rules. In the FLC for the BBC, there are two input variables involved the error, eV and the change of error, ceV. In this section, a FLC is used to regulate and stabilise the output voltage of a BBC. This controller is determined from the fuzzified input parameters, the inference rules and the deffuzzified output parameters [1-3-4-7]. There are few steps flows involved in modelling Fuzzy Logic Toolbox in the Matlab as illustrate in Figure 3.

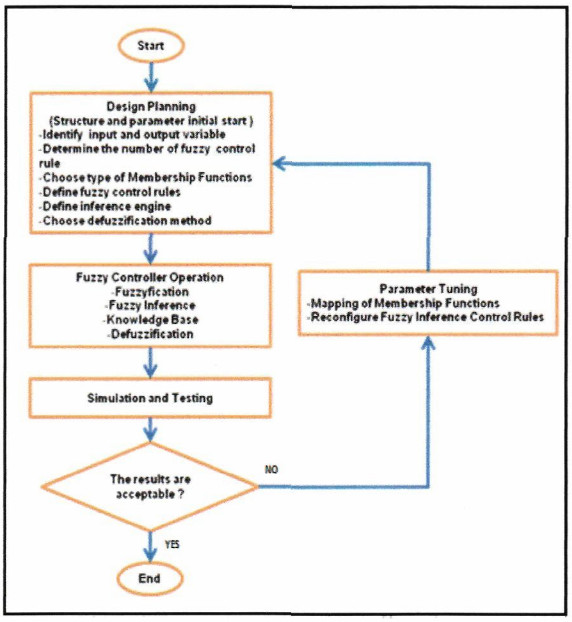

Figure 3: Illustrate Matlab Fuzzy Logic Toolbox steps flow.

The first step is to identify and configure number of input and output in the Fuzzy Inference System editor (FIS). The model type of FIS is set to Mamdani. The second step is to configure the input and output characteristics in the Membership Function editor. Third step to configure the rule based editor in the Rule editor. The proposed FLC is used 5 fuzzy levels (NB, NS, ZO, PS, and PB) from two input eV and ceV and denoted $5^2 = 25$ number of fuzzy control rules.

The inference engine used is minmax method and defuzzify method change of duty cycle used in this fuzzy is centroid. The Membership function plots input and output for FLC as shown at Figure 4.The most important part is to determine the control rules which are based on human knowledge and experience. For instance, the controller accepts the inputs and maps them into their membership functions and truth values. These mappings are then feed into the rules. The rule specifies an AND relationship between the mappings of the two input variables, as shown in the examples Figure 5, the minimum of the two is used as the combined truth value. The appropriate output states are selected and then defuzzify output changed in duty cycle feed to PWM generator as illustrated in Figure 6. The development of purposed FLC control rule as shown in Table I.

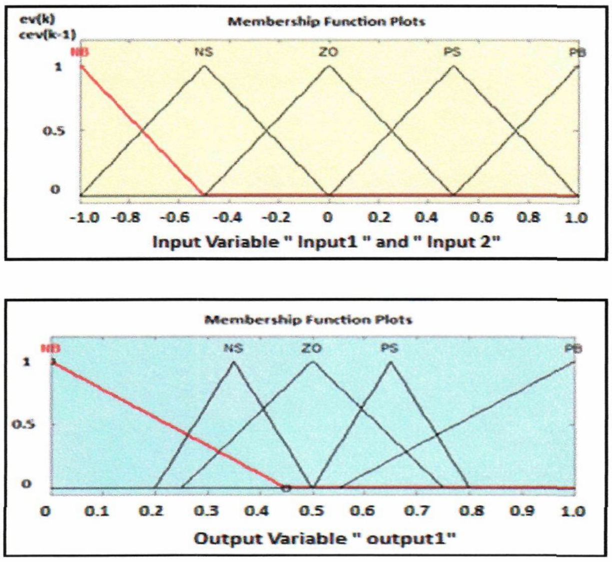

Figure 4: The Membership Function plots input and output for FLC voltage loop.

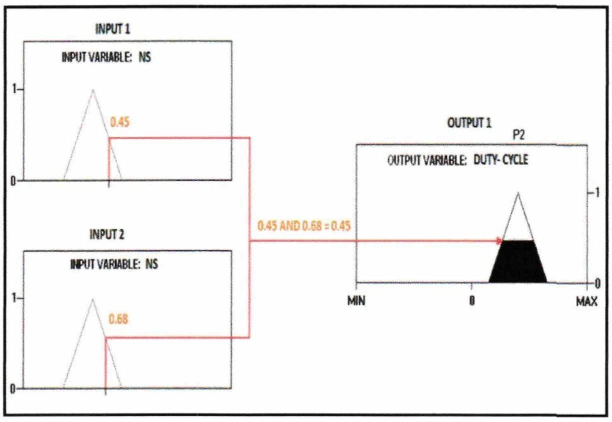

Figure 5: Example of mapping the Membership function and truth value.

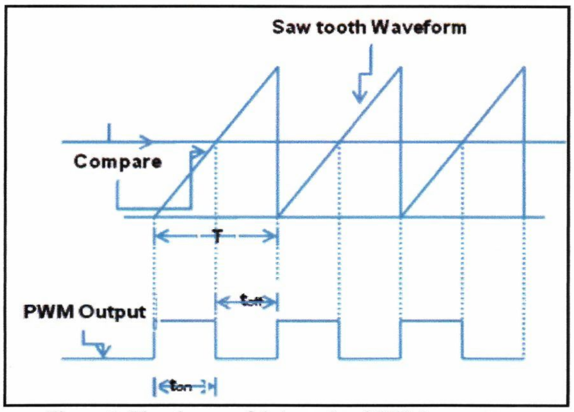

Figure 6: The change of duty cycle of PWM generator.

Table I:
The fuzzy control rules table.

ceV \ eV	NB	NS	ZO	PS	PB
NB	NB	NB	NB	NS	ZO
NS	NB	NB	NS	ZO	PS
ZO	NB	NS	ZO	PS	PB
PS	NS	ZO	PS	PB	PB
PB	ZO	PS	PB	PB	PB

The configurations of fuzzy control rules in Table I is simplified from Rule Editor as illustrated in Figure 7.

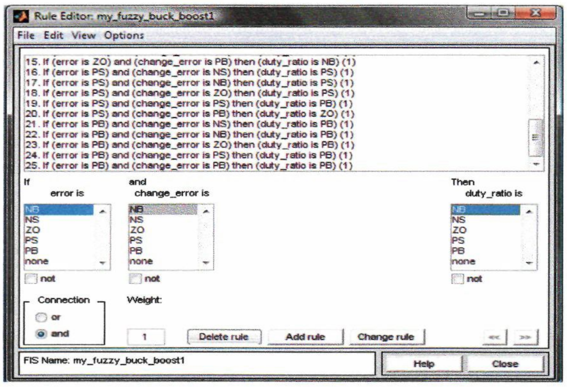

Figure 7: Rule Editor.

2.3 PROPORTIONAL-INTERGRAL CONTROLLER

The Proportional Integral controller is combination of proportional constant, namely K_p, and Integral gain, K_I. The equation as defined as below.

$$K_P = \frac{U(s)}{E(s)}, \qquad (1)$$

$$\frac{K_I}{s} = \frac{U(s)}{E(s)}. \qquad (2)$$

where $U(s)$ is the output signal and $E(s)$ is the error signal, measured in frequency domain. K_I is the integral gain.

Combining Equation (1) and Equation (2), Thus,

$$\frac{U(s)}{E(s)} = K_P + \frac{K_I}{s}. \qquad (4)$$

Rearranging (4)

Therefore,

$$\frac{U(s)}{E(s)} = K_P\left(1 + \frac{1}{T_I s}\right). \qquad (5)$$

where $T_I = K_P/K_I$ is known as the integral time or reset rate (times per minute), the rate at which K_P is repeated (duplicated). Note that K_P affects both proportional and integral parts of the controller. K_P controls the sensitivity of the controller output to the deviations between reference voltages, Vref.

Integral action, K_I, provides a high gain at low frequencies, thus reducing the error and eliminates the offset in the steady state [2, 6, 8].

There are few steps involved in modelling PIC configuration parameters in MATLAB and are illustrated in Figure 8.

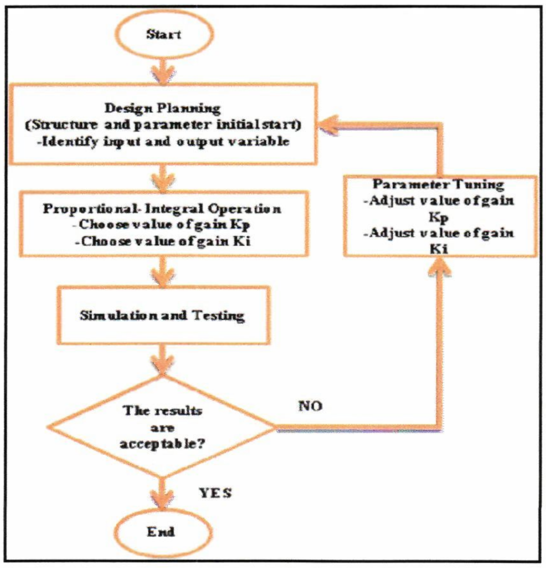

Figure 8: Illustrate Matlab Proportional Integral steps flow.

3. RESULTS AND DISCUSSION

The simulation results are based on output voltage deviation, voltage overshoot percentage, rise time, peak time and settling time for FLC and comparison with PIC. The Simulink model used for these simulations as illustrated at Figure 9 for FLC and PIC at Figure 10.

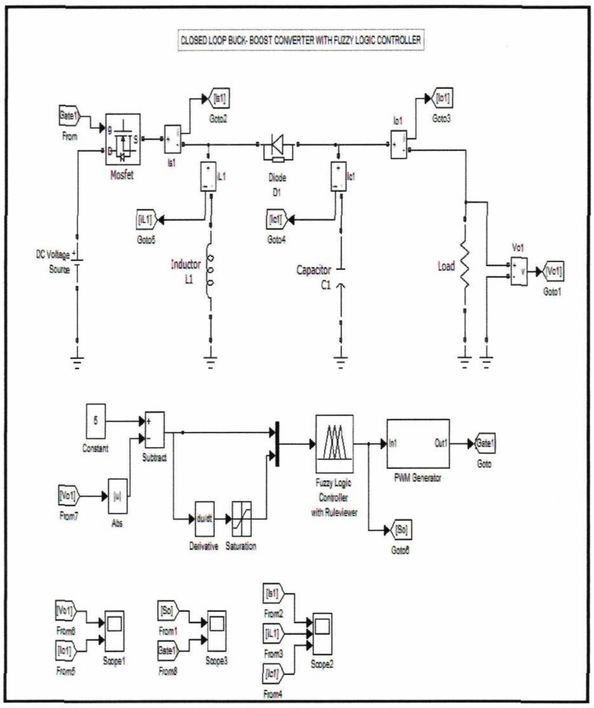

Figure 9: A Simulink model of Fuzzy Logic controller for Buck-Boost Converter.

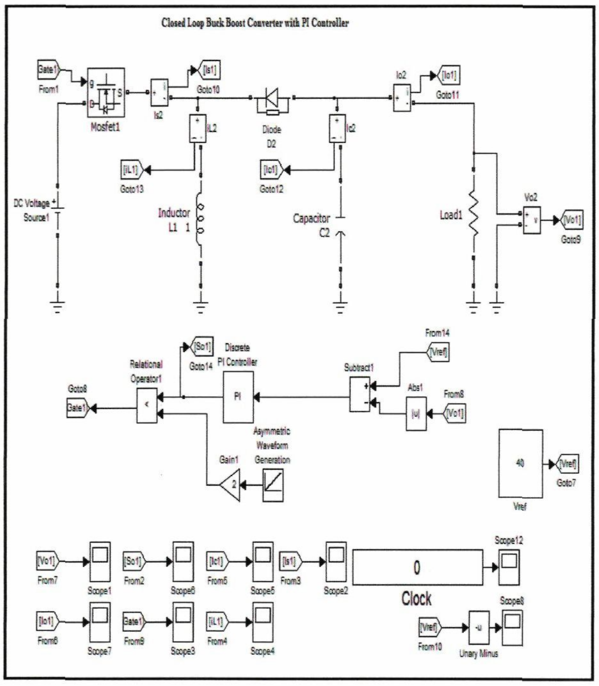

Figure 10: A Simulink model of PI for Buck- Boost Converter.

Table II shown simulation parameters for both types of controllers.

TABLE II
Parameters Circuit for Buck- Boost converter using FLC and PIC simulations.

Parameter Name	Fuzzy Logic Controller	Proportional Integral Controller
Input Voltage	20 Volt	20 Volt
Inductor	2.5 mH	2.5 mH
Capacitor	250 µF	250 µF
Load Resistance	40 Ω	40 Ω
Switching Frequency	20KHz	20KHz
Kp	Nil	0.01
Ki	Nil	0.55
Switching Type	MOSFET	MOSFET

The simulations for this FLC had been tested for two condition mode Buck (step down) and Boost (step up) with variations of reference voltage.

The sample output voltage, output current together with PWM Generator output as resulted from these simulations with Vref= 5 Volt (Buck mode) as shown at Figure 11 and Figure 12 respectively and for Boost mode (step up) for Vref= 40 Volt as shown at Figure 13 and Figure 14 respectively.

The PWM generator output shown variations of duty cycle during rise time, peak time and settling time as illustrated at Figure 12 and Figure 14 for FLC and PIC at Figure 16 and Figure 18.

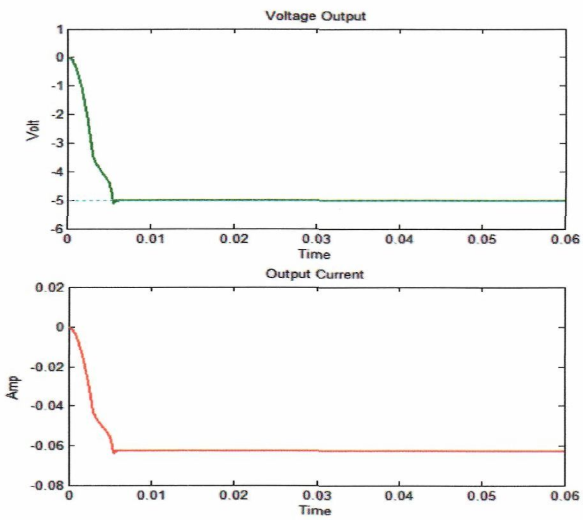

Figure 11: Output Voltage and Current from Buck- Boost Converter using FLC Vref= 5 Volt.

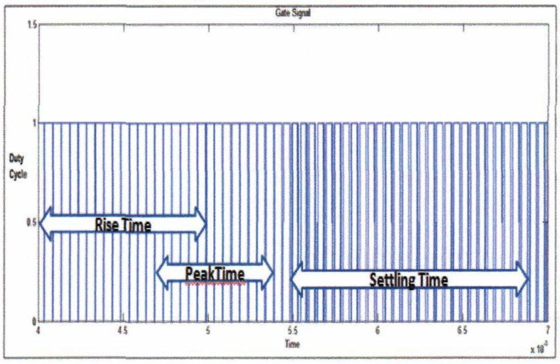

Figure 12: PWM signal output from FLC for Vref= 5 Volt.

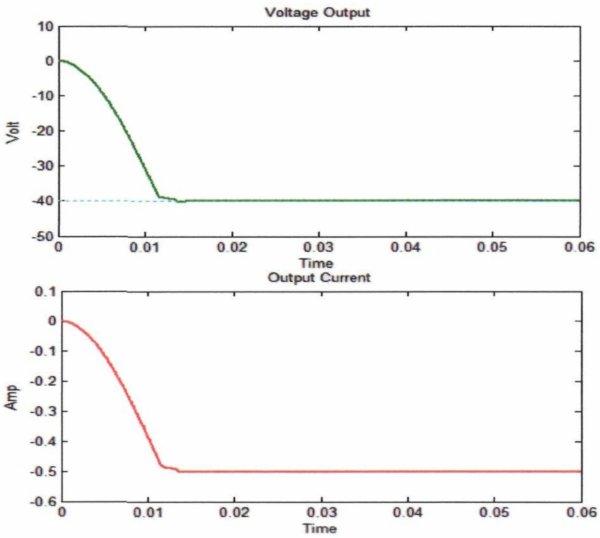

Figure 13: The Output voltage and Current Vref= 40 Volt using FLC Buck- Boost converter.

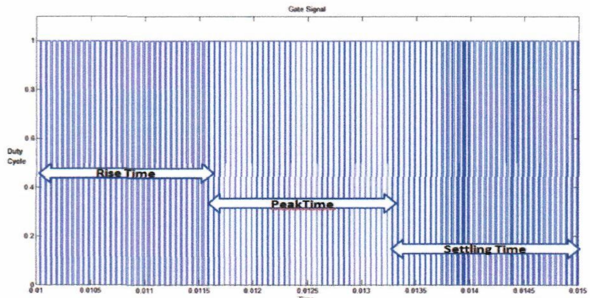

Figure 14: PWM signal output from FLC Buck- Boost converter for Vref= 40 Volt.

The simulation result generated from FLC Buck-Boost converter for various voltage references consists of peak overshoot ratio, rise time, peak time and settling time as tabulated in Table III.

Table III

Peak Overshoot Ratio, Rise Time, Peak Time and Settling Time From FLC Buck- Boost Converter.

Voltage Input (V)	Voltage Reference (V)	Peak overshoot ratio (%)	Rise time (sec)	Peak time (Sec)	Settling time (sec)
20	5	2.70%	0.005	0.005	0.006
20	10	1.87%	0.007	0.007	0.007
20	15	1.20%	0.008	0.008	0.009
20	20	0.95%	0.009	0.009	0.010
20	25	0.83%	0.010	0.010	0.010
20	30	0.77%	0.011	0.011	0.012
20	35	0.71%	0.012	0.013	0.013
20	40	0.56%	0.014	0.014	0.014

The deviation of voltage obtained from FLC Buck-Boost converter for various voltages references regulated tabulated in Table IV. Note that the negative sign of output voltage had been inverted to positive sign for analysis convenient.

Table IV

The deviations of voltage resulted from FLC Buck- Boost Converter.

Voltage Input (V)	Voltage Reference (V)	Voltage Output (V)	Deviation (v)	FLC Deviation (%)
20	5	5	0	0.000%
20	10	10	0	0.000%
20	15	15	0	0.000%
20	20	20.005	0.005	0.025%
20	25	25.005	0.005	0.020%
20	30	30.0075	0.0075	0.022%
20	35	35.0075	0.0075	0.021%
20	40	40.01	0.01	0.021%

The simulation resulted from PIC BBC as comparison controller was done in two different modes of operations same with FLC BBC. The sample output voltage and output current waveforms for various voltage references as illustrated Figure 15 with Vref= 5 volt and Figure 17 for Vref= 40 volt.

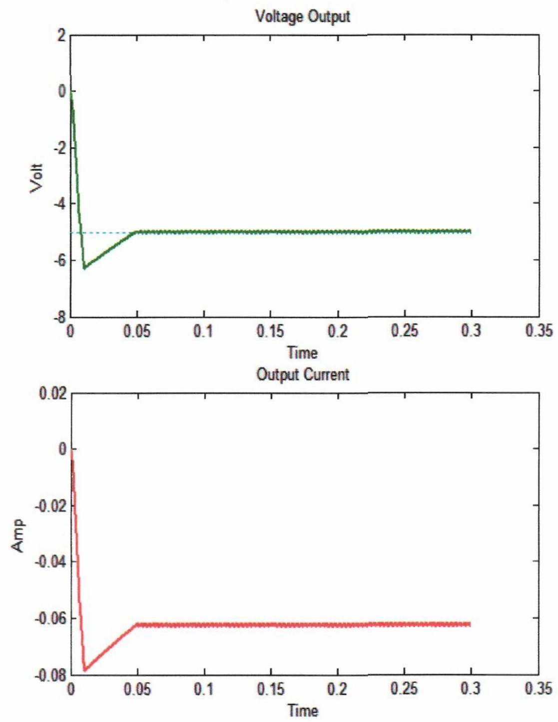

Figure 15: Output Voltage and Current from PIC Buck- Boost Converter using PIC Vref= 5 Volt.

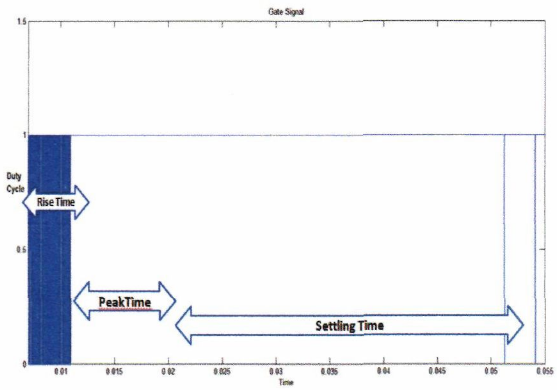

Figure 16: PWM signal output from PIC Buck- Boost converter for Vref= 5 Volt.

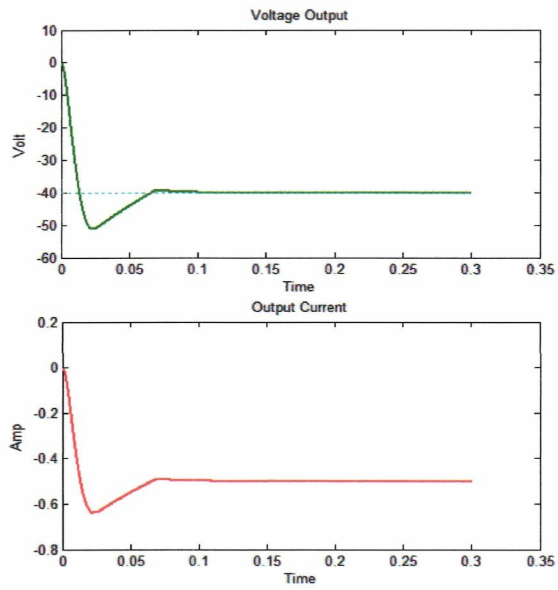

Figure 17: Output Voltage and Current from Buck- Boost Converter using PIC Vref= 40 Volt.

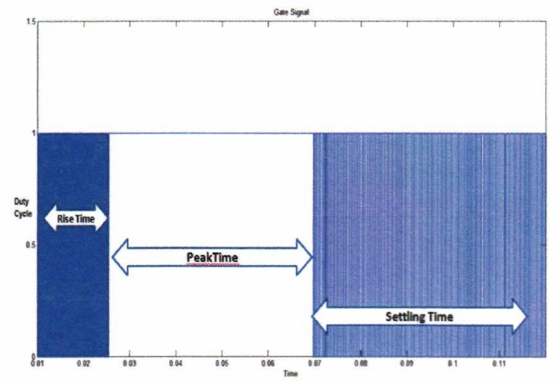

Figure 18: PWM signal output from PIC Buck- Boost converter for Vref= 40Volt.

The simulation result generated from PIC Buck-Boost Converter for various voltage references consists of peak overshoot ratio, rise time, peak time and settling time as illustrated in Table V.

Table V

Peak Overshoot Ratio, Rise Time, Peak Time and Settling Time From PIC Buck- Boost Converter.

Voltage Input (V)	Voltage Reference (V)	Peak overshoot ratio (%)	Rise time (sec)	Peak time (Sec)	Settling time (sec)
20	5	26%	0.009	0.011	0.054
20	10	27%	0.009	0.013	0.055
20	15	27%	0.010	0.015	0.061
20	20	27%	0.010	0.016	0.080
20	25	26%	0.011	0.018	0.080
20	30	27%	0.014	0.020	0.090
20	35	27%	0.012	0.022	0.104
20	40	28%	0.013	0.022	0.115

The simulation results generated from PIC for various voltages references with deviation of voltage as tabulated in Table VI.

Table VI

The deviations of voltage resulted from PIC Buck- Boost Converter.

Voltage Input (V)	Voltage Reference (V)	Voltage Output (V)	Deviation (v)	PIC Deviation (%)
20	5	5.0035	0.0035	0.070%
20	10	10.005	0.005	0.050%
20	15	15.006	0.006	0.040%
20	20	20.00695	0.00695	0.035%
20	25	25.0075	0.0075	0.030%
20	30	30.0065	0.0065	0.024%
20	35	35.008	0.008	0.025%
20	40	40.0105	0.0105	0.026%

The results obtained from both controllers shown that FLC is the fastest rise time compared to the PIC as illustrated at Chart 1.

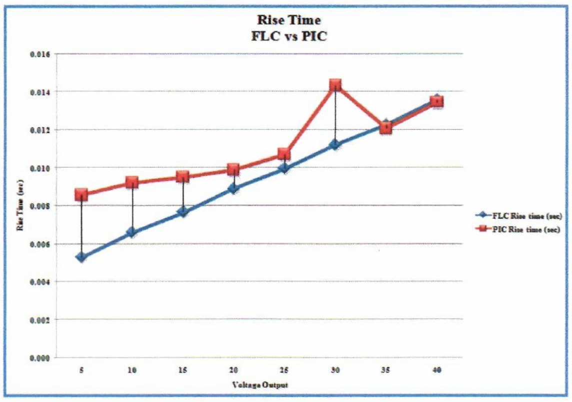

Chart 1: Rise Time FLC versus PIC.

The FLC took a shortest settling time to reach and stable at the desired output voltage as compared to PIC as illustrated at Chart 2. At Chart 3, peak overshoot ratio shown that PIC contributed the highest peak overshoot ratio and for FLC the peak overshoot ratio is less and can be neglected. The highest peak overshoot ratio at PIC is the main contribution why it takes long settling time to reach and stable at the desired output voltage.

The overshoot in PIC is contributed by the value of integral gain, Ki. The higher value of Ki the higher overshoot slope will appear.

The deviation of voltage as illustrated in Chart 4, for both controllers revealed that the difference between reference voltage setting and output voltage is less but PIC shown better result at Buck mode (step down) as compared to FLC. The deviation of voltage for FLC is a bit higher during Buck mode (step down) but for Boost mode of operation both controllers performance are better with less than 0.1%.

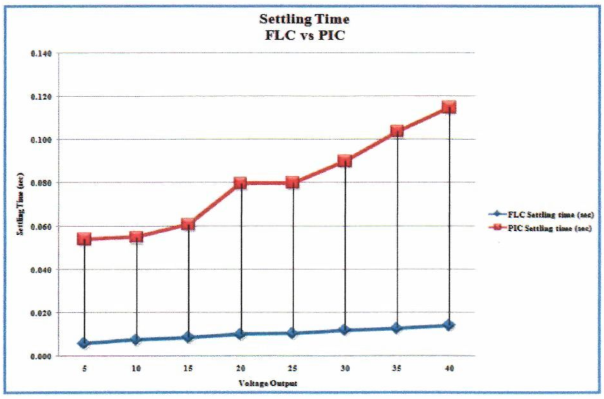

Chart 2: Settling Time FLC versus PIC.

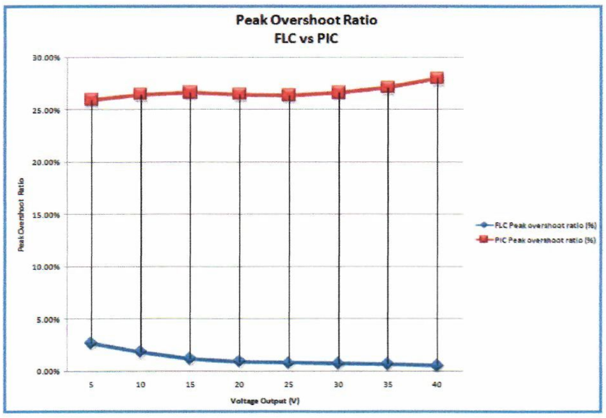

Chart 3: Peak Overshoot Ratio FLC versus PIC.

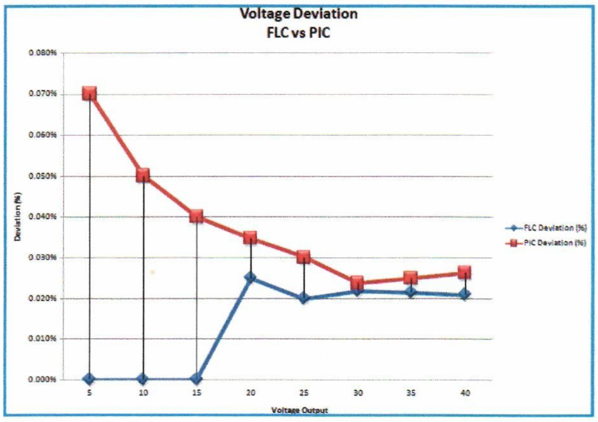

Chart 4: Voltage Deviation FLC versus PIC.

CONCLUSION

The results confirmed that the FLC achieved much better in term of fasters in rise time, peak time, settling time and robustness as compared to PIC. The FLC also produced less output voltage deviations from variations of voltage reference setting. It is also presented better dynamic performance, such as small overshoot, more damping and sensitive to parameter variations for BBC. Thus, FLC has been potential ability to improve the robustness of dc-to-dc converters.

This FLC can be applied to many converter topologies other than BBC such as Buck and Boost. Since the result shown that FLC is the fast response controller with higher accuracy the future development plan is to develop combination of FLC and PIC to control Buck- Boost converter. The FLC will automatically tune the gains of PIC to the optimum value. The gains value of PIC will changes rapidly until desired output voltage is stabilize.

4. REFERENCES

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