

Development and implementation of fuzzy logic using microcontroller for buck and boost DC-to-DC converter

J. Lorenzo Jr.¹, J.C. Espiritu², J. Mediavillo³, S.J. Dy⁴, R.B. Caldo⁵

Gokongwei College of Engineering, De La Salle University – Manila, 2401 Taft Ave. Malate, Manila, 1004 Metro Manila Philippines

E-mail: ¹jomel_lorenzo@dlsu.edu.ph, ²jean_espiritu@dlsu.edu.ph,
³jazelle_mediavillo@dlsu.edu.ph, ⁴stephen_dy@dlsu.edu.ph,
⁵rionel.caldo@dlsu.edu.ph

Abstract. This paper aims to develop and implement a Sugeno-style fuzzy inference system using a microcontroller for buck and boost DC-to-DC converter. The buck converter circuit is given an input voltage range of 4-5V and expected to have an output voltage of 1.5V, while the boost converter has an input voltage range of 2-3V and expected to have an output voltage of 15V. A microcontroller will be used for the input values, PWM signal, which is supplied through the MOSFET. The constants in the program in the microcontroller were manipulated to acquire desired accurate output voltages wherein the concept of fuzzy logic was applied. The proponents achieved less than 2.5% tolerance in the buck converter and less than 5% in the boost converter.

1 Introduction

Electronic circuits are typically sensitive low-power as it could handle up to the threshold voltage of 12V DC. However, batteries that serve as DC sources only give off voltages around its rating. This instance gives the need of devices that step up or step down the DC voltage, which is in the form of the boost converter and buck converter respectively.

DC-to-DC conversion is the process that changes one DC voltage to a different DC voltage level. The two conversion devices are the buck converters and boost converters, with the root word converter being also known as *choppers*, these are static devices which steps down or steps up the input voltages, respectively. These devices are powered by DC sources like batteries, solar panels, rectifiers, and DC generators that do not provide a stable voltage supply. Furthermore, DC-DC converter is essentially a useful electrical circuit for almost all electrical devices, such as laptops, portable radios, cellular phones, with components that run various levels of voltage requirements and those which are primarily supplied with power from batteries [1]. Applications of DC-DC converters include battery chargers, USB On-The-Go, Power Audio Amplifiers, and Brushless Motor Controllers.

The buck and boost controller involves the implementation of a fuzzy logic. **Fuzzy logic** is an approach to being computed based on the “degrees of truth” rather than the usual “true or false” Boolean logic the modern computer bases on. This logic includes 0 and 1 as extreme cases of truth but also various states of truth in between [7]. Thus, the rules that will be implemented in the program will control the Pulse Width Modulation (PWM) which will serve as the input for the dc-dc buck and boost converter [2].

Similarly, this study will develop and implement a Sugeno-style fuzzy inference system using a microcontroller for both buck converter circuit and boost converter circuit with an input voltage range



of 4 to 5V, and an output voltage of 1.5V and an input voltage range of 2 to 3V and an output voltage of 4V respectively. Both circuits aim to function similar to its theoretical values with a maximum of 10% percentage error. Furthermore, this study will utilize a microcontroller in order to control the Pulse Width Modulation (PWM) for the input gate of the metal-oxide silicon field effect transistor (MOSFET).

2 Theoretical Framework

2.1 Buck converter

A *step-down converter* called Buck converter is a DC-to-DC power converter which steps down input voltage and steps up current. As the name implies, it attenuates or chops the input voltage [2]. It efficiently converts a high voltage level to a low voltage level. The switch could come in either MOSFET or Bipolar Junction Transistor (BJT) as a switching transistor. This is useful where electrical isolation is not needed between the switching circuit and the output.

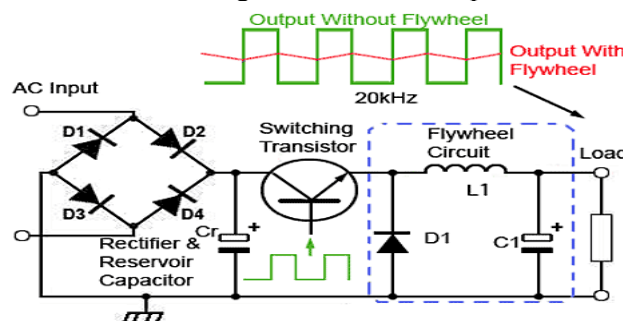


Figure 1: Buck converter circuit

The buck converter consists of the switching transistor and the flywheel circuit. While the transistor is on or serves as a closed switch, then the current flows through the inductor [5].

Initially, current flow on the load is restricted because of the magnetic field building up around the coil of the inductor. During this period, the capacitor C1 and the load will continuously build up charge as the transistor is on its ON state. The diode D1 however is negligible during the ON period since large positive voltage is on D1 making it reverse biased.

When the switching transistor is OFF, the energy stored in the collapsing magnetic field around L1 will flow back into the circuit, causing the current to flow through the load and D1, which is forward biased. Once L1 has released almost all the stored energy to the circuit, the load voltage begins to decrease. The C1 will be discharged as it becomes the main source of current to keep current flowing through the load until the next ON period begins.

2.2 Boost converter

On the other hand, a *step-up converter* called **boost converter** is a DC-to-DC power converter which steps up voltage and steps down current from its input at the supply to its output at the load. It gives off an output voltage greater than the supply voltage, which is dependent on the duty cycle of the switch. The output current is lower than the input or supply current as well.

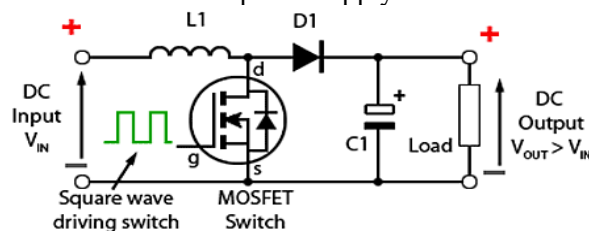


Figure 2: Boost converter circuit

A boost converter as shown in Figure 2, consists of a diode, switching MOSFET, capacitor, inductor and a load. During start-up, the MOSFET conducts, placing a short circuit from L1 to the negative input supply terminal, enabling a current flow which stores energy in its magnetic field [5].

Whenever the switching MOSFET is ON with the clock signal being logic high, D1 is turned off. The load is supplied from the charge on C1. Although the charge C1 drains away through the load during this period, C1 is recharged every time the MOSFET switches off, thus maintaining an almost steady output voltage across the load. Whenever the switching MOSFET is turned OFF with the clock signal being logic low, L1 will produce a back emf in the reverse polarity to the voltage across L1 due to a sudden drop in current.

The buck and boost controller involves the implementation of a fuzzy logic. Fuzzy logic is an approach to being computed based on the “degrees of truth” rather than the usual “true or false” Boolean logic the modern computer bases on. This logic includes 0 and 1 as extreme cases of truth but also various states of truth in between.

3 Design Consideration

3.1 Fuzzy Logic Model

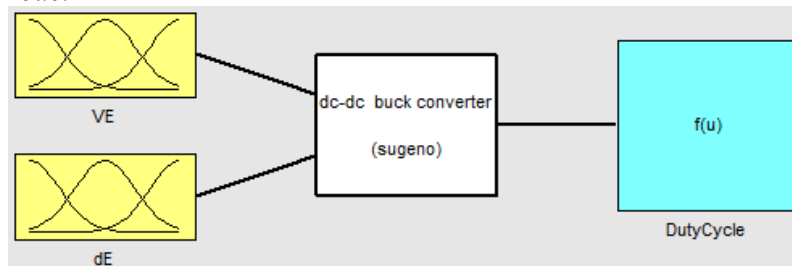


Figure 3: Model of the Fuzzy Logic in MATLAB

A significant tool based on fuzzy set theory is Fuzzy Interference System (FIS). It is made up of domain experts and used in automated control, decision analysis and other numerous systems [1]. The voltage output of the buck and boost converter is dependent to the input voltage and duty cycle applied to the gate of MOSFET. As shown in Figure 3, the proponents model the fuzzy logic using MATLAB and considered the voltage error (VE) and change in error (dE) as a factor in changing the duty cycle with respect to the input voltage. VE is the difference of the target output voltage and actual output voltage whereas the dE is the difference between the present error and previous error. After the VE and dE are obtained, Equation 1 will be used to compute the normalized values ranging from -1 to 1.

$$Xi_{-1 \text{ to } 1} = [Xi - ((Xmax + Xmin)/2)] / ((Xmax - Xmin)/2) \quad (1)$$

Where:

Xi = each data point i

Xmin = minima among all the data points

Xmax = maxima among all the data points

Xi_{-1 to 1} = data point i normalized between -1 and 1

After the normalization process, VE and dE will be used for the next step, the fuzzification process, as seen in the membership function in Figure 4 and 5. The voltage error (VE) and change in error (dE) is categorized into five variables namely Negatively Big (NB), Negatively Small (NS), Zero Area (ZO), Positively Small (PS), and Positively Big (PB).

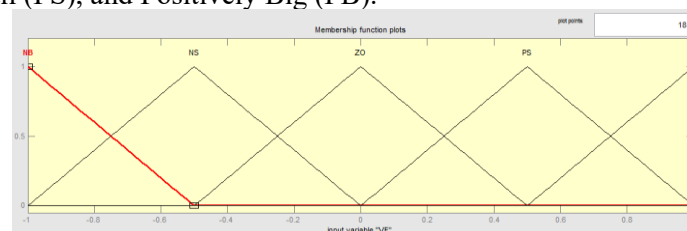


Figure 4: Triangular Membership Function for Buck and Boost Converter (Voltage Error)

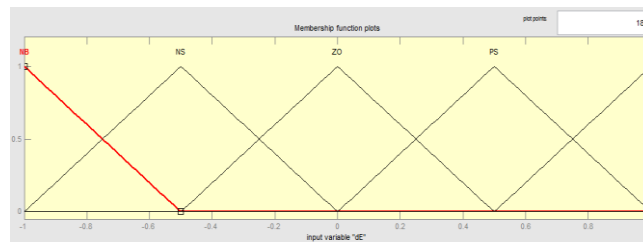


Figure 5: Triangular Membership Function for Buck and Boost Converter (Change in Error)

Figure 6 illustrates the Sugeno-style membership function of the duty cycle. Figure 7 and 8 illustrate the 3-D representation of the membership function of VE, dE, and output duty cycle.

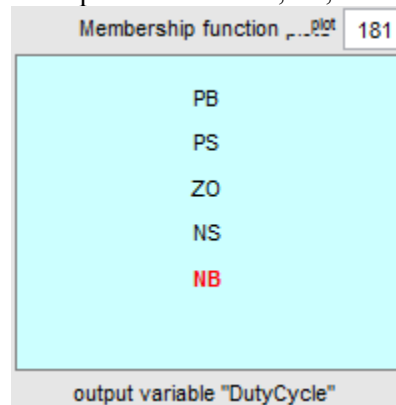


Figure 6: Membership Function in MATLAB

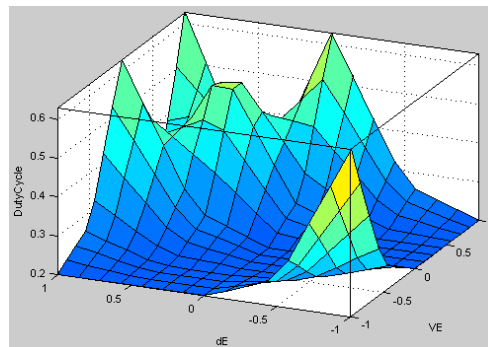


Figure 7: 3-D Representation of the Triangular MF for Buck Converter

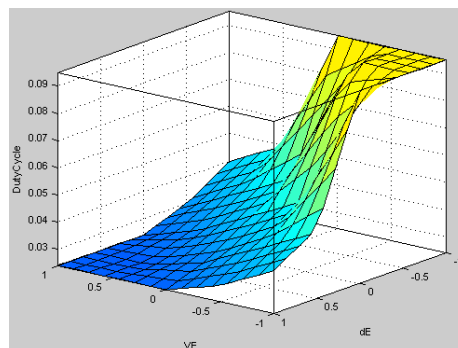


Figure 8: 3-D Representation of the Triangular MF for Boost Converter

3.2 Rule Assignment

After the fuzzification process, the values obtained for VE and dE in each category in the membership function will be used for the rule assignment. The proponents implemented AND function for the rules assignment to determine the output duty cycle. Moreover, the proponents implemented fuzzy

assessment matrix (FAM) of 25 rules to cover all possibilities of the input in voltage error and change in error. Table 1 and 2 shows the duty cycle rule assignment for Buck and Boost Converter.

Table 1: Duty Cycle Rule Assignment for Buck Converter

		dE				
		NB	NS	ZO	PS	PB
VE	NB	NS	ZO	PS	PB	PS
	NS	ZO	PS	PB	PS	ZO
	ZO	PS	PB	PS	ZO	NS
	PS	PB	PS	ZO	NS	NB
	PB	PS	ZO	NS	NB	NS

Table 2: Duty Cycle Rule Assignment for Boost Converter

		dE				
		NB	NS	ZO	PS	PB
VE	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

3.3. Output Duty Cycle

The application of rules assignment will be used to compute the output duty cycle by center of gravity or weighted average. The weights are determined for each rule by choosing the lesser value between VE and dE for each fuzzy set. Equation 3 is the formula to compute for the center of gravity.

$$\text{Center of gravity} = \frac{\sum_{i=1}^n o_i \cdot \mu_i}{\sum_{i=1}^n \mu_i} \quad (2)$$

3.4 Circuit Design

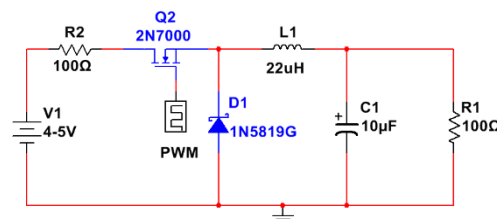


Figure 9: Buck converter portion

The buck converter portion has an input voltage ranging from 4 V to 5 V, a target output voltage of 1.5 V, and a tolerance of 10%. A digital clock signal, which is given off on the actual circuit by a microcontroller, is connected to the gate of the MOSFET serving as a switch. It has a frequency of 100 kHz, duty cycle of 73%, and no delay time. It uses 2N7000 N-Channel MOSFET as its switching transistor and the 1N5819G Schottky diode as its diode.

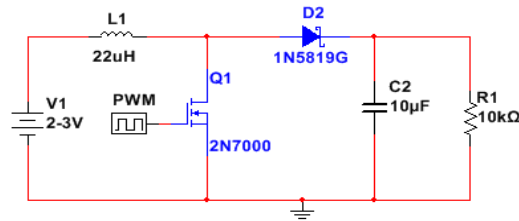


Figure 10: Boost converter portion

On the other hand, the boost converter portion has an input voltage range of 2 V to 3 V, a target output voltage of 4 V, and a tolerance of 10%. It also has a digital clock signal fed into the gate of the switching MOSFET. It has a frequency of 250 kHz, duty cycle of 70%, and no delay time. It uses 2N7000 N-Channel Small Signal MOSFET as its switching transistor and the 1N5819G Schottky diode as its diode.

A microcontroller is used to check the values of input and output voltages that goes through the circuit. It also manipulates the PWM signal and duty cycle going through the circuit. In order to be able to acquire the fuzzy values or constants, the code used in the microcontroller must be converted into C language to be able to run it using Dev-C++.

4 Experimental Result

After wiring and testing the circuit on the breadboard, the proponents immediately fabricated the circuit on a Printed Circuit Board (PCB). The microcontroller outputs a PWM signal to the switching MOSFET with a duty cycle which is a function of the output voltage. The output voltage was measured and checked whether it is within the range of the tolerance or the percent error. If the output voltage is not achieved, the duty cycle will be calculated repeatedly until the output voltage reached the target voltage or if it is within the range of the tolerance value.

Table 3 shows the obtained constant values for the duty cycle which produces the least error of the output voltage.

Membership function	Buck Converter	Boost Converter
PB	0.2	0.095
PS	0.2	0.05
ZO	0.27	0.04
NS	0.63	0.03
NB	0.2	0.024

Table 3: Obtained constant value for output duty cycle membership function for buck and boost converter

Given an output voltage of 1.5 V and assuming there is less than 10% tolerance, the duty cycle of the buck converter portion and its corresponding input voltages can be computed by using eqtn.1. The input voltage V_{in} was personally ranged from 4 V to 5 V, incrementing also by 0.1 V. This was set as it is dependent on the voltage capacity of the microcontroller, which could handle only up to a maximum of 5 V.

The input voltage ranging from 4 to 5 V is expecting an output voltage of 1.5V and the proponents managed to acquire less than 2.5% tolerance or percent error. The constants in the program in the microcontroller has a major effect in acquiring accurate output voltage. It was also observed that higher iterations lead to more stable result. Refer to Table 4 for the obtained output voltage and duty cycle of the circuit.

Table 4: Result for Buck Converter

V_{range}	D%	Iterations	V_{out}	% error
4	62.87	3	1.529	1.9333
4.1	61.03	7	1.533	2.2000
4.2	59.08	5	1.537	2.4667
4.3	56.43	5	1.535	2.3333
4.4	54.68	5	1.522	1.4667
4.5	51.86	5	1.52	1.3333
4.6	50.37	5	1.52	1.3333
4.7	48.93	5	1.521	1.4000
4.8	47.75	5	1.518	1.2000
4.9	46.28	5	1.521	1.4000
5	44.9	3	1.521	1.4000

Given an output voltage of 15 V, the duty cycle of the boost converter and its corresponding input voltages can be computed by using eqn.2 The input voltage ranges from 2 V to 3 V, incrementing also by 0.1 V and with the same condition on Arduino's capability.

The input voltage ranging from 2 to 3 V is expecting a boost of 15V and the proponents managed to acquire less than 5% tolerance or percent error. Unlike to buck converter, the boost only has a constant iteration of 1 which means it has less stable result but similar to the buck converter, the constants in the program in the microcontroller has a major effect in acquiring accurate output voltage. Refer to Table 5 for the obtained output voltage and duty cycle of the circuit.

Table 5: Result for Boost Converter

V_{range}	D%	Iterations	V_{out}	% error
2	6.63	1	14.28	4.8000
2.1	5.88	1	14.52	3.2000
2.2	5.55	1	14.86	0.9333
2.3	5.01	1	15.03	0.2000
2.4	4.15	1	15.07	0.4667
2.5	3.6	1	14.81	1.2667
2.6	3.31	1	14.8	1.3333
2.7	3.11	1	14.98	0.1333
2.8	2.96	1	15.25	1.6667
2.9	2.8	1	15.25	1.6667
3	2.43	1	14.88	0.8000

5 Conclusion

The proponents were able to implement buck converter circuit and achieved the desired output voltage of 1.5 V with an input voltage range of 4V to 5V, as well as the boost converter circuit with an input voltage range of 2-3V and achieved the desired output voltage of 15 V. A fuzzy logic controller was developed using Sugeno-style Method for buck and boost converters. By trial and error method, the constants were varied to produce the least error of the output voltage. A fuzzy logic technique was applied in this paper for acquiring the PWM duty cycle of both dc-dc buck and boost converters. The proponents achieved a 2.5% tolerance in the buck converter and 5% tolerance in the boost converter.

6 Recommendation

Further experiments and study must be performed to be able to build a more efficient buck and boost converter circuits. Mastery in using the fuzzy logic is still needed to acquire the best result.

Acknowledgements

The proponents would like to thank first and foremost the Almighty God, our Father in heaven for making everything in regards to our project possible, to Him be the glory, Engr. Rionel Belen Caldo for guiding us all the way and the whole team for accomplishing the project.

References

- [1] R. Caldo, "Fuzzy Logic Simulation of DC-DC Boost Converter Using Matlab Fuzzy Logic Toolbox", *International Journal Of Information Systems*, vol.1, pp. 36-41, (2014).
- [2] R. Caldo, "Realization of Fuzzy Logic Controller for DC-DC Buck Converter in an FPGA," *Journal of Engineering Science and Technology*, vol. XX, Y.
- [3] R. Caldo and R. Yap, "Design, Development and Implementation of a Fuzzy Logic Controller for DC-DC Buck and Boost Converter in an FPGA". pp. 73-78, (2013).
- [4] R. Caldo and R. Yap, "Simulation of Fuzzy Logic Controller for DC-DC Buck and Boost Converter in Three Programming Platforms". *Asia Pacific Industrial Engineering and Management System*.
- [5] E. Coates, "Buck and Boost Converters," 2007. [Online]. Available: <http://www.learnaboutelectronics.org/PSU/psu31.php>. [Accessed 24 November 2016].
- [6] MathWorks, "What Is Sugeno-Type Fuzzy Inference?," [Online]. Available: <https://www.mathworks.com/help/fuzzy/what-is-sugeno-type-fuzzy-inference.html>.
- [7] "What is fuzzy logic?," [Online]. Available: <http://whatis.techtarget.com/definition/fuzzy-logic>.