Analysis and Design of a Fuzzy Logic Controlled Buck Boost Converter For a Wind Turbine Power Generation

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Abstract

The problem of the wind Turbine power generator is that the available of wind is unpredictable, and its speed is generally variable in nature, such that the output voltage will be variable at all time, so it is necessary to compensate the power generated when the wind speed is low, by boosting the voltage output, and when the wind speed is high, it should be controlled to reach the required output voltage.
A Microcontroller Arduino UNO is used as the main controller to control the duty cycle of a PWM signal generated to regulate the output voltage of the system. Fuzzy logic control of the Mamdani type algorithm is used in this case. The system has been developed, analyzed, and validated by simulation study using Proteus Design Suite 8.4. and the results show that the target voltage can be regulated very well.

Keywords

buck-boost *converter*, fuzzy logic control, wind turbine, Proteus, Arduino.

1. Introduction

As the demand for electricity has been increasing lately, the development for small-scale power plants has been encouraged to meet the community electricity needs. As an alternative, a renewable energy source is used for a small to medium scale power plant. One of the Renewable energy source in this case is the wind turbine power generator. The problem of the wind Turbine power generator is that the available of wind is unpredictable, and its speed is generally variable in nature, such that the output voltage will be variable at all time, so it is necessary to compensate for the power generated. When the wind speed is low, it can boost(step-up) the voltage output, and when the wind speed is high, it should be able to buck(reduced) the voltage output, such that the required output voltage maintained reasonably constant at all time.

A battery array is often used to store the produced electric power but if the charging voltage is varied too much, it may shortened the battery life-time. By using buck-boost *converter*, the fluctuating voltage output from the wind turbine generator can be regulated to the rated value of the battery voltage so that it can be used to charge the battery, and it may not decrease the durability of the battery storage.

This paper is focused on the efforts design and build a buck boost converter to regulate the voltage produced by the wind-turbine in order to achieve a fixed desired output voltage of 12 V at all times

2. The Buck Boost Converter

Buck-boost converter is a type of converter that can convert the output voltage to be larger than (Boost-ing) or smaller than (Buck-ing) the input voltage. In this papaer we are considering an inverting buck coot converter, in which the polarity of the output voltage will be opposite to the polarity of its input voltage. The set-up of buck-boost converter is shown in Figure 1. The circuit consists of a switch S to be controlled, inductor L, diodes D, filter capacitor C, and a load resistor R_L, which represents the whole load such as batterays and electronic equipments.

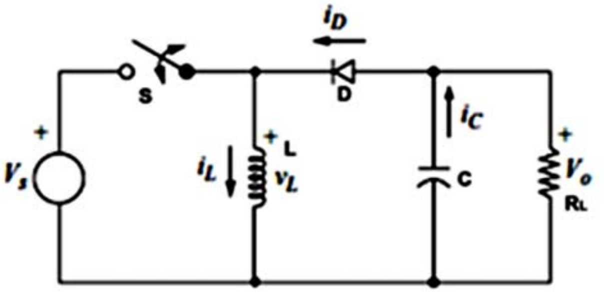


Figure 1. The Buck-Boost converter circuit.

The switch S is under controlled to “ON” or “OFF” state at the switching frequency(F_s) of 1/T, where T is the period, having a ratio of the “ON” condition known as the duty cycle(DT) that is equal to t_{on}/T, where t_{on} is the time interval when the switch is in the “ON” state.

The principle of operation of the buck-boost converter can be described as follows.. In the time interval $0 < t \leq DT$, switch S is “ON” and the diode is “OFF”, is shown in Figure 2. The voltage across the diode is $-(V_i + V_o)$ and keeping the diode reverse biased in the “OFF” state. The voltage across the inductor is V_i and add a linear increment in the inductor current with the slope V_i/L. The voltage across the switch is zero and the diode current is zero. The voltage across the inductor is $V_L=V_i$.

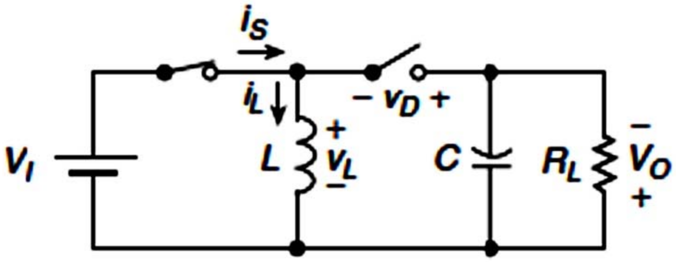


Figure 2. Condition when S is “ON” and D is reversed biased at time interval of 0<t<DT.

The current going through the switch and the inductor L is given by,

$$i_S = i_L = \frac{1}{L}\int_0^t v_L dt + i_L(0) = \frac{1}{L}\int_0^t v_i dt + i_L(0) = \frac{V_i}{L}t + i_L(0) \tag{1}$$

Where $i_L(0)$ is the initial current at the inductor L at time t=0. So the peak current going through the inductor becomes,

$$i_L(DT) = \frac{V_i DT}{L} + i_L(0) = \frac{V_i D}{F_S L} + i_L(0) \tag{2}$$

The peak to peak current is,

$$\Delta i_L = i_L(DT) - i_L(0) = \frac{V_i DT}{L} = \frac{V_i D}{F_s L} \tag{3}$$

The voltage accross the diode is,

$$V_D = -(V_i + V_o) = -V_o\left(\frac{1}{M_{VDC}} + 1\right) = -\frac{V_o}{D} \tag{4}$$

The peak current at the inductor, is the same as the peak current at the switch, ie.,

$$I_{SM} = I_{L(peak)} = I_i + I_o + \frac{\Delta I_L}{2} \tag{5}$$

This time interval ended when time reaches t=DT, and the switch is made to "OFF" state by an external driver. Inductor current i_L is a continuous function of time. The current $i_L(DT)$ is maintained when the switch is turned on, because the inductor acts as a current source. therefore the diode is turned into an "ON" state.

This condition happens during the time interval $DT < t \leq T$, the switch is in "OFF" state and the diode is in the "ON" state, as shown in the Figure 3. The voltage across the inductor is $-V_o$ and causes the inductor current to decrease linearly with a slope $-V_o/L$. The voltage on the switch is V_i+V_o. The current I_D flows through the switch and the diode voltage V_D becomes zero.

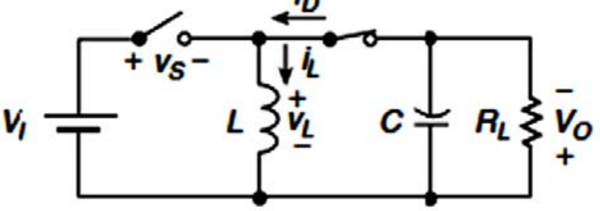


Figure 3. Condition when S is "OFF" and D is forward biased at time interval of DT<t<T

The voltage across the inductor L is $V_L = -V_o$, and The current flows through the diode and the inductor is,

$$i_D = i_L = \frac{1}{L}\int_{DT}^{t} v_L dt + i_L(DT) = \frac{1}{L}\int_{DT}^{t}(-v_o)dt + i_L(DT) = -\frac{V_o}{L}(t-DT) + i_L(DT) = -\frac{V_o}{L}(t-DT) + \frac{V_i D}{F_s L} + i_L(0) \tag{6}$$

$i_L(DT)$ is the initial current at the inductor at time t=DT. The peak to peak current going through the inductor L is,

$$\Delta i_L = i_L(DT) - i_L(T) = \frac{V_o T(1-D)}{L} = \frac{V_o(1-D)}{F_s L} \tag{7}$$

The peak voltage at the switch and the diode is,

$$V_{SMmax} = V_{DMmax} = V_{imax} + V_o = \frac{V_o}{D_{min}} \tag{8}$$

The peak current at the switch and the diode is,

$$I_{DM} = I_{L(peak)} = I_i + I_o + \frac{\Delta I_L}{2} = \frac{I_o}{1-D} + \frac{\Delta I_L}{2} \tag{9}$$

And the maximum peak current will be,

$$I_{DMmax} = I_{SMmax} \approx I_{imax} + I_{omax} + \frac{\Delta I_{Lmax}}{2} = \frac{I_{omax}}{1-D_{max}} + \frac{\Delta I_{Lmax}}{2} \tag{10}$$

The Maximum DC current Input occurs when the duty cycle is maximum,D_{max}, while the maximum ripple current peak-to-peak occurs when the duty cycle is minimum,D_{min}. At the time t=T when the switch in "OFF" state is ended then the switch is made return to "ON" state again by an external driver.

From the above equation, $V_i = V_o(1-D)/D$. so that[2]

$$\Delta I_{Lmax} = i_L(DT) = \frac{V_i DT}{L} = \frac{V_o(1-D_{min})}{F_s L_{min}} \tag{11}$$

Therefore the minimum value of the inductance is given by,

$$L_{min} = \frac{R_{Lmax}(1-D_{min})^2}{2F_s} \tag{12}$$

The output Section of the buck-boost converter is shown in Figure 4, which is indicated by a capacitance filter with a capacitor C and ESR (Equivalent Series Resistance of the capasitor) symbolized by the R_C. The DC component of the inductor current will be balancing the DC load current (I_o). The AC component of the inductor current flows through the capacitor C and load resistance R_L.

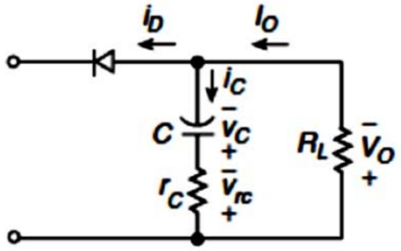


Figure 4. output section of the converter.

The capasitor peak to peak current is

$$I_{Cpp} = I_{DM} \approx I_i + I_o = \frac{I_o}{1-D} \tag{13}$$

The capasitor maximum peak to peak voltage is,

$$V_{Cpp} = \frac{V_o D_{max}}{F_s R_{Lmin} C_{min}} \tag{14}$$

The the minimum Capasitance value of the capasitor C is,

$$C_{min} = \frac{V_o D_{max}}{F_s R_{Lmin} V_{Cpp}} \tag{15}$$

3. The Fuzzy Logic Controller

The output voltage of the buck-boost converter is controlled by the varying the duty cycle of the PWM signal generated by a microprocessor, which is used to control the length of time the switch S closed as shown in the Figure 5 below.

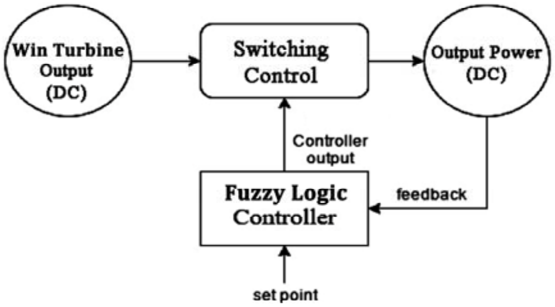


Figure 5. Closed Loop Control of the converter.

In respect to our past experience in designing the controller using a PID type control, which had been succesfull as reported in Wahab2016, in this paper we would like to extend our research to use a more sophisticated controller, such as the Fuzzy Logic controller. This is also due to the fact of having a non-linear switching characteristics of the buck boost converter. The fuzzy logic controller is shown in the Figure 6 below. And implemented using a microprocessor Arduino-Uno.

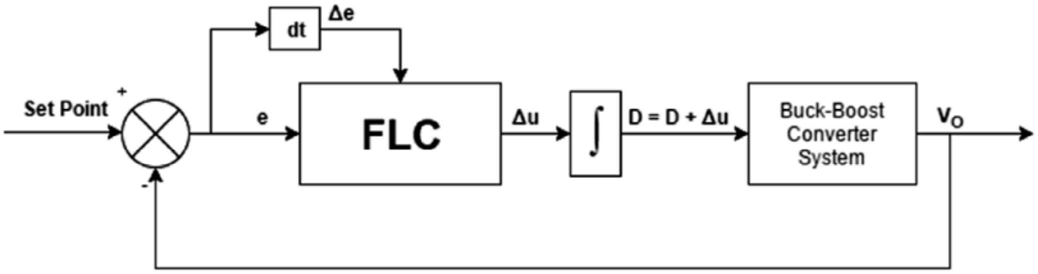


Figure 6. the Fuzzy Logic Controller set-up for closed loop control.

The Fuzzy logic system itself consists of four important components, which are: fuzzification, Knowledge base, inference mechanism, and defuzzification. As shown in figure 7 below. At the fuzzification process, it takes the crips inputs of error and the change of error, and convert them in to fuzzy quantity using the membership functions defined at the input stage. The Output Voltage V_o value is read, and sent to the micro controller, and then compared to the setpoint, the error and change of error are calculated as :

CurrentError= VoltageSet – ActualVoltage (16)

ChangeOfError = CurrentError – PastError (17)

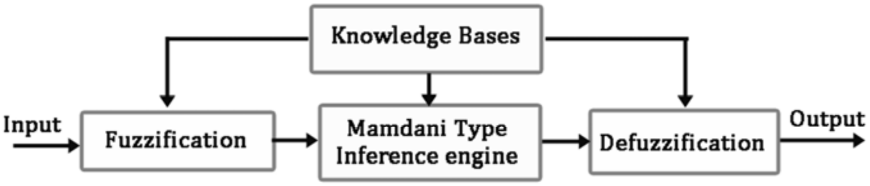
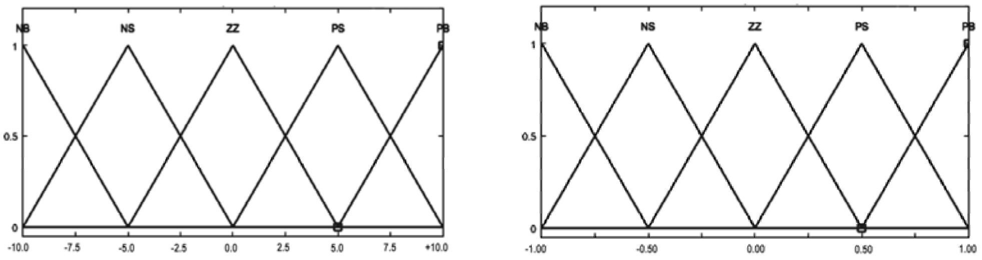


Figure 7. the four component inside the Fuzzy Logic system.

These two information is then fed in to the Fuzzy logic controller, to be fuzzified, using the membership function defined in the FLC for the Error(e) and the Change of Error(Δe) as shown in figure 4 below, each group contained only five triangular shaped membership functions, which named NB(=Negative Big), NS(=Negative Small), ZZ(=Zero), PS(=Positive Small) and PB(=Positive Big) with appropriate normalized scales.



Error(e) **change of error**(Δe)

Figure 8. Membership Function at input stage for Error and Change of Error.

At the output stage, the FLC uses 9(nine) triangular membership functions as shown in figure 9 below in order to have more variations to the out put stage. The memberships are NVB(Negative Very Big), NB(Negative Big), NM(Negative Medium), NS(Negative Small), ZZ(Zero), PS(Positive Small), PM(Positive Medium), PB(Positive Big) and PVB(Positive Very Big).

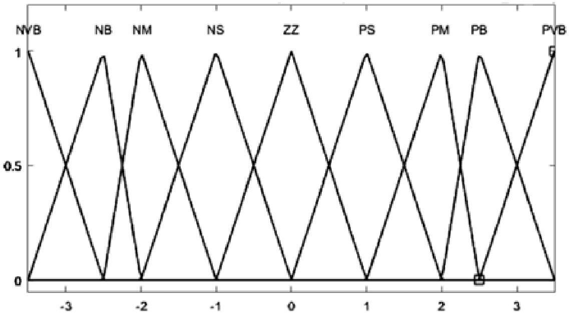


Figure 9. Membership Function at output stage.

In the knowledge base, it contains fuzzy rules in the form of IF-THEN rules as for example, one of the rule is as follows :

IF Error **IS** NB **AND** ChangeOfError **IS** PS **THEN** output **IS** NS

There are 25(twenty five) such rules are entered in the fuzzy knowledge base, as listed in the table 1 below, and it will be used by the Inference engine to deliver a conclusion of the rules, the inference engine applied in this work is the mamdani type inferences or The Max-Min inferences.

Table 1. A table of the Fuzzy rules in the knowledge base

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

At the Defuzzification proses, the Fuzzy logic system will convert the fuzzy quantity from the output of the inference engine, in to a crips quantity, such that it can be use by the controller, the defuzzification method uses the Centre of Area (CoA) as follows.

$$CoA = \frac{\int f(x).x.dx}{\int f(x)dx} \qquad (18)$$

The x is the fuzzy variable, and the integration is taken for the whole range of the inference result. The CoA is a crips quantity representing the value to be used as the increment or decrement of dutycycle(ΔD), by appropriate de-scaling in the algorithm. The control output is $u = (D_{(k-1)} + \Delta D)$, that will change the duty cycle of the PWM signal used to control the switching of the switch S.

4. The Circuit Design

The design of the buck-boost converter is done by first determining the values of each type of component using the equations (12) to (15) given before, then the apropriate component values are adjusted to the nominal values that available in the market. The design is based on the specification listed in table 2. below. And the results of the design calculation is given in table 3 below. The switch S is replaced by a MOSFET Transistor IRF7233 which is capable of high current flow. The MOSFET is driven by a BJT transistor 2N2222 to quarantee the proper switching of the MOSFET since the PWM signal output from the microcontroller is very small, so that this BJT transistor may provide the required current to drive the MOSFET to go in to saturation when switching occurs.

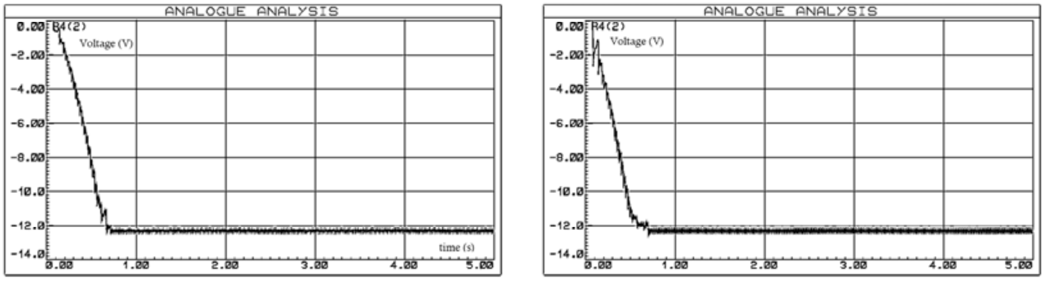
Tabel 2. The Design Specification Parameter

Description	specification
The minimum input Voltage $V_{i(min)}$	5 V
The maximum input Voltage $V_{i(max)}$	50 V
The output voltage V_o	12 V
The Target Load Resistance	3.6 Ω
The minimum output current $I_{o(min)}$	2 A
The maximum output current $I_{o(max)}$	5 A
The Minimum output Power $P_{o(min)}$	50 W
The Maximum output Power $P_{o(max)}$	100 W
switching frequency (fs)	7812,50 Hz
Ripple Voltage (ΔV_O)	< 1% of V_o
Minimum Duty cycle D_{min}	0,20
Maximum Duty cycle D_{max}	0,80

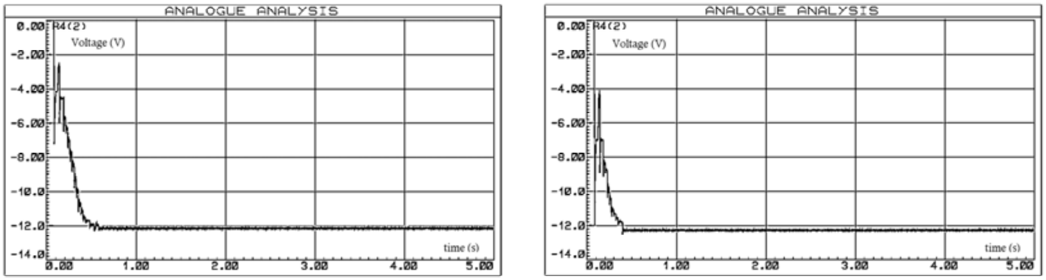
Table-3. Design Results for component values.

Description	specification
The rated output current Io	3.0 Amp
The load resistance (RL)	3.6 Ohm
The minimum value of Inductance (Lmin)	220 μH
The peak-to-peak inductor current ΔiL(min)	3,20 A
The maximum current input Ii(max)	9 Amp
The Output Capasitance (Cout)	4000 μF

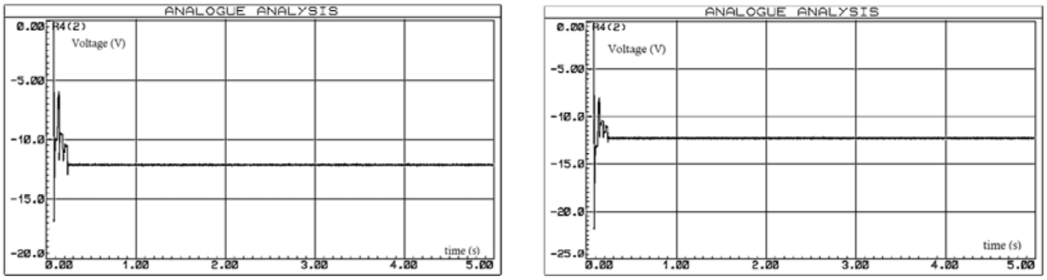
5. Experiment Results and Discussions



(a) Time Response for input Vi=5V **(b) Time Response for input Vi=10V**



(c) Time Response for input Vi=20V **(d) Time Response for input Vi=30V**



(e) Time Response for input Vi=40V **(f) Time Response for input Vi=50V**

Figure 10. the time response results for inputs 5V to 50V.

The experiments are done for several cases where the input voltage applied is set to start from as low as 5 V, then increases to 10 V, 20 V and so on until reaching as high as 50 V. The value of the input voltage is set to constant value for each experiment as a step function in order to see the transient response time and the settling time of the output characteristics. The experiment results are showin in figure 10. And all the output voltages are in the negative value due to the fact that this is an inverting-type Buck boost converter.

It is shown that for input voltage from 5V to 10 volts, the output voltage may achieved 12.4Volts with a settling time of 0.7 seconds, and the ripple is 0.1V as required. When the input voltage is 20V to 30V, the settling time reduced to 0.4-0.5 seconds and the output voltage reach 12.2V. the experiment with input voltage 40V and 50V, the output voltage is 12.2V to 12.3V for with the settling time is less than 04.secodns, but there are high peaks voltage during the transient response. For all experiments the ripple can be as small as 0.1 volt as expected and the transient time tends to be longer when the input voltage is lower than the value of the desired output voltage.

6. Conclusions

This paper has presented the design of a buck-boost converter to meet the specifications using the available components in the market. The output voltage of the Wind Turbine can be well regulated by the converter to achieve the voltage around 12.2V to 12.4V such that it can be used for charging the batterays as required. The ripple voltage can achieved 0.1V as required, the settling time is around 0.4 to 0.7 seconds, the settling time tends to be longer when the input voltage is lower than the value of the desired output voltage.

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