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Hybrid Fuzzy-PID Controller for Buck-Boost Converter in Solar Energy-Battery Systems

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HYBRID FUZZY-PID CONTROLLER FOR BUCK-BOOST CONVERTER IN SOLAR ENERGY-BATTERY SYSTEMS

by

Karime Farhood Hussein

A thesis submitted to the Graduate College in partial fulfillment of the requirements for the degree of Master of Science in Engineering (Electrical) Electrical and Computer Engineering Western Michigan University May 2015

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HYBRID FUZZY-PID CONTROLLER FOR BUCK-BOOST CONVERTER IN SOLAR ENERGY-BATTERY SYSTEMS

Karime Farhood Hussein, M.S.E.
Western Michigan University, 2015

In the present work, we propose a hybrid fuzzy PID control system to prevent overshoot and oscillations in DC-DC buck-boost converter for solar-battery system. We design and simulate a PID, a Fuzzy logic controller, and hybrid fuzzy PID control system to stabilize the output voltage of the buck-boost converter. The performance results using dynamic response of all of these controllers in terms of rise time, overshoot, peak time, and voltage oscillation are presented. The simulation results support the validity and advantages of the hybrid method.
ACKNOWLEDGEMENTS

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Karime Farhood Hussein
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CHAPTER 1
INTRODUCTION AND RESEARCH OBJECTIVES

1.1 Background

There is no doubt that Photovoltaic (PV) systems will have great significance in the future of energy systems if not the center spot among all. In fact, solar energy systems offer the advantage of low fuel costs and lower maintenance needs over other energy systems. However, PV systems do come with some disadvantages such as: (1) relatively low conversion efficiency, and (2) inconstant output voltage due to irregular sun power which due to weather changes which makes PV systems nonlinear. PV systems have been used for many different applications including smart grids. A PV system is able to produce wide ranges of voltages and currents at terminal output; however, a PV output is inconsistent due to unregulated sun power. A PV cell, therefore, must generate a constant DC voltage at the desired level for the application, regardless of variations of light illumination and temperature. In this thesis, we investigate how to design and simulate a control system to stabilize the output voltage of the buck-boost converter due to changing the solar cell’s output voltage. We will present the performance differences among different intelligent controllers including hybrid fuzzy PID controllers, fuzzy logic control, PID, PI, and PD.

To address the inconstant output voltage, DC-DC converters have been used to control the PV output voltage and power. DC-DC converters allow DC voltage source to become a controlled DC voltage source, where the output voltage of the converter can be controlled directly by changing the duty cycle of the switch. The value of the output voltage of the converter can be lower or higher than the value of the input voltage.
depending on the type of DC-DC converter used. There are many different types of DC-DC converters, such as buck, which is a step down converter, boost, which is a step up converter, and buck-boost, which is a step down-step up converter. The DC-DC converter is widely used in electronics applications as a voltage regulator and as isolation tool between the source and the load to provide protection for the load. For example, boost converters are used in satellite dish auxiliary power supplies, cellular phones, smart phones, and LCD TVs[4]. In all PV systems a DC-DC converter is used as an interface between the PV array and the load, this converter will control the PV output voltage so that we can harvest maximum power under varying environmental conditions.

Fuzzy control has been found to be a very suitable control method for nonlinear applications, such as controlling the speed of DC motors. In fact, FLC has been shown to have faster transient response and better results over other controlling methods [1]. Fuzzy logic control (FLC) has been proposed to control the converter of PV systems [6, 8, & 9]. FLC controls the behavior of PV systems by converting a linguistic control strategy into an automated decision strategy achieved by using a predetermined rule base. Indeed, fuzzy sets provide a simple way to reach specific decisions from vague or imprecise information.

The proportional-integral-derivative (PID) controller is considered an important controller for industrial applications. The two primary factors leading to the continuous use of PID controllers in industrial applications are (1) the ease of understanding of the PID controller setting, and (2) the availability of PID controller functionality in SCADA software and programmable logic controllers (PLCs)[2]. A proportional-integral (PI) controller is a common control close loop feedback used in industrial control system. PI
controllers are the same as PID controllers; however, PI controllers do not use the derivative (D) of the error. A PI controller is used when fast response of the system is not required but a large noise is present during the process. Another controller similar to PID is the proportional-derivative (PD), which is also a classic control technique, but does not use the integral of the error. One advantage of this control is the ability to measure temperature with a low level of noise making the measurement more accurate. PD controllers are often used in controlling moving objects including aircrafts and rockets. The PID controller depends on the value of the gains, namely the $K_p$, $K_i$, and $K_d$ values [3].

1.2 Problem Statement

The problem that PV systems have is that the output voltage is dependent on weather conditions, namely temperature and irradiance. These conditions, especially irradiance, can change rapidly leading to severe variations in the output voltage from the source. This will change the load operating point. The necessity of a voltage regulator is obvious. The problem at hand is how to control the regulator, achieving satisfactory specifications such as transient response and steady state error. Classical controllers such as PI, PID have been used previously that may have undesirable transient response. In this work, a hybrid fuzzy logic based PID controller is analyzed and designed to control the Dc-Dc converter acting as a regulator. The transient response parameters and steady state errors are investigated to conclude the benefits of such a control system.
1.3 Pertinent Literature

The control of the output voltage of the DC-DC converter has been widely and successfully implemented using different control techniques. Recently, Sahin and Okumus proposed an FLC of the buck-boost DC-DC converter PV for a battery-load system [5]. In another study, Sahin and Okumus used FLC with two membership functions to control the output voltage of the converter [6]. Using gauss membership functions, they presented an output voltage that was very close to value of the reference voltage, and it did not show any overshoot or large ripples.

Martínez-Teran et al. [7], also, have designed and implemented a buck converter for a PV system using a PIC18F4550 microcontroller to control the battery charging voltage. Their results show that the fuzzy controller is capable of stabilizing the output in a time of 30ms. If the buck converter is subjected to a change in load. Ismail et al. discussed two control methods, PID controller and FLC, to fix the output voltage of the DC-DC buck-boost converter for PV arrays [8]. By comparing the results of these techniques, it appears the FLC is more stable when dealing with different reference voltage value than PID controller [8].

Reshmi et al. have used a new technique to control the output voltage of the DC-DC converter using the hybrid fuzzy PI controller [9]. The output voltage has less variation when using the hybrid fuzzy PI controller over FLC. Abbas et al. presented the fuzzy logic based robust PID controller for pulse-width modulation based switching converter, which provides a robust control for non-linear power electronics variable switching structures [10]. Simulation results showed that fuzzy logic based PID controller is a perfect alternative way to control power converters than the classical controllers.
Abbas et al. were also able to present the ease of applying fuzzy control for DC-DC converters as an interesting alternative to conventional methods.

It should be noted that most designs and implementations in the literature are used to control the DC-DC converter using FLC or PID controller. In this work, we aim to use the hybrid fuzzy PID controller to control the output voltage of the buck-boost converter. In addition, we aim to compare the results of the fuzzy logic control and the classical controller with the hybrid fuzzy PID controller to give a thorough study of the methods. More on classical controller, fuzzy logic control, and hybrid fuzzy PID controller is presented in Chapter 2.

1.4 Goals and Objectives

The objective of this work is to design a model of PV power system which can provide the optimum regulated output voltage. This will be achieved by analyzing performance of seven different control techniques. To achieve such a system, we aim to pursue the following objectives:

1. Design and implement the system’s DC-DC converter (buck-boost) using the proposed hybrid fuzzy PID controller.

2. Design and implement the systems converter using classical controllers. All simulations are performed using MATLAB/SIMULINK environment.

3. Compare and discuss the results of the seven control methods in terms of transient and study state performance or what specifics on the comparison tools.

1.5 Thesis Outline

Apart from the Introduction, this thesis is spread over five further chapters. Chapter 2 provides an introduction to the DC-DC converter, classical controllers, and
fuzzy structure. Chapter 3 presents the mathematical modeling of the buck-boost converter by using different controller methods. In Chapter 4, implementation issues and simulation results are presented. Chapter 5 provides conclusions and further work suggestions for the controlling of the voltage of solar system energy by using the DC-DC converter.
CHAPTER 2
BACKGROUND

2.1 Solar Radiation

The intensity of solar radiation reaching earth’s surface, which is known as solar constant, is 1360 watts per square meter on a sphere with the radius of 149,596,000 km, and with the sun at its center. Total solar irradiance, which is the maximum power that can be delivered by the sun to a surface, is where the surface becomes vertical to the path of incoming light. Only areas near the equator at midday come close to being vertical to the path of incoming light, because of the earth’s spherical shape. The solar radiation that reaches the earth’s surface varies by time and latitude. Figure 2.1 shows the relationship between latitude, time, and solar energy through the equinoxes, and how time of the day (A-E) changes the angle of the sunlight, thus influencing the amount of sunlight reaching the earth. For example, from sunrise until noon, the intensity of sunlight increases where the sun is directly overhead over the equator, while from afternoon to sunset, the intensity of sunlight is decreases [11].

Figure 2.1: The Relationship between Latitude, Time, and Solar Energy [11].
In Figure 2.1, points A to E mark changes in the time of day from 6:00am to 18:00pm.

2.2 Solar Energy

Solar energy is considered a clean and plentiful renewable energy source. Modern technology can take advantage of this energy and use it in different applications. For example, electric power can be generated from solar energy to provide light, a relaxing internal environment, or to heat water for trade and industrial use. In fact, there are several ways to take advantage of solar energy. The most common uses of solar energy are photovoltaic, solar heating and cooling, use in mechanical and electrical devices, and converting the sun’s light or heat to another shape of serviceable energy. There are also passive solar buildings, which are designed to collect, store, and distribute heat energy, and use it without the need of moving parts of electronics. Moreover, because of the flexibility of the solar energy, solar energy plants can be built as a center station or near the point of use [12].

Today, solar cells are becoming an important part of electric power systems, specifically in smart grids. The modern technology, which focuses on power electronics, can also play an important role in solving problems of solar energy generation. Power electronics applications such as AC-DC converter, DC-DC converter, DC-AC inverter, plug-in electric vehicles, and variable speed devices as newer forms of renewable generation are now improved to reduce the cost and increase efficiency of renewable energy sources[13]. Figure 2.2 shows solar cells connected into a smart grid system to provide solar energy.
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![Figure 2.2: Solar Cells in a Smart Grid Model [14].](image)

In Figure 2.2, solar power is connected with the grid system to provide the power for the home. Smart meter is part of the smart grid system and is used to communicate between the load and control center of the grid.

### 2.3 DC-DC Converters

As in AC applications, voltage control devices are needed to step-up and step-down output voltage. The DC-DC converter can be considered as the DC equivalent to an AC transformer with continuously variable turns-ratio. DC-DC converters are very important in all voltage levels applications whether power, medium power or high power
applications low. They are much more efficient than the old way of conversion with transformers, and designed to deliver an output within any desired range. Moreover, DC-DC converters are extensively used in control of electrical drives, one such application is regenerative braking of DC drives, where energy is returned back into the supply [15].

2.3.1 Functions of DC-DC converters

The DC-DC converter is designed to function as follows:

1. Convert a DC input voltage into a different value of a DC output voltage.
2. Regulate the DC output voltage depending on the load and line variations.
3. Provide speed control for many applications by controlling the frequency.
4. Provide protection between the input source and the load.
5. Provide protection for the supplying system and the load from electromagnetic interference [15].

2.3.2 The buck (step-down) converter

The buck converter is a step-down DC-DC converter. The average output voltage is always less than the input voltage. There are two modes for the buck circuit as shown in Figure 2.3. In the first mode, the diode becomes reverse biased when the switch is on, which leads to storage of the supplied energy in the inductor. In the second mode, the diode (D1) becomes forward biased when the switch is off and the load receives the energy from the inductor. The input remains isolated from the output [4].

![Buck Converter Circuit](image)

**Figure 2.3: Buck Converter Circuit. Output voltage (V_o) to be regulated and the input voltage (V_s) is the inconsistent input.**
The main applications of buck converter are in regulated DC power supplies and control dc motor speed [16]. Duty cycle (D) is the ratio of the on time of the switch to the total switching time, and also the ratio of output voltage to the input voltage. The ratio of output to input voltages, which is duty cycle (D), is given by:

\[ \frac{V_o}{V_s} = D = \frac{I_s}{I_0} \]

Where \( V_o \) is the output voltage and \( V_s \) is the input voltage. The \( I_o \) is the output current, and \( I_i \) the input current.

In Figure 2.3, \( V_s \) is the input voltage, \( S \) is a switch, \( V_L \) is the voltage across the inductance, \( V_o \) is the output voltage on the load, \( V_{ref} \) is the reference voltage, \( L, C, D1 \) and \( D2 \), and \( R \) are inductance, capacitance, two diodes, and resistance respectively.

The voltage across the inductor when the switch is closed is expressed by the equation below:

\[ V_L = V_s - V_o = L \frac{dI_L}{dt} \]

\[ \frac{dI_L}{dt} = \frac{V_s - V_o}{L} \]

The voltage across the inductor when the switch is open is determined by:

\[ V_L = -V_o = L \frac{dI_L}{dt} \]

\[ \frac{dI_L}{dt} = \frac{-V_o}{L} \]

### 2.3.3 The boost (step-up) converter

The boost converter, as shown in Figure 2.4, is another switching converter. The output voltage of the boost converter is always larger than the input voltage. As in the
buck converter, the boost converter also has two modes. During the first mode, the switch is closed and the diode is reverse biased. The energy store is in the inductor [4, 15].

![Boost Converter Circuit](image)

**Figure 2.4: Boost Converter Circuit. Output voltage ($V_o$) to be regulated and the input voltage ($V_s$) is the inconsistent input.**

In Figure 2.4, $V_s$ is the input voltage, $S$ is a switch, $V_L$ is the voltage across the inductance, $V_o$ is the output voltage on the load, $V_{ref}$ is the reference voltage, and $L$, $C$, $D1$ and $D2$, and $R$ are inductance, capacitance, diodes, and resistance respectively. The voltage across the inductor is given by:

$$V_L = V_s = L \frac{di_L}{dt} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 2.6$$

The current across the inductor is given by:

$$i = \frac{1}{L} \int_{0}^{t} V_s dt + io \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 2.7$$

In the second mode, the diode becomes forward biased when switched off, and the energy transfers from the inductor to capacitor and the load. The voltage across the inductor is given by:

$$V_L = V_s - V_o = L \frac{di_L}{dt} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 2.9$$

### 2.3.4 The buck-boost converter

A buck-boost converter, which is also known as an *inverting regulator*, is shown in Figure 2.5. As its name clearly indicates, a buck-boost converter provides an output voltage which may be less than or greater than the input voltage. It is a circuit that
combines a buck converter topology with a boost converter topology in cascade. The polarity of output voltage is opposite of the polarity of the input voltage.

![Buck-Boost Converter Diagram](image)

**Figure 2.5: Buck-Boost Converter Diagram. Output voltage \((V_o)\) to be regulated and the input voltage \((V_s)\) is the inconsistent input.**

In Figure 2.5, \(V_s\) is the input voltage, \(S\) is a switch, \(V_L\) is the voltage across the inductance, \(V_o\) is the output voltage on the load, \(V_{ref}\) is the reference voltage, and \(L, C, D1, D2, \text{and } R\) are inductance, capacitance, diodes, and resistance respectively.

There are two modes for the circuit operation. The first mode appears when the transistor is turned on, and diode \(D1\) is reversed biased. During this mode, the input current \(I_L\) flows through the transistor and inductor \(L\). The second mode appears when the transistor Switch is turned off, and the current flows from \(L\) through \(C\), the diode, and the load. The transistor is switched on again in the next cycle when the energy that stored in inductor \(L\) would be transferred to the load and inductor current falls down [4, 15]. The equivalent circuits for both modes are shown in Figure 2.6.
In Figure 2.6, Mode 1 and Mode 2 are the stages of the switch moving during the on and off. Inductor1, capacitor1, diode, Inductor (L), capacitor, and diode are the circuit parameters. $V_{in}$ is the input voltage. The relationship between the input and output voltage with the switch-duty cycle is given by:

$$\frac{V_0}{V_S} = \frac{D}{1 - D} = \frac{I_S}{I_0} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 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• If $D = 0.5$ the output is equal in magnitude to the input [4].

Therefore, we can utilize the buck-boost converter in our PV system such that if the array experiences rapid changing environment conditions load output voltage will be regulated to the reference value by controlling the duty cycle of the converter such that it operates either in buck or boost mode.

2.3.5 **Steady state analysis of the buck-boost converter**

Analysis for the buck-boost converter when the switch is closed is as described below and using figure 2.6.

The voltage across the inductor when the switch is closed is given by:

$$V_L = V_S = L \frac{di_L}{dt}$$  \[2.11\]

$$\frac{di_L}{dt} = \frac{V_S}{L}$$  \[2.12\]

Because the rate of change of inductor current is a constant, Equation (2.12) can be expressed as:

$$\frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_S}{L}$$  \[2.13\]

By solving for $\Delta i_L$ when the switch is closed we get:

$$(\Delta i_L)_{closed} = \frac{V_S DT}{L}$$  \[2.14\]

Analysis for the buck-boost converter when the switch is open is as described below. The current in the inductor cannot change instantaneously when the switch is open [4, 15]. In this case, the voltage across the inductor is given by:

$$V_L = V_0 = L \frac{di_L}{dt}$$  \[2.15\]
\[
\frac{di_L}{dt} = \frac{V_S}{L} \quad \ldots \ldots \ldots \ldots \ldots \ldots .2.16
\]

The same is true when the switch is closed; the rate of change of the inductor current is constant. The change in current is expressed as:

\[
\frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1 - D)T} = \frac{V_0}{L} \quad \ldots \ldots \ldots \ldots .2.17
\]

By solving for \(\Delta i_L\) when the switch is open we get:

\[
(\Delta i_L)_{\text{open}} = \frac{V_0(1 - D)T}{L} \quad \ldots \ldots \ldots .2.18
\]

The net change in inductor current must be zero over one period for the steady-state operation. By solving the two equations 2.14 and 2.18:

\[
(\Delta i_L)_{\text{closed}} + (\Delta i_L)_{\text{open}} = 0 \quad \ldots \ldots .2.19
\]

\[
\frac{V_S DT}{L} + \frac{V_0(1 - D)T}{L} = 0 \quad \ldots \ldots \ldots .2.20
\]

Solving for \(V_0\):

\[
V_0 = V_S \left( \frac{D}{1 - D} \right) \quad \ldots \ldots \ldots \ldots .2.21(a)
\]

Solving for \(D\):

\[
D = \left( \frac{V_0}{V_0 + V_S} \right) \quad \ldots \ldots \ldots \ldots .2.21(b)
\]

Naturally, since the power absorbed by the load must be the same as the power of the source, we get:

\[
P_o = \frac{V_0^2}{R} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots .2.22
\]

\[
P_s = V_S I_S \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots .2.23
\]

By solving the two equations 2.22 and 2.23:
\[ \frac{V_0^2}{R} = V_S I_S \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 2.24 \]

The average source current is related to average inductor current by:

\[ I_S = I_L D \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 2.25 \]

\[ \frac{V_0^2}{R} = V_S I_L D \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 2.26 \]

By substituting for \( V_0 \) and using equation 3.3 and solving for \( I_L \) we find:

\[ I_L = \frac{V_0^2}{V_S DR} = \frac{P_o}{V_S D} = \frac{V_S D}{R(1 - D)^2} \ldots \ldots \ldots 2.27 \]

By solving equations 2.27 and 2.14:

\[ I_{\text{max}} = I_L + \frac{\Delta I_L}{2} = \frac{V_S D}{R(1-D)^2} + \frac{V_S D T}{2L} \ldots \ldots \ldots 2.28 \]

\[ I_{\text{min}} = I_L - \frac{\Delta I_L}{2} = \frac{V_S D}{R(1-D)^2} - \frac{V_S D T}{2L} \ldots \ldots \ldots 2.29 \]

To determine the boundary between continuous and discontinuous current, \( I_{\text{min}} \) is set to zero, which leads to:

\[ (Lf)_{\text{min}} = \frac{R(1-D)^2}{2} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 2.30 \]

\[ L_{\text{min}} = \frac{R(1-D)^2}{2f} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 2.31 \]

Where, \( f \) is the switching frequency and \( L_{\text{min}} \) is minimum value of inductance to insure continuous mode of operation.

The steady state voltages and currents of buck-boost converter are shown in Figure 2.7. In the figure, we notice:

- At the period from zero to \( D \) which is the duty cycle, the value of voltage is one, \( I_L \) is moved from a minimum to maximum at \( D \), \( I_D \) is zero, \( I_C \) is negative value because the discharging from capacitor to the load, \( V_C \) is moved from a maximum value to minimum value at \( D \), and \( I_O \) is constant at one.
• However, from D to T which is the switching time of one period, the value of voltage is negative one. \( I_L \) is moved from a maximum to minimum at T, \( I_D \) goes to maximum point then starts to decrease to the minimum at T, \( I_C \) goes to maximum point then starts to decrease to the negative point at T, \( V_C \) is moved from maximum value to minimum value at T, and \( I_O \) is constant at one [15].

**Figure 2.7: Waveforms of Current and Voltage in a Buck-Boost Converter Operating in Continuous Mode.**
2.4 Fuzzy Logic Controller (FLC)

FLC is widely used in many fields, including the development of household materials such as dishwashers and TVs, and in industry applications. The use of FLC has also been very popular in control systems. The reason for increasing use of FLC is because is ability to use a linguistic form instead of mathematical form to manipulate knowledge. FLCs are designed to fit any model, and are not dependent deterministic mathematical models. FLCs also have other advantages such as low cost and simplicity of control, which makes FLC more used than other classical controllers in many control systems. It is the most important control method for nonlinear systems [1].

2.4.1 Structure of fuzzy logic

There are three principal elements to a fuzzy logic controller, as shown in Figure 2.8. These elements are: 1) the fuzzification module (fuzzifier), 2) the rule base, and 3) the defuzzification module (defuzzifier). The fuzzifier converts the crisp values of the input into fuzzy values to send to the rule base. The rule base is expressed as a set of if-then rules, based on predetermined expert knowledge. The defuzzifier converts the output values of rule base to the crisp values [1][17].

In Figure 2.8, X is the input data. Y is the output data. Fuzzification converts the input data to the fuzzy values. Defuzzification converts the fuzzy output values to crisp values. Fuzzy rule base transfers the fuzzy values to (if) and (then) rules. Decision making logic is used to decide the output value. Membership function is the type of function that is used in fuzzy control, such as triangular MF and Gaussian MF.
2.4.2 Types of membership functions

There are various types of membership functions used in fuzzy set theory, including trapezoidal MFs, Gaussian MFs, and generalized bell MFs. The types of membership functions are shown in Figure 2.9.
2.5 Classical Controller

A general feedback control system is shown in Figure 2.10. The feedback element contains a sensor or transducer that measures physical parameters such as speed and heat, and then converts them into voltage. The main goal of many control problems is to make the output follow the reference input and make the transfer function. Transfer function, the ratio of the Laplace transform (LT) of the system’s output to the LT of the reference signal, is set to equal 1, as shown in Equation 2.32.

\[ T(s) = \frac{C(s)}{R(s)} = 1 \quad 2.32 \]

Where, \( C(s) \) and \( R(s) \) are the LT of the output and the reference signals respectively. The error between the output and reference is given in Equation 2.33, and the output is given in Equation 2.34 and by solving these two equations, the transfer function is found can be determined as shown in Equation 2.35.

\[ E(s) = R(s) - H(s) C(s) \quad 2.33 \]

\[ C(s) = G(s) E(s) \quad 2.34 \]

Figure 2.10: General Feedback Control System[18].
The step response of a control system will be affected by changing the value of the gain due to the adding the feedback of the control system. In Figure 2.11, the P controller had been added to the control system forcing the output to follow the input faster and reduce the error value. By increasing the gain of the P controller, the rise time of system can be decreased, which makes the output follow the input faster and decrease the error. The equation of transfer function is given by:

\[
T(s) = \frac{C(s)}{R(s)} = \frac{G(s)}{1 + G(s)H(s)} = \frac{(s-z_1)\ldots(s-z_m)}{(s-p_1)\ldots(s-p_n)} \quad m < n \quad \ldots \quad 2.35
\]

Where \(G_c(s)\) is the transfer function of the controller, and the \(G_p(s)\) is the transfer function of the plant to be controlled.

**Figure 2.11: General Feedback Control System with Compensation [18].**

In Figure 2.10, \(R(s)\) and \(C(s)\) are the Laplace Transform of the output. \(H(s)\) is the feedback factor. \(G_c(s)\) is the transfer function of the controller. \(G_p(s)\) is the transfer function of the plant to be controlled. \(E(s)\) is the error between feedback factor and open-loop gain. However, by increasing the gain of P to reduce the rise time, the overshoot of the output is increased too, which causes a damped oscillatory output. The system will become critically stable at some point and the output will oscillate with the continuous increase of the gain:
• Adding a derivative term to the system with the gain of P is considered one way to reduce overshoot. Moreover, the derivative term works on decreasing the steady-state error.

• The contribution of the derivative term is zero, while the steady-state error is constant.

• If the steady-state error is time-varying, the derivative term will have a nonzero value which can then be used to reduce the offset; however, the output of a system exhibits an offset of approximately 0.37 for a unit-step input with the PI or a PD controller. Therefore, using PD controller will work as a highpass filter, which passes high frequency components.

• To get output that exactly matches the reference input the system must have zero steady-state errors. One way to remove the error is to add an integral term to the P controller. The transfer function for a PID controller is given below:

\[ G(s) = K_d s + K_p + \frac{K_i}{s} = \frac{K_ds^2 + K_ps + K_i}{s} \]  \hspace{1cm} \ldots \ldots 2.37

By adding an integral term to the control, the control will have the ability to remember the past. The system will have a nonzero output for a zero input when using a PID controller. Figure 2.12 shows the step response of a closed-loop feedback system for P, PD, and PID controllers [18]. In Figure 2.12, a, c, and b show how the type of controller is affected on the step response of the closed-loop feedback system.
2.5.1 PI controller

The PI controller has been used in many industrial applications due to its ability to compensate most practical industrial processes. Most processes of low to medium order are controlled by using PI and PID controllers. More than 85% of control loops are controlled by single input and single output that have led them to use PI and PID controllers [18].

2.5.2 PD controller

A PD controller is a proportional-derivative controller that responds to the rate of change in process error. A PD controller can affect a control system by improving the damping, decreasing the maximum overshoot, and also decreasing the rise and setting time; however, and show noise at higher frequencies [18].

2.5.3 PID controller

Process automation technology has made a great deal of progress since the 1980s. In particular, the processing power of controllers has grown very fast and has influenced the types of controls used in applications. In the past, most controllers used single-loops and a single-variable. Today multi-loop and multi-variables controllers are used in many
applications. The PID controller is the main building block of these control strategies. It consists of a proportional element, an integral element, and a derivative element. Figure 2.13 shows a block diagram of PID controller within any system where all three PID components are connected in parallel. $K_p$, $K_i$, and $K_d$ are the gains of P, I, and D elements, respectively. The error sigma is considered the input of a PID controller.

![Functional Diagram of a PID Control Loop](image)

As stated, in Figure 2.13, $K_p$, $K_i$, and $K_d$ are proportional gain, integral gain, and derivative gain, respectively. Set-point voltage is the desired reference voltage. Error or $(e)$ is the different between set-point voltage and the output voltage. Process is the system to be controlled. Output is the value of the voltage and power used for control, and the time $(t)$ is the instantaneous time (the present). $K_p e(t)$ is the proportional term $K_i \int_0^t e(\tau) d\tau$ is integral term (I). $K_d \frac{de(t)}{dt}$ is the derivative term.

### 2.6 Hybrid Fuzzy PID Controller

The fuzzy logic controller does not need to update precise information for system variables. This is contrary to the classical controller, which does need to update precise information for the system variable to perform to the sensitivity of the classical controller within variations in the system variables. However, the classical controller is better able cannot eliminate steady-state error. Combining of these two controller structures, to
control and minimize the steady state error of the system, while the fuzzy logic control cannot eliminate steady-state error. Combining of these two controller structures, therefore, is one good way to take advantage of categories, i.e., fuzzy logic control and PID controller (hybrid22). Figure 2.14 shows a block diagram of a hybrid fuzzy PID controller with any system.

![Figure 2.14: Block Diagram of Hybrid Fuzzy PID Controller][20]

In Figure 2.14, Error signal is the value of the difference between the reference and the output voltage. Fuzzy logic control in this figure is the proposed fuzzy based control method while the PID is the classical control to control the output voltage. Control voltage process is the processing where the voltage is fixed by the changing the duty cycle. Output voltage is the output delivered to the load.
CHAPTER 3

PROPOSED CONTROLLER METHOD: PV MODEL AND SYSTEM DESIGN

This chapter discusses the design of the whole modules system developed for this study, which includes the buck-boost converter, the photovoltaic arrangements and characteristics, and the fuzzy logic control and classical controller for the buck-boost conversion. The analysis and discussion of the results are in Chapter 4. The flowchart, shown in Figures 3.1, 3.2, and 3.3 presents an overview of the project. We used MATLAB and Simulink to simulate the design of the buck-boost converter, PV cells, the fuzzy logic controller and the classical controller.

3.1 The Design of Buck-Boost Converter

The buck-boost converter was designed with fuzzy logic control, classical controller, and hybrid fuzzy PID control as shown in Figure 3.4, 3.5, and 3.6. To generate the error signal (e), which is the feedback signal of the control, the output voltage \( V_{\text{out}} \) was measured and compared with reference voltage \( V_{\text{ref}} \), that is

\[
e = V_{\text{ref}} - V_{\text{out}} \]

3.1
Figure 3.1: Project Flowchart Featuring Design of the Fuzzy Logic Controller.

Start

Input converter parameters

Setout specifications of the system under consideration

Design DC-DC buck-boost converter circuit to operate in continuous current mode and analysis of converter behavior using MATLAB/ SIMULINK

Design PV Array using MATLAB toolbox software

Design fuzzy logic controller using MATLAB toolbox software

Are specifications met?

Yes

Adopt controller

Results and analysis

End

No

Tune parameters
Figure 3.2: Project Flowchart Featuring Design of the Classical Controller.

Start

Input converter parameters

Setout specifications of the system under consideration

Designing DC-DC buck-boost converter circuit to operate in continuous current mode and analysis of converter behavior using MATLAB/SIMULINK

Design PV Array using MATLAB toolbox software

Designing of classical controller using MATLAB toolbox software

Are specifications met?

Yes

Adopt Controller

Results and analysis

End

No

Tune parameters
Figure 3.3: Project Flowchart Featuring Design of the Hybrid Fuzzy PID Controller.
The two input of fuzzy logic are the error and the change in error. The error was calculated by comparing the output voltage with reference voltage. The change in error was calculated by the present error with previous error.

![DC-DC Buck-Boost Converter FLC Diagram](image)

**Figure 3.4:** DC-DC Buck-Boost Converter FLC. Showing the way of calculating the error using the output and reference voltage and pulse with modulation as output of FLC.

In Figure 3.4, $V_s$ is the input voltage from the PV array, $S$ is a switch. The role of the switch is to alter the topology of the converter. During the On state, the inductor builds and stores energy. When the switch is Off, energy is transferred to the load. $V_L$ is the voltage across the inductance. $V_o$ is the output voltage on the load. $V_{\text{ref}}$ is the reference voltage.

The error ($e$), as shown in Figure 3.5, is found by comparing the reference voltage and the output voltage of the converter that should follow a specified reference value. The output signal of the control is denoted as duty cycle for switch ($S$) of buck-boost converter.
In Figure 3.5 as well as Figure 3.6, $V_s$ is the input voltage from the PV array, $S$ is a switch. The role of the switch is to alter the topology of the converter, when the switch is turned on, the inductor stores energy supplied from the DC source while during the off state this energy is supplied the load. In more details, during the “ON:” state, the inductor accumulates and stores energy. When the switch is “OFF”, energy is transferred to the load. $V_L$ is the voltage across the inductance. $V_o$ is the output voltage on the load. $V_{ref}$ is the reference voltage. The capacitor maintains the load voltage, D2 prevents reverse current, and D1 separates the two modes of operation for this buck boost topology.

The hybrid fuzzy PID control was developed by combining the classical controller and fuzzy logic control to improve the output voltage of the DC-DC buck boost converter. The design circuit is shown in Figure 3.6.
Figure 3.6: DC-DC Buck-Boost Converter with Hybrid Fuzzy PID Control.

In Figure 3.6, the DC-DC buck-boost converter is controlled by using hybrid PID control.

3.2 Photovoltaic Arrangement

The photovoltaic arrangement consists of the photovoltaic cell, the photovoltaic model, and the photovoltaic array. These are as described in the following sections.

3.2.1 Photovoltaic cell

A photovoltaic system is a system that uses one or more panels that consist of many solar cells to convert the solar power into electricity. The photovoltaic cells, which are called also solar cells, are made of semiconductor materials such as silicon and gallium arsenide. A thin semiconductor chip is treated to shape an electric domain and makes the solar cell positive on one side and negative on other side. Electrons are moved in semiconductor materials when light energy strikes the solar cell. If any electrical conductors are connected between the positive and negative sides of solar cell, the electrons can be captured as electric current, which is called electricity[21]. This electricity can be used as a power for loads. The basic structure of the PV cell is shown in Figure 3.7
Figure 3.7 depicts the photovoltaic material (i.e., the silicon structure) in a PV cell, which absorbs sunlight and knocks electrons within the material loose. This process allows the electrons (i.e., negative electrode and positive electrode) to flow within the material structure, and generates an electrical current.

### 3.2.2 Photovoltaic model

The voltage that can be generated by a PV cell is very low, about 0.5V. Therefore, to get the desired power from PV module, several PV cells are connected in series for high voltage, and in parallel for high current. Also, some diodes are put in PV models to avoid reverse currents that are due to the partial or total shading and night. Reverse currents harm the shaded cells by wasting power. They can also lead to increases in temperature, which then decrease efficiency. To avoid this, it is important to provide good ventilation behind solar panels [21].

### 3.2.3 Photovoltaic array

One PV cell cannot produce enough power to meet the demands of a home or business. Therefore, several PV cells are connected for a desired voltage, and then these modules are connected in a series called a *PV array* to reach a desired current. Most PV arrays are connected to a converter to convert DC power to AC power, which can power...
lights, motors, and other loads [21]. Figure 3.8 shows individual PV cells, which are connected into modules, and then into an array.

![Figure 3.8: Photovoltaic Cells, Modules, and Array [23].](image)

As mentioned, Figure 3.8 shows the cell, which is a single PV cell; the module, which is several PV cells, connected together a series of parallel combinations and where all cells are identical; and the array, which consists of several modules connected together in a parallel series to generate the required voltage.

### 3.3 Characteristics of a PV Cell

The PV cell shown in Figure 3.7 can be modeled using the schematic shown in Figure 3.9. The circuit of a PV cell is modeled by a current source in parallel with a diode, adding shunt and resistance in series. In Figure 3.9, the current $I_L$ is the light-generated current as a response to light exposure to the cell, $I_D$ is the current through the diode, $I_{SH}$ is the current through the shunt resistance, $R_{SH}$ is the shunt resistance, $R_S$ is the surface resistance, and $V$ is the output voltage.

![Figure 3.9: Equivalent Circuit of a PV Cell [21].](image)
\[ I_L = I_D + I_{SH} + I \] \[ I_L - I_D - I_{SH} = I \]

The current through the diode can be calculated by using Equation 3.4:

\[ I_D = I_0 \left\{ \exp \left( \frac{q(V + I R_S)}{nKT} \right) - 1 \right\} \] \[ I = I_L - I_0 \left\{ \exp \left( \frac{q(V + I R_S)}{nKT} \right) - 1 \right\} - \frac{V + I R_S}{R_{SH}} \]

Where:

- \( I_D \) is the current through the diode (A),
- \( I_L \) is the light-generated current,
- \( I_0 \) is the reverse saturation current of the diode (A),
- \( q \) is the election charge (1.602x10e-23 C),
- \( K \) is the Boltzmann’s constant (1.381x10e-23J/K),
- \( T \) is the junction temperature in Kelvin (K),
- \( V \) is the output voltage, V
- \( n \) is the completion or factor, A
- \( R_{SH} \) is the shunt resistance which has a very high value, ohm,
- \( R_S \) is the surface resistance, which has a small value, ohm.

Changing the irradiance and temperature changes the value of the current. The characteristic of a PV cell depends on the short circuit current and open circuit voltage, which are provided on the manufacture’s data sheet [21]. The mathematical model that used to represent the PV array is given in Equation 3.6:

\[ I = N_p I_{ph} - N_p I_{Rs} \left[ \exp \left( \frac{q}{K T A} \cdot \frac{V}{N_s} \right) - 1 \right] \]
Where I and V are the output voltage and current of PV array; \( N_s \) is the number of cells in series and \( N_p \) is the number of cells in parallel; \( I_{ph} \) is the PV current; A is the p-n junction ideality factor, which ranges between 1-5; T is the cell temperature (K); \( I_{rs} \) is the reverse saturation current of cell. The value of the reverse saturation current of cell \( I_{rs} \) changes with temperature according to the following equation:

\[
I_{rs} = I_{rr} \left( \frac{T}{T_r} \right)^3 \exp \left( \frac{qE_g}{KAT} \left( \frac{1}{T} - \frac{1}{T_r} \right) \right) \quad \ldots \ldots \ldots 3.7
\]

Where \( T_r \) is the cell reference temperature, \( I_{rr} \) is the cell reverse saturation temperature at \( T_r \), and \( E_g \) is the band gap of the semiconductor used in the cell. The photo current (\( I_{ph} \)) depends on the temperature of cell and the solar radiation; it is given in Equation 3.8:

\[
I_{ph} = [I_{scr} + K_i(T - T_r)] \frac{S}{100} \quad \ldots \ldots \ldots \ldots 3.8
\]

Where \( I_{scr} \) is the short-circuit current of cell at reference temperature and radiation, \( K_i \) is the short circuit temperature coefficient, and S is the solar radiation in mW/cm\(^2\). The power of PV can be found by using Equation 3.9:

\[
P = VI = N_pI_{ph}V \left[ \left( \frac{q}{KTA} \right) \left( \frac{V}{N_s} \right) - 1 \right] \quad \ldots \ldots 3.9
\]

### 3.4 PV Array Characteristic Curves

It is difficult to determine the maximum power point (MPP) for a solar array because the characteristics of current and voltage of the solar array are non-linear. Figure 3.10 shows the MPP and the characteristic of I-V and P-V curves for a solar array at a fixed level of temperature and irradiation [24].
In Figure 3.10, the I-V curve shows the relationship between the array current and the array voltage. The P-V curve shows the relationship between the array power and the array voltage. The MPP is the maximum power point that can be reached by the PV array. \( I_{sc} \) is the maximum short current at the load. \( V_{oc} \) is the maximum voltage at the open circuit.

The curves of I-V and P-V are shown in Figures 3.10 under a fixed temperature (i.e., 25\( ^{\circ} \)C) and various levels of irradiance. The characterized I-V curve shows that there are two regions in the curve, which are the current source region and the voltage source region. In the left hand side of I-V characteristic, one can observe the output current is nearly constant as the voltage changed from zero to the voltage at the knee point. In the right hand side of I-V characteristic, we can notice that the output voltage is nearly constant as the current falls from its \( I_{sc} \) value to zero. Both the irradiance and the temperature affect the characteristics of I-V. Therefore, during the design of a PV system, the effects of temperature and irradiance have to be considered [21].

### 3.5 Fuzzy Logic Control for the Buck-Boost Converter

The output voltage of a DC-DC buck-converter is controlled by the fuzzy logic control (FLC). The FLC uses linguistic variables as input instead of numerical variables.
The fuzzifier converts the numerical values of the input into fuzzy values (i.e., linguistic variables). The error \( e(k) \) and change in error \( \Delta e(k) \) are calculated from the two equations below. The error is the difference between the buck-boost output voltage and reference voltage, while the change in error is difference between the present error and previous error [1].

\[
e(k) = V_{\text{ref}} - V_{\text{out}} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 3.10
\]

\[
\Delta e(k) = e(k) - e(k-1) \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 3.11
\]

The variables and rule base table describe the control algorithm. The rule base depends on the error signal \( e(k) \), the change in error signal \( \Delta e(k) \), and switching duty-cycle signal. For this project, the rules for inputs and output of the fuzzy logic controller are represented in Table 3.1. The \( e(k) \), \( \Delta e(k) \), and duty cycle axes are divided into three regions which are positive, negative, and zero regions. Each region is divided into sub-regions, including Negative Big (NB), Negative Small (NS), Positive Small (PS), and Positive Big (PB). There are different types of membership functions that are used to represent the rules base infuzzy logic control (FLC) such as Gaussian membership function and trapezoidal membership function [1].

Table 3.1: Rules Base of Fuzzy Logic Controller.

<table>
<thead>
<tr>
<th>( \Delta e(k) )</th>
<th>NB</th>
<th>NS</th>
<th>Z</th>
<th>PS</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>PB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z</td>
<td>PS</td>
<td>PS</td>
<td>PB</td>
<td>PB</td>
</tr>
<tr>
<td>PS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NS</td>
<td>Z</td>
<td>PS</td>
<td>PB</td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td></td>
<td>NS</td>
<td></td>
<td>PS</td>
<td>PS</td>
</tr>
<tr>
<td>NS</td>
<td></td>
<td>NB</td>
<td>NS</td>
<td>Z</td>
<td>PS</td>
</tr>
<tr>
<td>NB</td>
<td></td>
<td>NB</td>
<td>NS</td>
<td>NS</td>
<td>Z</td>
</tr>
</tbody>
</table>
In Table 3.1, 25 fuzzy control rules are used according to the practical operation experience.

In this thesis, triangle membership functions were used for each error \( e(k) \) and the change in error \( e(k) \), change in error, and duty cycle of fuzzy variable. In Figure 3.11, 3.12, and 3.13, the error, the error variation, and the duty cycle of the input and output data of the FLC’s input and output variables are shown. The input space data of the FLC for the error vary between -10 and 10 [25], while the data for the error variation vary between -1 and 1 [25]. The output space data vary between -0.8 and 0.8 (which was decided by trial and error). Due to the 5-ruled input variables, there are 25 rules in total [25].

![Figure 3.11: Triangle MF for Error.](image1)

![Figure 3.12: Triangle MF for Change in Error.](image2)
In Figures 3.11, 3.12, and 3.13, the vertical axes represent the degree of membership, which is normalized from zero to one. The horizontal axes represent the selected inputs and output parameters of the error, change in error, and the duty cycle. The N, P, and Z are negative, positive, and zero region respectively. The NB, NS, PS, and PB are sub-region of positive and negative region such as NB is negative big, NS is negative small, PS is positive small, and PB is positive big.
Figure 3.14: Fuzzy Rules in Simulink. Where the NB, NS, PS, and PB are negative big, negative small, positive big and positive small sub-region respectively.

In Figure 3.14, I show the units for the rule processing. The general rules can be written as:

- If $e(k)$ is PB and $\Delta e(k)$ is NB, then $D$ is Z.
• If $e(k)$ is PS and $\Delta e(k)$ is NB, then $D$ is NS.

• If $e(k)$ is Z and $\Delta e(k)$ is NB, then $D$ is NS.

• If $e(k)$ is NS and $\Delta e(k)$ is PB, then $D$ is PS.

In Figure 3.14, there are 25 rules due to the 5-ruled input variables, which are NB, NS, Z, PS, and PB. The derivation of the fuzzy logic control rules is heuristic in nature, and based on the following criteria:

1. When the output voltage ($V_0$) is far from the set point, which is the reference voltage ($V_{ref}$), the change of duty cycle must be large to bring the output voltage ($V_0$) to the nearest value as same as of the reference voltage ($V_{ref}$) quickly.

2. A little change of duty cycle value is necessary when the output voltage ($V_0$) of the converter is approaching the set point, which is the reference voltage ($V_{ref}$).

3. The duty cycle must be kept constant to prevent overshoot when the output voltage ($V_0$) of the converter is near the set point, which is the reference voltage ($V_{ref}$), and is approaching it rapidly. The speed of changing can be measured by the period of time changing between the input and the output voltage converter.

4. The duty cycle must be changed a little bit to prevent the output voltage from moving away from the reference voltage ($V_{ref}$).

5. The duty cycle remains unchanged when the set point, which is the reference voltage ($V_{ref}$), is reached and the output voltage ($V_0$) is steady.

6. The sign of the change of duty cycle must be negative, and vice versa when the output voltage ($V_0$) is above the set point, which is the reference voltage ($V_{ref}$) \[26]\[27].

The triangle membership function is expressed in Equation 3.12, and its Simulink subsystem is shown in Figure 3.15.
\[ \mu_{MU}(x) = \left( \min \left( \frac{x - x_1}{x_T - x_1}, \frac{x_2 - x_1}{x_2 - x_T} \right), 0 \right) \]  

Figure 3.15: Simulink Subsystem on the Triangular Membership Function [27].

In Figure 3.15, X, X1, X2, and XT represent the points that are specified the width of membership function on horizontal axis, which is represented by the error and changing in error values.

3.6 Classical Controller for the Buck-Boost Converter

The classical controller is used instead of fuzzy logic control for the photovoltaic model with buck-boost converter to compare its performance with FLC. The proportional integral derivative (PID) controller is used as classical controller. A PID controller uses proportional, derivative and integral operations to reduce the tracking error in a system to get the desired step response for the system. The function of each of these operations is controlled by the value of the gain. These gains are called \( K_p \), \( K_d \), and \( K_i \). The parameters
are usually fixed during an operation. Therefore, the PID controller is inefficient for controlling a system while the surrounding environment of the system is changed [28]. The main equation of PID controller is given by:

\[ U(t) = Kp e(t) + Ki \int_0^t e(\tau) d\tau + Kd \frac{d}{dt} e(t) \]  

\text{3.13}

Where, \( e(t) \) the input error that is calculated by compared the output voltage with reference voltage.

In Figure 3.16, the PID controller in MATLAB/Simulink is shown.

**Figure 3.16: Structure of the PID Controller in MATLAB/Simulink.**

In Figure 3.16, the parameter \( u \) is the error signal, \( P \), \( I \), and \( D \) represent the PID gain parameters, and \( y \) represents the output signal of PID.

Finally, decreasing and increasing of the value of gain is affected by the response speed, stability, and accuracy, as explained in Table 3.2.
Table 3.2: Rules for the Gains of the PID Controller [3]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Speed of Response</th>
<th>Stability</th>
<th>Accuracy of the output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increasing $K_p$</td>
<td>Increases</td>
<td>Deteriorates</td>
<td>Improves</td>
</tr>
<tr>
<td>Increasing $K_i$</td>
<td>Decreases</td>
<td>Deteriorates</td>
<td>Improves</td>
</tr>
<tr>
<td>Increasing $K_d$</td>
<td>Increases</td>
<td>Improves</td>
<td>No impact</td>
</tr>
</tbody>
</table>
CHAPTER 4

RESULTS AND DISCUSSION

4.1 Parameters used in the MATLAB/SIMULINK

The values of the parameters used in developing the MATLAB/Simulink for photovoltaic array with buck-boost converter using different controllers under varying environmental conditions as shown in Table 4.1.

Table 4.1: Simulation Parameters of the DC-DC Buck-Boost Converter. The PV model parameters are: \((N_s=90, N_p=1, R_s=0.0051, P_o=85W, I_o=4.75A@18V; P_o=18W, I_o=2.25A@8V;\) and PV input voltages are 8 Volt & 18 Volt)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>PI</th>
<th>PD</th>
<th>PID</th>
<th>Fuzzy</th>
<th>Fuzzy &amp; PI</th>
<th>Fuzzy &amp; PD</th>
<th>Fuzzy &amp; PID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Voltage</td>
<td>12 Volt</td>
<td>12 Volt</td>
<td>12 Volt</td>
<td>12 Volt</td>
<td>12 Volt</td>
<td>12 Volt</td>
<td>12 Volt</td>
</tr>
<tr>
<td>Filter Inductance</td>
<td>133e-5H</td>
<td>133e-5H</td>
<td>133e-5H</td>
<td>133e-5H</td>
<td>133e-5H</td>
<td>133e-5H</td>
<td>133e-5H</td>
</tr>
<tr>
<td>Filter Capacitance</td>
<td>100.67e-3F</td>
<td>100.67e-3F</td>
<td>100.67e-3F</td>
<td>100.67e-3F</td>
<td>100.67e-3F</td>
<td>100.67e-3F</td>
<td>100.67e-3F</td>
</tr>
<tr>
<td>Output Resistance</td>
<td>10ohm</td>
<td>10ohm</td>
<td>10ohm</td>
<td>10ohm</td>
<td>10ohm</td>
<td>10ohm</td>
<td>10ohm</td>
</tr>
</tbody>
</table>

| \(K_p\)      | 0.0033    | 0.01765   | 0.00641   | 0         | 800        | 50         | 900         |
| \(K_i\)      | 0.0081    | 0         | 0.01385   | 0         | 300        | 0          | 0.1         |
| \(K_d\)      | 0         | 0.00167   | 0.00053   | 0         | 0          | 0.5        | 0.1         |

In MATLAB environment, PID Tuner provides a fast and widely applicable single-loop PID tuning technique for the Simulink PID controller blocks. By using this method, the PID parameters, which are \(K_p\), \(K_i\), and \(K_d\) can be easily tuned to achieve a robust design and reach the desired response time.
4.2 Output Waveform of the PV Array

The design of the PV model is built by using MATLAB/Simulink software. In order to model the PV model, solar cells are connected together in series/parallel combinations, and where all cells are identical to build a PV array to generate the required voltage to generate the desired power. The numbers of solar cells that are used in this project are 100 cells, which are connected in series to generate the required voltage for this model. The structure of PV model is shown in Figure 4.1 below.

![Figure 4.1: Structure of the PV Module.](image)

In Figure 4.1, the PV cells are connected together in series/parallel combinations and, where all cells are identical to build a PV array to generate the required voltage.

In Figure 4.2, the output voltage of PV array is shown. The value of the output voltage is between 18V and 8V.
In Figure 4.2, the output voltage that is generated by using PV cells. The voltage value, which depends on weather conditions, is 18V from 0 sec to 5 sec, and then changes to 8V from 5 sec to 10 sec.

4.3 Generation of the PWM Signal

The pulse width modulation (PWM) is a modulation technique that is used to control the width of the pulse signal. The main use of the PWM is to control the power supply of the electrical device, and to control the value of the voltage in photovoltaic array output by controlling the switch between the supply and the load. The PWM controls the switch by turning it on and off in a very fast manner, which is the duty cycle of the switch. Figure 4.3 shows a comparison of a ramping waveform with the intended DC level generation of the PWM. Moreover, the output of the op-amp swings high when the triangle waveform voltage is greater than the DC level. However, the output of the op-amp swings low if the triangle waveform voltage is lower[29].
Figure 4.3: Comparison of a Ramping Waveform with a DC Level PWM.

In Figure 4.3, the triangle wave is compared with DC level voltage, which is represented by the input error signal of the control, and has a value that depends on the difference between the output converter voltage and the reference voltage.

4.4 Simulation Results and Discussion

The developed model of PV is simulated for different solar irradiation and constant temperature level. Simulation results are demonstrated in Figures below. These Figures show that with change in the input voltage of PV system, the output voltage on the load is constant.
The output voltage of the buck-boost converter is dependent on the value of the duty cycle. The value of the duty cycle is changed between 0 and 1. The relationship between the duty cycle and the output and input voltage is found by equation (2.21(b)), and explained by the following two points:

1. If the duty cycle value $D < 0.5$, the output voltage $(V_o)$ < input voltage $(V_{in})$.
2. If the $D$ is larger than 0.5, the output voltage will be more than the input voltage

Therefore, the control is important to make the output voltage be constant at 12V for any value of the duty cycle. In this thesis, we used the classical, fuzzy, and hybrid fuzzy control to make the output voltage constant while keeping stable acceptable system performance as the numerical values will show in the following sections.

In classical control, I started with PI control testing. When reference voltage was at 18V, the output voltage has a rise time equal 0.246 seconds with 1.2157V maximum overshoot and settling time 1.35 second. The system arrives to steady state output voltage which is equal 12V without overshoot and voltage oscillation. However, the output voltage at a voltage reference of 8V has dropped to 1.2157V at the 7th second mark. The
steady state output voltage reaches then the desired 12V without oscillation as shown in Figure 4.5 and Table 4.3.

**Figure 4.5: Output Voltage with PI Control. Reference of 12 volts.**

The PD control results, shown in Figure 4.6, show no overshoot. However, the output voltage at 18V reference is 11.63V and at reference 8V the output voltage is 11.2V also without oscillation. It is clear that PD controller has failed to reach the desired voltages.

**Figure 4.6: Output Voltage with PD Control. Reference of 12 volts.**
Third, the PID control results are as shown in Figure 4.7 and Table 4.3. The output voltage has maximum overshoot which is equal 0.7318V, the rise time is 0.217 seconds, and settling time 1.345 seconds. The output voltage at steady state is equal 12V after 1.8sec. However, the output voltage at 8V reference has dropped voltage which is equal 0.7318V until arrive to 7sec. The steady state output voltage after that is 12V without overshoot and voltage oscillation.

![Output Voltage with PID Control](image)

**Figure 4.7: Output Voltage with PID Control. Reference of 12 volts.**

By using the fuzzy logic control, as shown in Figure 4.8, the rise time is 1.5457 second, settling time 2.5 second, and the output voltage has a 0.3941V voltage oscillation at steady state voltage, which is 12V. In this case, the system has long rise time and voltage oscillation at steady state voltage.
Figure 4.8: Output Voltage with Fuzzy Logic Control. Reference of 12 volts.

In hybrid fuzzy logic control, fuzzy PI control response, which is shown in Figure 4.9, shows that the output voltage has a rise time which is equal 0.12 sec with overshoot 0.2554V and settling time 0.3713 second, but the output voltage has a voltage oscillation equal to 0.255V until arrival at 5 sec. After that, the output voltage is a pure 12V without any voltage oscillation. The system has a better rise time and voltage oscillation than the output voltage using the fuzzy logic case.

Figure 4.9: Output Voltage with Hybrid Fuzzy PI Control. Reference of 12 volts.
In fuzzy PD control, as shown in Figure 4.10, the output voltage has voltage oscillation equal to 0.2V until arrival at 5 sec. After that, the output voltage is pure 12V without voltage oscillation. Also, the rise time equals 0.12 second with overshoot0.1304V and settling time 0.166 second. In this case, the system has less voltage oscillation, less overshoot, and less settling time than fuzzy PI control response. The comparison between various controllers is summarized in tables 4.3 & 4.4.

![Output Voltage with Hybrid Fuzzy PD Control](image)

**Figure 4.10: Output Voltage with Hybrid Fuzzy PD Control. Reference of 12 volts.**

In fuzzy PID control as shown in Figure 4.11, the output voltage has a rise time equal to 0.12 sec without overshoot and voltage oscillation and settling time 0.158 second. The system in this case has robust characteristics because it has very short rise time, no voltage oscillation, and accurate desired voltage compared to all cases before. Therefore, the circuit under this control always makes satisfactory results.
Figure 4.11: Output Voltage with Hybrid Fuzzy PID Control. Reference of 12 volts.

Table 4.3: Rise Time, Maximum Overshoot, and Oscillation. As well as drop voltage values when the reference voltage is changed, and steady state voltage for the classical controllers and hybrid fuzzy PI, PD, and PID controllers with a 12V reference voltage.

<table>
<thead>
<tr>
<th>Controllers</th>
<th>PI</th>
<th>PD</th>
<th>PID</th>
<th>FLC</th>
<th>FPI</th>
<th>FPD</th>
<th>FPID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise time (sec.)</td>
<td>0.2460</td>
<td>0.3220</td>
<td>0.2170</td>
<td>1.5457</td>
<td>0.1200</td>
<td>0.1200</td>
<td>0.1200</td>
</tr>
<tr>
<td>settling time (Sec.)</td>
<td>1.3500</td>
<td>0</td>
<td>1.3450</td>
<td>2.5007</td>
<td>0.3713</td>
<td>0.1660</td>
<td>0.1580</td>
</tr>
<tr>
<td>Maximum overshoot (V)</td>
<td>1.2157</td>
<td>0</td>
<td>0.7318</td>
<td>Not applicable</td>
<td>0.2554</td>
<td>0.1304</td>
<td>0.0939</td>
</tr>
<tr>
<td>Oscillation (V)</td>
<td>No applicable</td>
<td>No applicable</td>
<td>No applicable</td>
<td>0.3941</td>
<td>0.255</td>
<td>0.13</td>
<td>0</td>
</tr>
<tr>
<td>Steady stats voltage at 18V</td>
<td>12</td>
<td>11.6349</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Drop voltage (V) at 18v input voltage</td>
<td>No applicable</td>
<td>0.37</td>
<td>No applicable</td>
<td>Not applicable</td>
<td>Not applicable</td>
<td>Not applicable</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Drop voltage (V) at 8v input voltage</td>
<td>1.2157</td>
<td>0.8</td>
<td>0.7318</td>
<td>Not applicable</td>
<td>Not applicable</td>
<td>Not applicable</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Steady stats voltage at 8V</td>
<td>12</td>
<td>11.2</td>
<td>12</td>
<td>12.5</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
</tbody>
</table>
CHAPTER 5
CONCLUSION AND FUTURE WORKS

In this thesis, buck-boost converters modeling and performance analysis using classical, fuzzy, and hybrid fuzzy PID controllers is presented. The three types of the classical controllers, PI, PD, and PID tested in the DC-DC buck-boost converter for PV system. In PI control, the system was unstable for long time because it had a very short rise time with high overshoot. In PD control, the system had a short rise time without overshoot, but the output voltage did not stabilize at the desired voltage. In PID control, the system had a very short rise time with overshoot; however, the system took a long time to settle into the steady state value of 12V.

The fuzzy logic controller had the system arrive at the desire voltage after a long rise time and with a high voltage oscillation. In fuzzy PI control, the system had a very short rise time with a very small overshoot, but the system had voltage oscillation too. In fuzzy PD control, the system had a short rise time with less oscillation than fuzzy PI. In fuzzy PID control, the system had a very short rise time without overshoot, and the system had less voltage oscillations than the fuzzy PI and fuzzy PD controls. The hybrid fuzzy PID control system was also very stable showing a good performance and outperforming all the other classical controllers and the same system conditions.

Future work should include more realistic time analysis that includes a variety of non-uniform irradiance conditions onto the PV array. This can be conducted by using a microcontroller and perhaps varying the load on the buck-boost converter while still allowing variations in input voltage to the buck-boost converter. Also, it is important to include other fuzzy controller designs to include more complex mappings to improve the
performance of a DC-DC buck-boost converter in conjunction of a photovoltaic (PV) array usage.
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